Cybersickness induced by movement within virtual reality on a mobile platform

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Abstract

This project will be facing the movement challenges of mobile virtual reality experiences based on mobile platforms, by testing empirically five different ways of locomotion (teleportation, tunnel vision, blink step, dash step and swinging the controller) within a given virtual space (climbing/hiking on a mountain and walking/reading in a museum). Exploring a mountain requires a more goal-directed approach in User Experience (UX), while the other relies on storytelling design. The experiment will consist of a mobile application encompassing the two scenarios and five locomotion techniques followed by a survey to quantify the participants' feedback. The application will be developed in Unity and its scripts written in C#.

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1. Introduction

1.1. Background

Virtual reality (VR) is now ongoing extensive amount of research, as the new technology has implications in many fields including medicine. Its reach extends to treating mental health problems such as PTSD (McLay et al. 2011), anxiety (McLay et al. 2011; Repetto et al. 2011) and pain control (Sato et al. 2010; Hoffman et al. 2014; Hoffman et al. 2011). However, exposure of an user within a virtual environment (VE) has shown a range of uncomfortable symptoms such as headaches, nausea, vertigo, disorientation and eye strain (LaViola 2000; Stanney & Hash 1998; Lo & So 2001; Regan & Price 1994; Kim et al. 2005). Many of them are due to cybersickness (LaViola 2000; Stanney & Hash 1998; Lo & So 2001; Regan & Price 1994; Kim et al. 2005), a newly founded term denoting a sense of nausea and disorientation similar to sea sickness or car sickness, produced by a disbalance between what the inner ear of the user perceives and what the visual cues observe (Davis et al. 2014).

The current research focus relies on desktop systems such as Oculus Rift and HTC Vive (Davis et al. 2014; Cobb et al. 1999; Regan 1995), in contrast to mobile ones like Samsung Gear VR, Daydream or Google Cardboard which are more affordable on the market (Powell et al. 2016). The former have considerable hardware advantages to the smartphones, offering room-scale sensors for user tracking within a set spatial space (Waller et al. 2007), better display resolution and greater processing power. The best VR hardware available on mobile platforms is incapable of reaching the major headsets' performances and it lacks in creating visual feedback about the real world to the user (Fang et al. 2017). Moreover, standalone systems such as Lenovo Mirage Solo or Oculus Go are just launching, henceforth no specific published research has been conducted just yet. They are head-mounted displays (HMD) which use frontal cameras to map the surrounding space of an user, compared to the sensors the desktop headsets use. For this study, the Daydream VR headset for smartphones is used, which provides a small Bluetooth-connected controller. Hence it allows VR developers with more possibilities of implementing movement, compared to any other mobile headset.

One of the components of virtual reality inducing cybersickness is the locomotion mechanics (So & Lo n.d.; McCauley & Sharkey 1992; Howarth & Finch 1999; Chance et al. 1998). The current paper defines "locomotion" as the ability to move from one place to another by feet, and "movement" will be often times used as a synonym. In Nabiyouni et al. (2015), the authors categorised locomotion techniques in natural, semi-natural and non-natural types. The natural way of moving in a virtual space would be to physically walk or run (Slater et al. 1994), while the semi-natural one involves the use of additional systems such as a treadmill (Slater et al. 1995). Non-natural ways of locomotion include the use of game controllers, which desktop headsets and DayDream currently use. These require the user's engagement with the buttons and following certain visual cues for relocation within a virtual space.

Keywords: cybersickness, locomotion, mobile platform, movement, virtual reality

1.2. Aims and objectives

The experiment will examine and evaluate the cybersickness effects of 5 different commonly used locomotion types within the context of two scenarios.

Objectives:

1. **Research report**

- Research and find at least two cybersickness causes and effects in virtual reality within two days (1-2 days)
- Research and discuss the most common locomotion techniques used by head-mounted displays experiences and mobile platforms within a working week (3-5 days)
- Research and analyse at least two user experience studies in mobile virtual reality for exploration scenarios within three days (2-3 days)
- Write 700 words for the Introduction Chapter within three days (2-3 days)
- Write 2000 words for the Literature review Chapter within a working week (3-5 days)

2. **Design documentation**

- Research and apply at least two user interface guidelines used in virtual reality interfaces within three days (2-3 days)
- Explore and compare at least three leading industry companies' blogs from their research departments on virtual reality projects by the end of the day (1 day)
- Write 1000 words for the Product Design Chapter within three days (3 days)

3. **Product implementation**

- Develop wireframes for four screens within three days (2-3 days)
- Build five locomotion techniques to be used by the product, within three days (2-3 days)
- Build the Mountain scenario of the product within three days (2-3 days)
- Build the Museum scenario of the product within three days (2-3 days)
- Refine the product's code for experiment use by the end of the day (1 day)
- Write 1500 words for the Product Implementation Chapter within three days (2-3 days)

4. **Experiment**

- Create eight survey questions for the experiment by the end of January (1-2 days)
- Conduct 10-15 experiments lasting 15-20 minutes long in campus, within a working week (up to 5 days, depending on number of participants)
- Interpret and analyse the experiment data within two days (1-2 days)
- Write 2000 words for the Results & Discussion Chapter by the end of February (3-4 days)

5. **Evaluation and reflection**

- Evaluate the project against requirements and expectations from the first academic term by the end of the day (1 day)
- Write 1000 words for the Reflection Chapter within two days (1-2 days)
- Analyse and plan future improvements in the report by the end of the day (1 day)
- Write 700 words for the Conclusion Chapter within two days (1-2 days)

1.3. Approach

Kanban is a Lean methodology heavily used in today's leading digital organisations in developing software products (Anderson 2010). Its incremental (but not iterative) nature allows a steady and focused development of the project, given the objectives defined at point 3 and the timeline containing hard deadlines in January and April. The Work In progress (WIP) limitations structure the different objectives within the lifecycle, and maintains focus on the task at hand, making sure every deadline is met in advance (Kniberg & Skarin 2010).

During the course of first semester, I would be initiating my research in how locomotion techniques have been approached in the major headsets, how Daydream proposes to be conducted and new ways of achieving re-location. Moreover, I will study the approaches researchers took in compensating for all types of discomfort in the virtual reality experience. The prototyping and building of case scenarios will be done with the Unity engine and programmed in C# using Microsoft Visual Studio.

In the second semester I will conduct my research, by user testing on a Google Pixel XL phone with a Daydream VR headset and controller. In April, the results will be analysed and the findings will complete the project.

2. Literature Review

2.1. Approach to literature searching

For this paper, a combination of paper-based and online references are being used, compiled after the keywords: *virtual reality, locomotion, mobile VR, cybersickness, movement.* After an initial online search in June 2018, it came across that the University's library did not have a hold of the book *Human Walking in Virtual Environments: Perception, Technology, and Applications*, edited by Anatole Lécuyer, Jennifer Campos and Yon Visell, and thus requested it for this academic year. It has proven to be of great insight for this study, as it is structured on every perspective around walking in virtual reality: perception, biomechanics, algorithms and even applications.

Online sources include curated studies in accordance with the keywords and blog posts from leading companies in the industry, of their in-house research projects in virtual reality. In particular, documentation made available from Unity and Google Daydream, along with blogs from game development agencies such as CloudHead Games offered a practical approach to understanding more the challenges of moving in virtual environments.

2.2. Identifying the problem

Over the past eight years the virtual reality industry boomed in variety, as new technologies are capable of challenging Sutherland's 1965 "Ultimate Display" concept of a multi-sensorial screen. Head mounted displays connected via cables to a desktop computer offer new areas and possibilities for researchers and developers alike (Anthes et al., 2016), as they provide better hardware than seen before in a virtual reality headset at a lower price. On the other hand, in comparison with the desktop and console video games on the market the VR industry is still catching up, as the demand for this technology is not profitable enough (Sherr, 2017). Nevertheless, most smartphones today are capable of running small VR and AR experiences, determining leading companies of the mobile industry to compete with each other on updating their hardware as soon as possible, as Sherr pointed out in the same article. These upgrades have the potential to lift the industry again within the upcoming future, after smartphone sales dropped down in a worrying rate in 2018, in accordance with The Telegraph (Field, 2018).

On the other hand, the VR content available today for mobile platforms is limited to 360 view videos and small interactive novel stories. For research purposes, mobile VR is currently used in medical studies, exploring the benefits of such experiences in pain control for different disabilities, conditions and age (Li et al., 2016; Choi et al., 2016; Gerber et al., 2017; Alshatrat et al., 2018; Wiederhold et al., 2018) and coping with mental health issues (Poyade et al., 2017; Kompus, 2018; Kemp, 2018;). However, HMDs are perceived more efficient than mobile platforms in pain reduction by patients undergoing surgery (Mosso et al., 2018). Upcoming uses of mobile VR are explored in education as well, to enhance learning and provide a practical approach to it (Olmos et al., 2018).

At the same time, current technology cannot support a fully ergonomic VR experience without common side-effects such as nausea, dizziness or eye strain. The current Guinness world record for being continuously immersed into VR without feeling sick is of 36 hours, using an HTC Vive headset and only the Google Tilt Brush game (Cosmic Interactive, 2017; Guinness World Records, 2017). In contrast, the greatest challenge of VR at the moment is simulating human perception, the cause of cybersickness for this technology. Since the user's vision is constrained to the headset's display resolution, the other senses are in conflict with the optic flow as they perceive real-world information which is entirely different than what the eyes see. As this paper discusses this issue later on, the magnitude of this conflict in perception determines the intensity of cybersickness felt by the user. This way, movement of any kind (flying, swimming, walking, running, climbing etc) is difficult to implement ergonomically in present day, and is a common motivation for users to not purchase a headset just yet. Small and big companies innovate different infrastructures for HMDs to facilitate locomotion in virtual reality, but they are too voluminous for personal use. There are no efforts in commercialising such solutions for mobile VR at the moment, but recent progress highlights Google's decision to patent a pair of omnidirectional shoes for mobile devices (United States Patent and Trademark Office, 2018).

2.3. Navigation and movement in Virtual Reality

Locomotion is considered both as a basic ability and as a great challenge to implement in virtual reality experiences. Bowman, et al. (1998) points out that the effectiveness of moving within a given virtual environment is crucial for the user's immersiveness and sense of presence into the virtual space. Such an intuitive reflex as walking, however, is a combination of so many different systems in the human body, that it is difficult for developers to simulate and facilitate completely into virtual simulations. Hence, developing a locomotion technique that is immersive, free of any biological discomfort and maintains a low cognitive load throughout the whole experience is yet to be implemented. Towards achieving a full-rounded locomotion interface, Whitton and Peck (2013) formulated a list of user-centred targets, completed with an inclination for less required hardware. In other words, this list tackles the individual aspects of locomotion researchers and developers struggle with to this day: smooth learning curve, low cognitive load, does not impose any sickness, does not depend on additional infrastructure and maintains a safe pathway in real-world while the user is immersed in virtual reality. Moreover, the study highlights two other lists, specifically for manipulating speed and direction of the user, encouraging full accessibility of movement variables to them. This is left to be further explored, as beginners might find it inconvenient at first to finely tune such a natural movement before enjoying the virtual experience.

To accommodate for this technological challenge, HMDs use head tracking in order to place and follow the user within a given space, updating their location in the virtual world. Unfortunately for big world simulations, most users do not afford the physical space to accommodate such experiences.

Hence, developers and designers have to explore methods of building VR experiences that incorporate movement while the user is stationary or confined to a limited real-world space. Current solutions are based on redirected walking (Nescher et al., 2016), an algorithm that manages the mapping between the virtual and real movements, by gradually rotating the virtual space around the user's head to change their direction in the physical world (Suma et al., 2013). These "gains", as the study names them, can be applied while the user is stationary (rotation gains) or while they're walking (curvature gains). The latter, if induced smoothly, will determine the user to follow a curved real-world path. Even though visual cues dominate the body's proprioception (Berthoz, A., 2000), the intensity of this conflict may induce simulator sickness. To complement that, virtual objects can be assigned the roles of attractors, detractors or distractors (Peck et al., 2009), to encourage the user to change direction. These are either points of interest, obstacles against the wrong path, or points of focus while the rotation executes in order to diminish the likelihood of sickness. Building up on this method, motion compression (Nitzsche et al., 2004; Su, J., 2007) not only rotates the scene, but remaps the content to fit into the tracked real-world space. It calculates the target destination of the user by considering all the points of interest they were directed to and generates the largest arc available within the tracked space. These algorithms contribute to the feeling of presence within the virtual world, while offering software solutions against more voluminous hardware that discourages the use of an HMD at home.

In this study, the locomotion techniques tested are all dependent on the Daydream controller, through its buttons and location in space. Already-documented techniques for mobile platforms are tunnel vision, teleport and chase camera (Google VR developers, 2018a, b, c), however the latter does not have a first-person view, being less immersive. Research shows that point & click teleportation is favoured to a gamepad or joystick (Bozgeyikli et al., 2016a; Bozgeyikli et al., 2016b), being the best solution for covering long distances. It is also further explored by Leap Motion to grab and bring to focus distant objects, by using the same dynamics as teleportation (Fox and Schubert, 2018). However, this can only be achieved through gesture-control, implemented through an HMD's controller. Due to the nature of the Daydream remote, this dynamic cannot be yet implemented on mobile platforms. Tunnelling is another method proposed by the Daydream developer team (Jagnow, 2017), using as analogy the scenario of watching TV. The scene of action (the preview of the target location) is surrounded by a stationary environment (the user's peripheral vision is static, not inducing sickness), offering the user the choice of refusing to move just yet. In the analogy most people do not experience motion sickness from television, hence why tunnel vision has the potential to be a preferred means of movement in mobile VR. Other developer solutions for providing a smooth experience while moving in VEs include the Dash Step and Blink Step (Kong, 2017). By pressing a button on the controller, the user is advanced into the virtual space on a short predefined distance, like a step. In addition, Blink step provides rapidly a black screen before the user is moved to the next position, hence the name. According to Kong, the Dash step is more prone to motion sickness than the other, because it provides a smooth transition between steps which can be perceived as continuous, compared to blinking. Lastly, the fifth locomotion technique tested in this paper is the swinging of the user's hand containing the controller. As current research focuses on natural gestures (Ferracani et al., 2016) and walking-in-place solutions for movement (Tregillus & Folmer, 2016), arm swinging proved to be more efficient than using a joystick and is close to achieving the same orientation accuracy as walking on foot (McCullough et al., 2015). Moreover, it does not suffer from space constraints and is more affordable than the tracking systems required for normal walking.

2.4. Cybersickness in Virtual Reality

In the age of laptops, smartphones and online streaming services, users experience side-effects from prolonged use of digital screens. Symptoms such as eye strain, headache, thumb shaking or disorientation occurring after an extended usage of digital devices is known as cybersickness (Regan & Price 1994; LaViola 2000; Lo & So 2001). Common factors such as blue light or size of screen can be easily adjusted in present day, but the rise of VR devices on the market challenges the human perception in new ways. In this medium, cybersickness occurs as a conflict between the body's external and internal sensory systems.

In detail, humans rely on vision to analyse spatial information, being one of the most researched sensory modality (Waller and Hodgson, 2013). Due to the anatomy of the eye, this rich and accurate information is distorted by the optic flow, on account of the individual's position and orientation. The former induces a radial pattern of changing focus between expansion and contraction, while the latter is rather laminar across the retina, in an opposite direction to the movement (Waller and Hodgson, 2013). Together with gustation, olfaction, audition and somatosensory stimulation, these modalities form the external sensory system of the human body.

Another anatomical actor in producing cybersickness is the vestibular system, responsible for the sense of balance. It is located within the inner ear and is performed through the otoliths and semi-circular canals. Because it senses the angular and linear acceleration of the head, misinformation against visual stimulation causes side-effects such as disorientation, vertigo or nausea. The body perceives real-world stimulation, while the mind is focused on the virtual reality information it is given. Furthermore, the direction of gravity and the stationary position or movement of a limb also represent internal sensory information crucial for the sense of presence in real or virtual world. Waller and Hodgson's (2013) study adds the importance of efference copy to this list, the mind's causal expectations over the body's internal actions. This information illustrates the intention to interact and move in the environment, together with the strength. Understanding this aspect of perception can enable developers to implement more intuitive user journeys in virtual reality, by including visual illusions of self-motion.

On the other hand, vestibular sensations are prone to be dominated by visual stimulation (Suma et al., 2013), therefore the feeling of self-motion is better facilitated by vection. The most common example illustrating this concept is the stationary train passenger, watching a moving train through the window. Often times, the passenger may perceive the feeling of self-motion, as if their train is moving and not the one next to it. Riecke and Pelkum (2013) differentiate between linear and circular vection, as the latter can induce nausea on two axes, due to visual and gravitational conflict. However, both can be easily implemented into virtual reality with present technology (Riecke, 2010; Hettinger et al., 2014). Vection is dependent on several cognitive contributions, some dependent on hardware performance of the headset, while the rest can be manipulated by developers. Current HMDs have disadvantages such as small field of view (FOV) and limited refresh rate (around 60 Hz), which diminish the illusion of self-motion and limits the stimulus velocity. Whereas eccentricity and the contrast density of the moving stimulus can be modified at a software level. As both central and peripheral areas have the same potential of inducing vection (Andersen and Braunstein, 1985; Post, 1988; Howard and Heckmann, 1989; Wolpert, 1990; Nakamura, 2008), in order to maximise efficiency the latter has to lower the spatial frequency of the stimulus (Moss and Muth, 2011). Moreover, the number of moving objects and the density of their contrasts directly influence the intensity and frequency of vection. Thus, these should be artificially enhanced in blurry situations such as clouds or fog. Similar to this effect, the relationship between an object in the foreground and its surrounding background can impact vection, by restraining the optokinetic reflex (Warren, 1895; Wallach, 1940). Static, central objects can improve vection, while peripheral stationary stimuli in the background can diminish its effect (Brandt et al., 1975; Howard and Howard, 1994; Nakamura, 2006). Lastly, presence and naturalism can easily influence vection (Van Der Steen and Brockhoff, 2000; Riecke, 2006), as we are inclined to assume a stationary environment. While understanding how vection can be induced, one must keep in mind that this visual illusion is purely subjective and can be significantly reduced if the user knows that it is unlikely for real motion to occur during a VR experience (Riecke and Pelkum, 2013).

2.5. Conclusions

Current research focus on mobile VR is directed towards medicine and education, leaving gaming and entertainment as the main commercial application (Frommel et al., 2017) for HMDs. However, both platforms lack in locomotion ergonomics, by not accommodating for all the biomechanics of movement. This leads to an avoidance of the technology from consumers, as cybersickness can be experienced early in the VR session. In order to diminish the discomfort of side-effects, VR developers and designers ought to consider from the user's perspective every aspect of the experience they are creating. This paper attempts to achieve an exploration experience inducing the least amount of cybersickness, by applying these findings into the product for experimental use.

3. Product Research

Since the appearance of the Oculus Rift headset in 2011, leading mobile and technology companies have competed in developing the most performant headset and VR-ready smartphone on the market. **Table 1** presents the highest specifications achieved by the industry as of 2018 (Chi, 2018; Harper, 2018), sectioned into the type of device that can support virtual reality: smartphones, desktop HMDs and standalone HMDs. Field of view (FOV) is the maximum available area the display allows the user to see at a given time, measured in degrees as an angle. It plays a crucial part in how immersed the user can feel wearing the headset, as anything less than 150 degrees limits the peripheral view.

For this study, the experiment uses a Google Pixel XL phone, the first edition of its series. In comparison to the latest one (third edition), the display technology is crispier with just a slight increase in resolution, while the screen is bigger by nearly an inch. The processor has improved considerably (from Qualcomm ADRENO 530 to Qualcomm Snapdragon 845), surpassing even the performance of current standalone HMDs. Both phones have all the required sensors to support VR experiences. On another note, the Daydream View headset used in this study has a FOV of 90, in contrast with its second edition (the latest, released with Google Pixel XL 3) having 100 FOV, similar to Oculus Rift and Oculus Go. HTC Vive, HTC Vive Pro and Lenovo Mirage Solo are the only headsets having the highest FOV on the market, 110.

One of the obstacles of having an HMD is the physical space required to be tracked by the headset's sensors. For virtual worlds bigger than a standard living room with furniture, it is challenging to explore and develop software solutions for a continuous, undisturbed navigation of the map. Despite the HTC Vive headsets enabling the user to track a space of 15 x 15 feet (4.5 x 4.5 metres) and Oculus Rift 8 x 8 feet (2.4 x 2.4 metres), first-person shooters (FPS) and open world games take place in large simulated worlds which cannot fit within the real-world limits. The industry saw this inconvenience as an opportunity to develop specialised infrastructure for locomotion in VR, such as treadmills, chairs, shoes or modifications to current available gadgets.

Treadmills are the most commonly developed solution to solving the locomotion problem, as they come in different forms: linear, concave, omni-directional, with a harness or with a supporting edge (similar to baby walkers). The omni-directional treadmill is recommended by researchers (Souman et al., 2011; Warren and Bowman, 2017;) as it is actively used in the U.S. Army's Dismounted Infantry Training Program (Darken et al., 1997), while the U.S. Naval Research Lab explores Gait Master (Iwata et al., 2001; Suma et al., 2013), a turntable with two stepping platforms that simulate uneven terrain to the user. In contrast, with the rise of multiplayer VR games, the demand for Huge Immersive Virtual Environment (HIVE) tracked spaces increased, as large warehouse-like buildings can be rented for such games. This concept is not new, just as paintball fields and laser tag venues are already a popular form of entertainment in big cities.

Type	Device name	Display	FOV (Field of View)	Processor	Sensors	Controller
Smartphone	Samsung Galaxy Note 8/S8+	6.3-inch Super AMOLED, 2960x1440	101 (Samsung Gear VR)	Qualcomm Snapdragon 835	Iris sensor, Pressure sensor, Accelerometer, Barometer, Fingerprint sensor, Gyro sensor, Geomagnetic sensor, Hall sensor, HR sensor, Proximity sensor, RGB light sensor	Yes (Samsung Gear VR)
	Google Pixel XL 3	6.3 inch QHD+ OLED, 1440 x 2960	100 (Daydream View 2)	Qualcomm Snapdragon 845	Active Edge™, Back-mounted Pixel Imprint™ fingerprint sensor for fast unlocking, Proximity/Ambient light sensor, Accelerometer/Gyrometer, Magnetometer, Barometer, Android Sensor Hub, Advanced x-axis haptics for sharper/defined response	Yes (Daydream View 2)
	Moto Z2 Force	5.5 inch Quad HD (1440 x 2560) POLED	Any mobile headset	Qualcomm Snapdragon 835 octa-core	Fingerprint Sensor, Accelerometer, Ambient Light, Gyroscope, Magnetometer, Barometer, Proximity, Ultrasonic, Audio monitor	Any mobile headset
Desktop HMDs	HTC Vive	Dual AMOLED 3.6'' diagonal, 2160 x 1200	110	Required: Intel® Core™ i5-4590 or AMD FX™ 8350, equivalent or better	SteamVR Tracking, G-sensor, gyroscope, proximity	Yes
	HTC Vive Pro	Dual AMOLED 3.5" diagonal, 2880 x 1600	110	Required: Intel® Core™ i5-4590 or AMD FX™ 8350, equivalent or better.	SteamVR Tracking, G-sensor, gyroscope, proximity, IPD sensor	Yes
	Oculus Rift	3.5in, OLED, 2160x1200	100	Required: Intel i3-6100/AMD FX4350 or greater	Accelerometer, Gyroscope, Magnetometer	Yes
Standalone HMDs	Oculus Go	Fast-Switch WQHD LCD, 2560x1440	100	Qualcomm Snapdragon 821	gyroscope, accelerometer, and magnetometer	Yes
	Lenovo Mirage Solo with Daydream	5.5 inch QHD (2560 x 1440) LCD	110	QualcommSnapdragon™ 835 VR	P-Sensor, Gyroscope, Accelerometer, Magnetometer	Yes

Table 1. VR devices sorted by the most performant in its category, in 2018

Other researchers see the use of pressure sensors from a Wii Balance board as sufficient input to facilitate walking in a virtual environment (de Haan et al., 2008), or some explore different containers for movement, such as human-sized “hamster balls” (Medina et al., 2008). However, Whitton and Peck (2013) indicate in their general goals for locomotion to “minimise required supporting infrastructure” and “prevent users from running into real-world obstructions and walls”. Therefore, to minimise sickness, be affordable and keep the user safe within the physical space, a standing or sitting position is recommended for virtual movement. Such examples include the development of wheeled shoes (Hayden, 2018a) or software solutions to walking in place (Templeman et al., 1999). All this additional hardware is developed for HMDs-only, leaving software solutions for movement in virtual space to be implemented for mobile platforms by developers.

4. Legal, Social, Ethical and Professional Issues and Considerations

The experiment for this project will be conducted as a 15 minutes long period of time given to the participant, in which they explore the features of a mobile virtual reality application, the product of this project.

The data will be gathered digitally under the form of a survey completed by the participants after the allocated 15 minutes. The only personal information that is being recorded are their gender and age. This information is crucial for the deduction of the research question and will be used only for this study alone. The final report and project presentation will include this information and it will be erased after the completion of this project. All data gathered during this project is anonymous, as no name or identification is requested of the participants.

The participants can refuse to take part of the experiment at any time. While focusing on the virtual reality (VR) application, participants are likely to be prone to any of the following cybersickness: dizziness, eye strain, nausea, headaches or ataxia*. Whenever they feel uncomfortable they can take the headset off, either take a break or leave the experiment. Since the participants will not be aware of their surroundings while immersed in VR, the experimenter will be monitoring the space around them for any obstacles. Moreover, the experiment will be conducted in safe and quiet indoor space. Two rooms in the maritime university campus will be chosen to conduct the experiment, one in Dreadnought building and the other on first floor of Queen Anne Court.

*postural disequilibrium or a lack of coordination

5. Requirements

5.1 Determination

In order to form a selection of guidelines for the implementation of the mobile application used in the experiment phase, a set of requirements must be established. This is achieved by deducting terms of reference, performing a feasibility study and conducting product research.

To begin with, the mobile application is developed in order to be used as a research tool for examining cybersickness induced by movement within a virtual space. This requires for the system to present several different methods to achieve movement the user and at least one virtual map to use them within. This can be achieved by centralizing these functionalities within an accessible menu.

On another hand, the target audience of this study is defined by the hardware utilised, mainly a VR-ready smartphone. Hence, people of all ages and genders who are owners of such a device are susceptible to this issue, who are engaging in mobile VR experiences outside of 360 degrees videos. Their informational need is sufficed by providing them with relevant instructions about the study's application without the examiner's constant guidance. This can be achieved with appropriate interface design and initial training for the participants with no previous experience in VR.

The hardware used for this study is technically feasible for mobile platform VR experiences, as the Google Pixel XL smartphone presents a 5.5 inch Quad HD AMOLED screen with a 2,560 x 1,440 pixels resolution. These display specifications are still considered as performant in 2018 (see Table 1), two years after the phone's release. In particular, the device supports NFC connection (required to pair with the Daydream headset) and has the 4.2 version of Bluetooth technology (required to pair with the Daydream controller), which are essential for implementing a variety of interactions within the VR environment. To enumerate its sensors, the Google Pixel XL presents a gyroscope, accelerometer, compass, barometer and a proximity sensor, which are sufficient to enable immersiveness to the full capacity on a mobile platform. However, as later discovered during the experiment phase of this study, the device's Qualcomm Snapdragon 821 processor and 4GB RAM could maintain an optimal functioning for only the duration of one session (15-20 minutes), before the smartphone encountered performance issues due to overheating. This problem was managed by scheduling at least 10 minutes between sessions for cooling, which were already in place due to the time the Unity platform takes to build and install the VR application on the device.

In terms of legal and regulatory feasibility, the VR application, survey and experimenter's notes do not store any personal data except for the age and gender of the user/participant and only operates on a local level. There are no communications towards an external entity, the application serving only as an exploration experience to study physical sickness encountered by the user. To manage the potential risks of the participant's safety within the real-life environment, the experimenter acted as a supervisor, to ensure no harm is caused to them while they were engaged in the VR application.

Finally, examining current solutions that implement locomotion ergonomically offers an opportunity to assess the applicability of the methods the current study explores in the mobile application. George Kong's Freedom Locomotion system was developed to explore different movement techniques that reduce the level of motion sickness experienced in virtual reality, for HMDs (Kong, 2017). He proposes Dash step and Blink step among them, as a simulation of real-life walking, respectively with blank screen frames designed to reduce visual motion. The former is further elucidated in Cloudhead Games' "The Gallery – Episode 1: Call of the Starseed" (Cloudhead Games, 2016) VR experience for HMDs. They categorized the blink functionality as Cinematic, Precision and Volume, to accommodate the user's real-life assigned space for VR. However, instead of an incremental advancement in navigation (Kong's approach to implementing the Blink Step), the developers opted out for teleportation, thus referring to the step only from a visual standpoint. Following the route of real walking simulation, this study also proposes the use of the "Shake the controller" step, which is often known as Arm Swinger in commercial VR applications. This method takes advantage of the sensors present in the controller's hardware, specifically the accelerometer and gyroscope, in order to monitor the user's arm movement. However, this restricts the amount of actions they can perform outside of walking, which can be problematic in games of first-person shooter (FPS) or role-play combat.

In contrast to simulating real-life walking, tunnelling follows the biological route of the visual sense. Taking inspiration from the eye's focal view, tunnelling applies a visual effect on the screen, usually encountered as either a circular central limitation of the user's view (Google VR Developers, 2018c) a blurred peripheral view of the starting position against a more saturated central frame of the active position. Ultimately, the most common method of movement on the HTC Vive is teleportation (Koo, 2016), which requires controller interaction in order to advance. The user chooses a point of destination, and upon pressing a button they're position changes. Considered a more comfortable option to explore vast virtual spaces without inducing any motion sickness, this step influences the amount of immersiveness applicable to the user, as it doesn't mimic any real-life method of locomotion.

5.2 Specification

Firstly, the functional requirements reflect this paper's objectives for the product implementation (see Table 2). Prioritised using the MoSCoW methodology, the development of the five locomotion techniques are essential for this study. Nevertheless, the implementation of two different scenes representing distinct user experiences provides a more complex set of data, to analyse the efficiency of the movement techniques in specific scenarios. Hence, the main processes the application will perform are the five different movements and the ability to change between these scenes. However, later in the implementation phase of the project, resetting the user's position to the start of the scene has been added as a requirement, for situations when the user finds themself outside of the given map. In terms of data holding, the system should be able to store information about the map areas explored within one session, along with the timeline of steps used. This is not crucial for the system, as the experimenter can additional check this information with the participant during the session.

Secondly, to further improve the user experience of this application, a set of non-functional requirements is formed (see Table 2). Specifically, to facilitate training during a session without constant guidance from the experimenter (which can decrease the level of immersiveness perceived by the participant), the system should display instructions for initiating the movement techniques. Furthermore, the application should display a virtual model of the controller, which reflects the physical position and rotation of the one in the user's hand, to confirm visually their tactile feeling of it. These requirements are not time-sensitive, and can be developed towards the end of the implementation phase. Lastly, due to hardware limitations the system must optimise performance heavily. Compared to PC VR experiences, mobile applications are limited to the device's technological capabilities, demanding the least amount of 3D virtual models present in one scene, with a significantly reduced level of detail (LOD). Hence, this requirement is essential for the application to behave accordingly.

Functional	MoSCoW
Dash step	Must
Blink step	Must
Tunnel vision	Must
Teleport	Must
Shake the controller step	Must
Universal menu to access steps	Must
Museum scenario	Should
Mountain scenario	Should
Change between scenes	Should
Reset user position to the start of the scene	Could
The application stores information about the areas explored and the route chosen by the user, with timestamps and names.	Would have
The application stores the order of the steps used by the user, with timestamps, scene name and step name.	Would have
Non-functional	
The different assets in the application are optimized for performance	Must
The user interface contains instructions of how to advance with every step	Could
Virtual model of the controller	Would have

Table 2. List of requirements, prioritised with MoSCoW

6. Design Specification

6.1 System architecture

Interactivity in the Unity platform is implemented by assigning classes to objects placed within a given scene. For example, to create a moving sphere, the developer must first place the object (a 3D Sphere) in the scene and then attribute a C# script (class) as a component to it, responsible for the moving behaviour. For this project, all classes responsible for a movement technique are assigned to the “Player” object, but are enabled from the “MenuController” class, through the “MenuButtonClick” public method (see Figure 1). However, this class can only be invoked if the “Menu” object is active in the scene, which is called upon within the “PlayerButtonController” class attached to the “Player” object. This class manages the interaction with the physical buttons on the Daydream controller in the user’s hand.

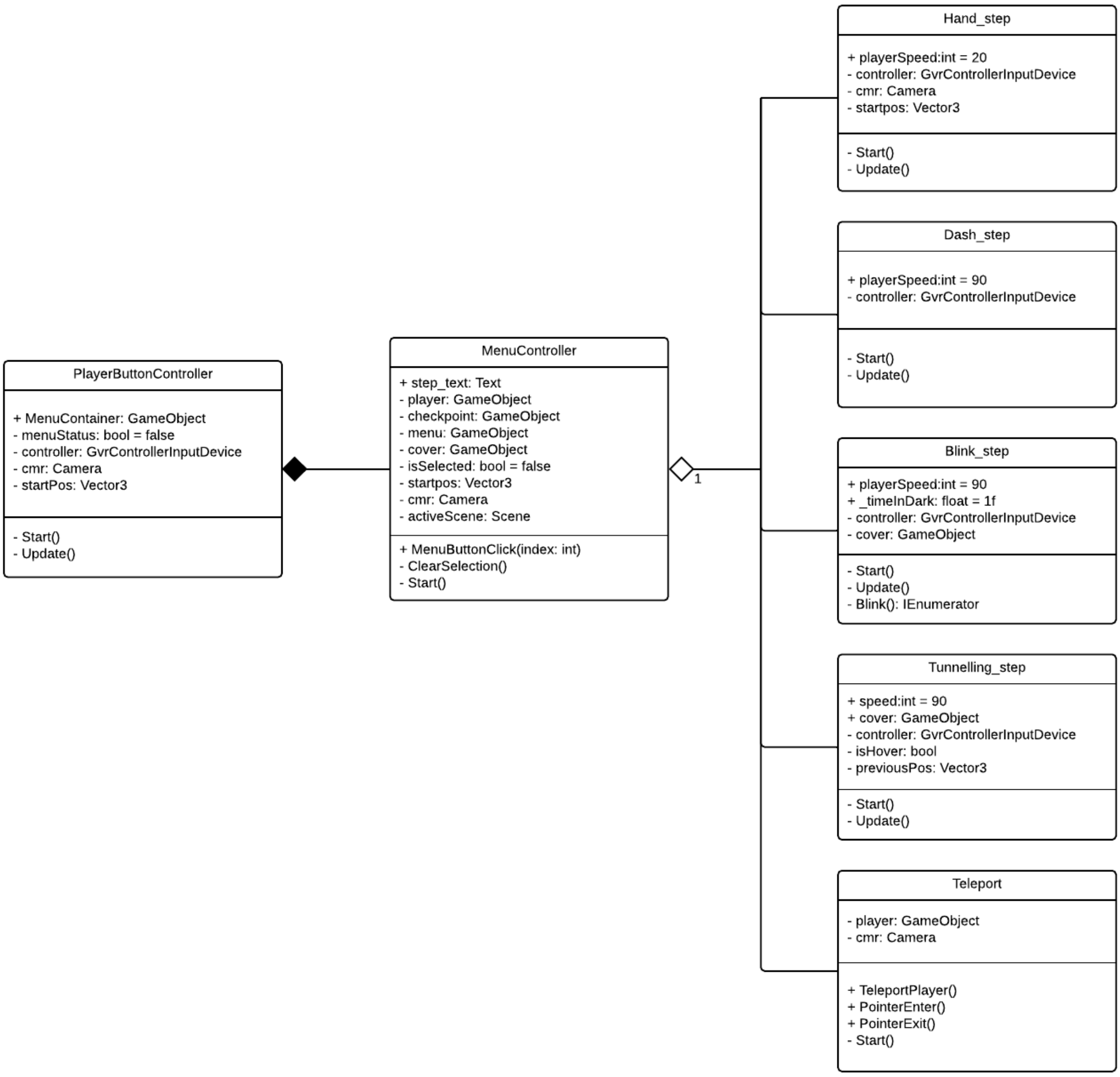

Fig 1. UML class diagram of system

6.2 User interface

To examine the five movement techniques (“Shake the controller”, “Dash step”, “Blink step”, “Teleport”, “Tunnel vision”), the user has to be provided with an interface encompassing these options, which can be accesed at any time during the session and be invoked from any point in both “Museum” and “Mountain” scene. Thus, the solution is a menu (see Figure 2) accessed via the App button on the controller (see Figure 3). In order to interact with objects, the user is provided with a visual representation (small yellow circle) of the centre of their focal view, refered to as the “Reticle pointer” (Google VR Developers, 2018d). By pressing down on the Touchpad button (see Figure 3), they can perform the selection on an object (or button) by pointing with their centre of view towards it.

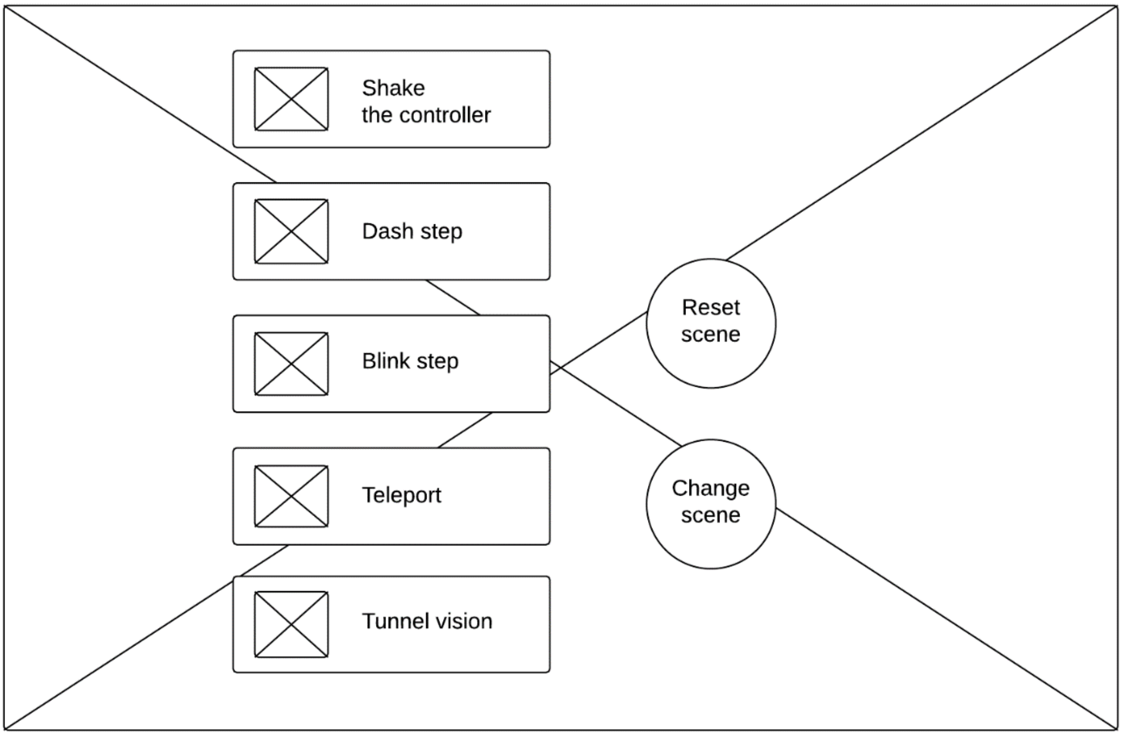

Fig 2. Wireframe of Menu, the main interface of the system

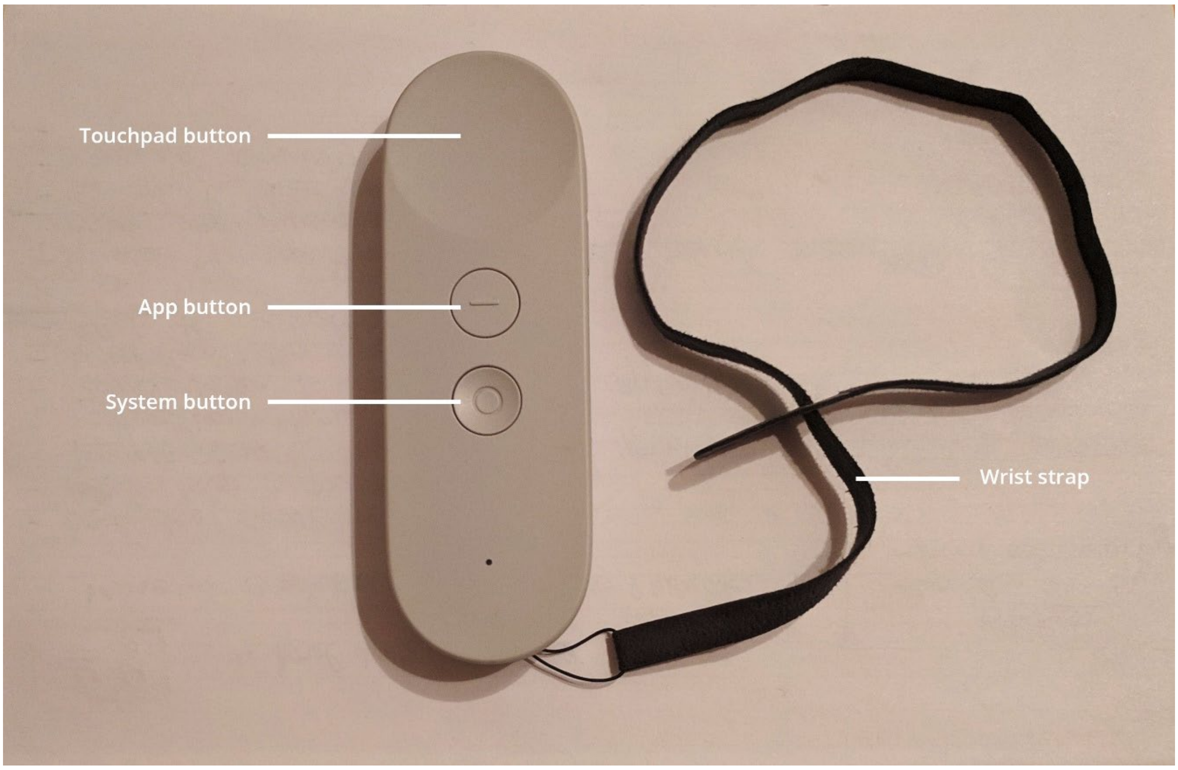

Fig 3. Picture of Daydream controller

In order to study efficiently the level of cybersickness encountered, it is required for the user to feel immersed in the virtual world presented. To facilitate this, the scenes contain various points of interest, to encourage curiosity and motivate further exploration. Therefore, the user is expected to shift their focus from the digital look of objects (the differences against their real-life appearance) to the content surrounding them.

With this purpose in mind, the layout of the "Museum" scene is assembled of four rooms (see Figure 4) containing different exhibits: the Statues room, the Warfare room, the Paintings room, the Antique Furniture corner and the Viking and Medieval Weaponry corner. The pieces displayed in this scene are limited in variety to the number of free models available in the Unity Asset Store (Asset Store, 2019), and were selected based on their relevancy to the museum environment. When introduced in this scenario, the user's position is placed at the back of the Paintings room (see Figures 6 and 7). Consequently, their journey will either follow a clockwise or counter-clockwise path (see Figure 5) relative to the layout of the scene.

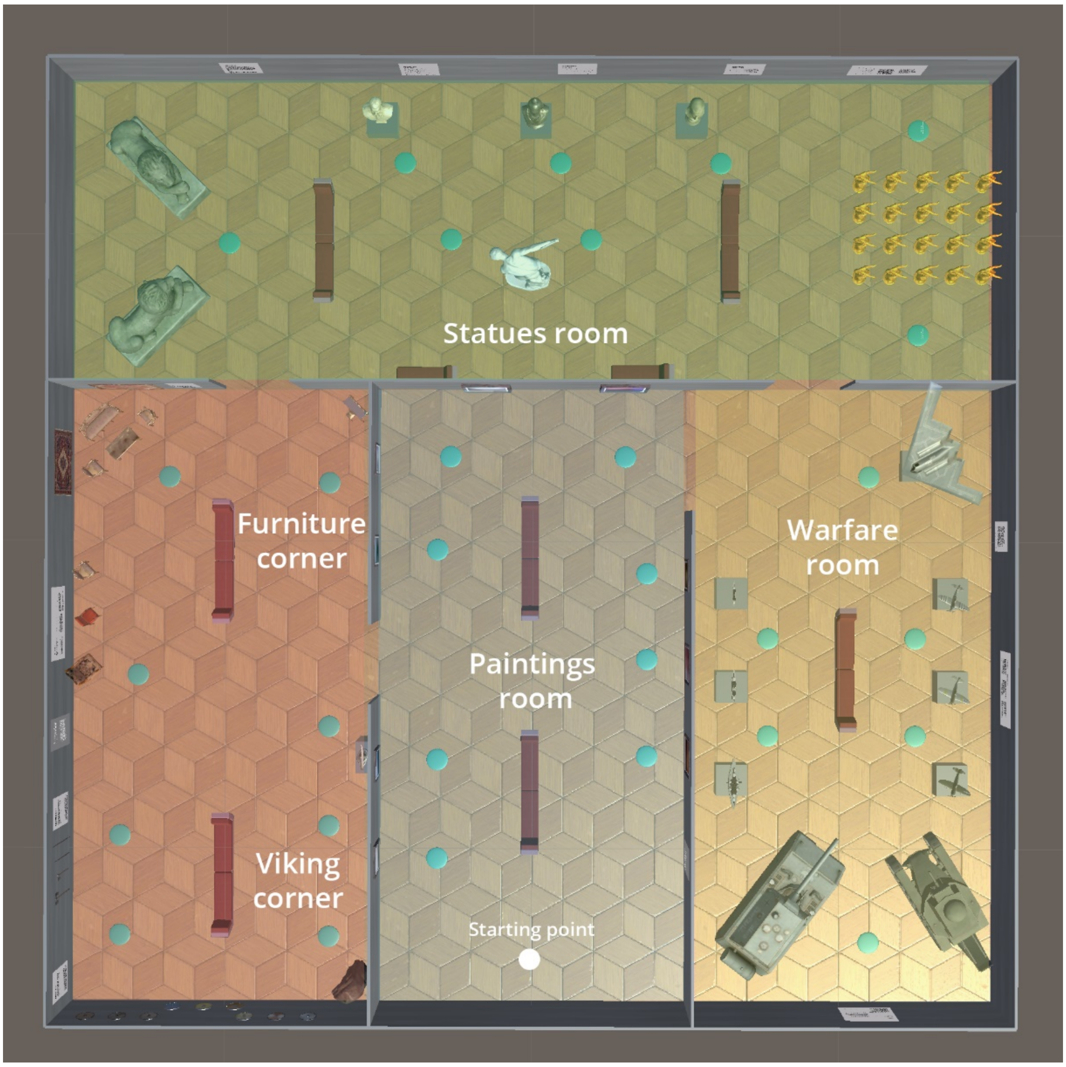

Fig 4. Map of "Museum" scene, with colour-highlighted areas of interest

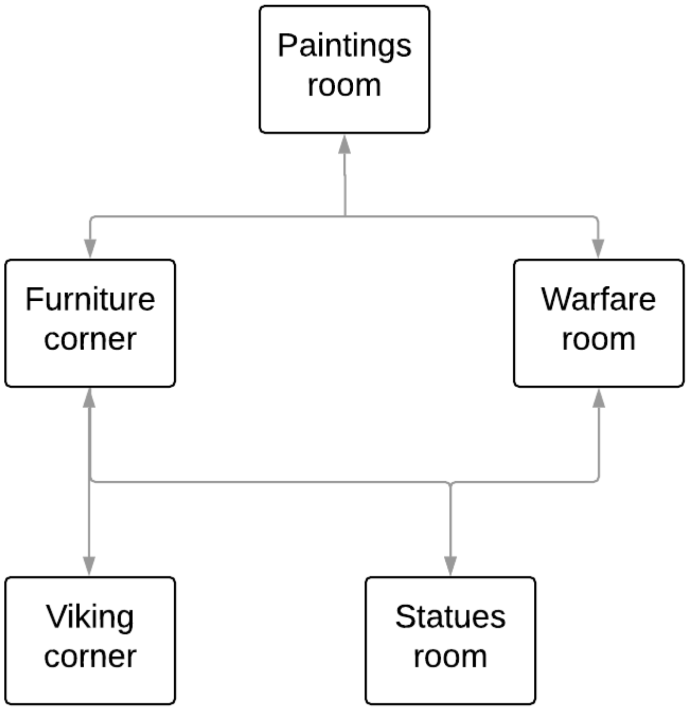

Fig 5. User journey in “Museum” scene

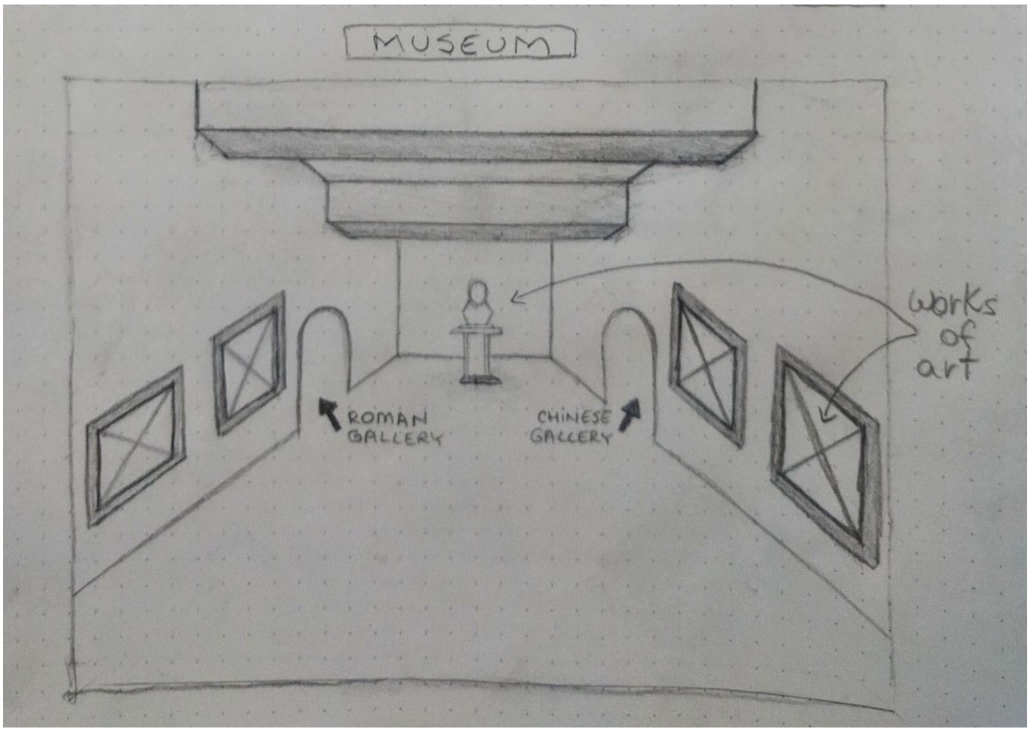

Fig 6. Initial sketch of “Museum” scene design;
User’s view in the starting position

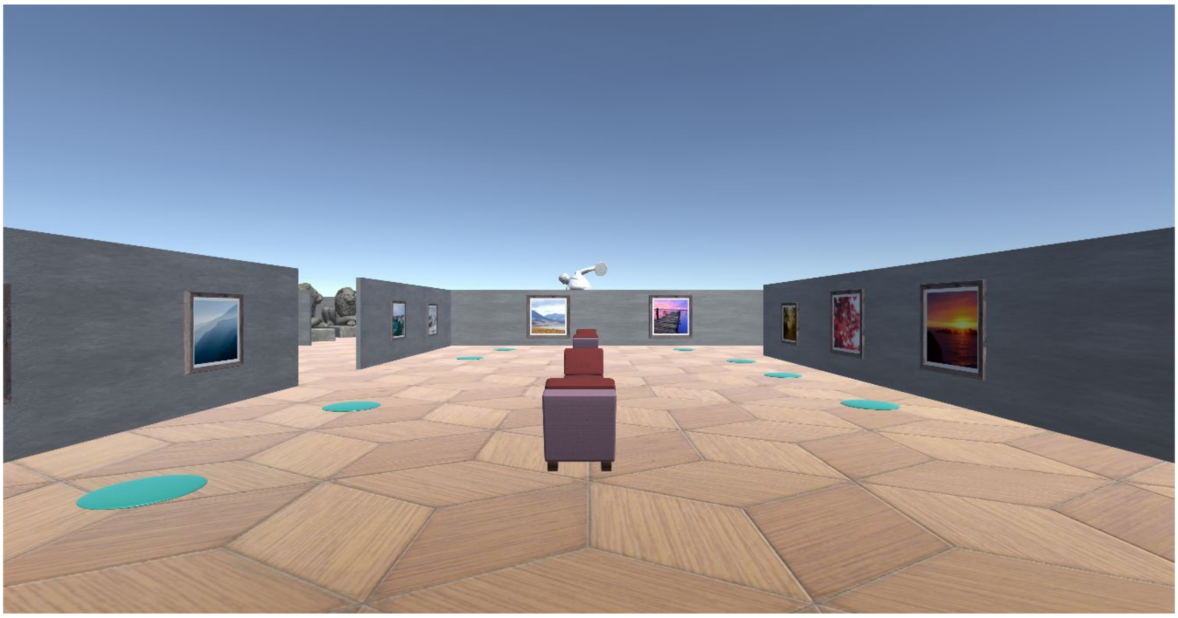

Fig 7. Final design of "Museum" scene;
User's view in the starting position

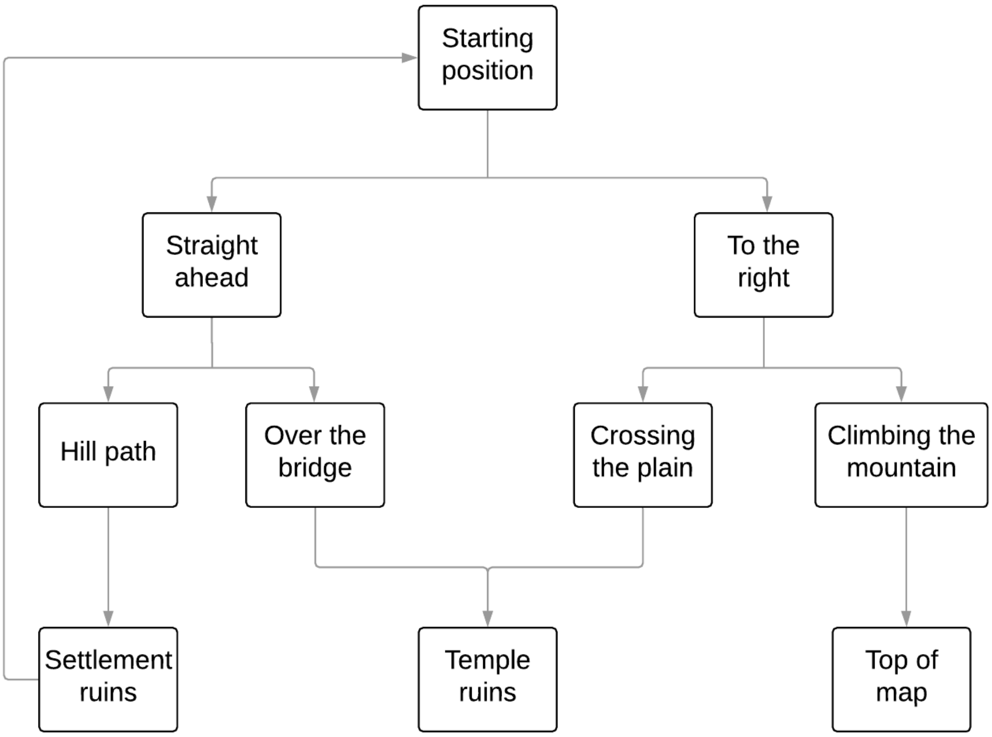

Fig 8. User journey in "Mountain" scene

Fig 9. Map of "Mountain" scene, with highlighted areas of interest

The "Mountain" scene is composed of three points of interest: a high mountain, an area where temple ruins are found and another where few traces of former human occupation can be discovered (see Figure 9). In order to direct the user in finding these hidden places on the map, additional elements such as rivers, waterfalls, trees, bushes and a tall horse statue are added as guiding points for orientation. The starting point in this scenario is placed in the lower left corner of the map, while the points of interest are placed within the areas of the other three corners. Thus, the user is expected to first move outside of the meadow (see Figures 10 and 11) and either climb the hill in front of them or notice the river at their right and head towards it (see Figure 8).

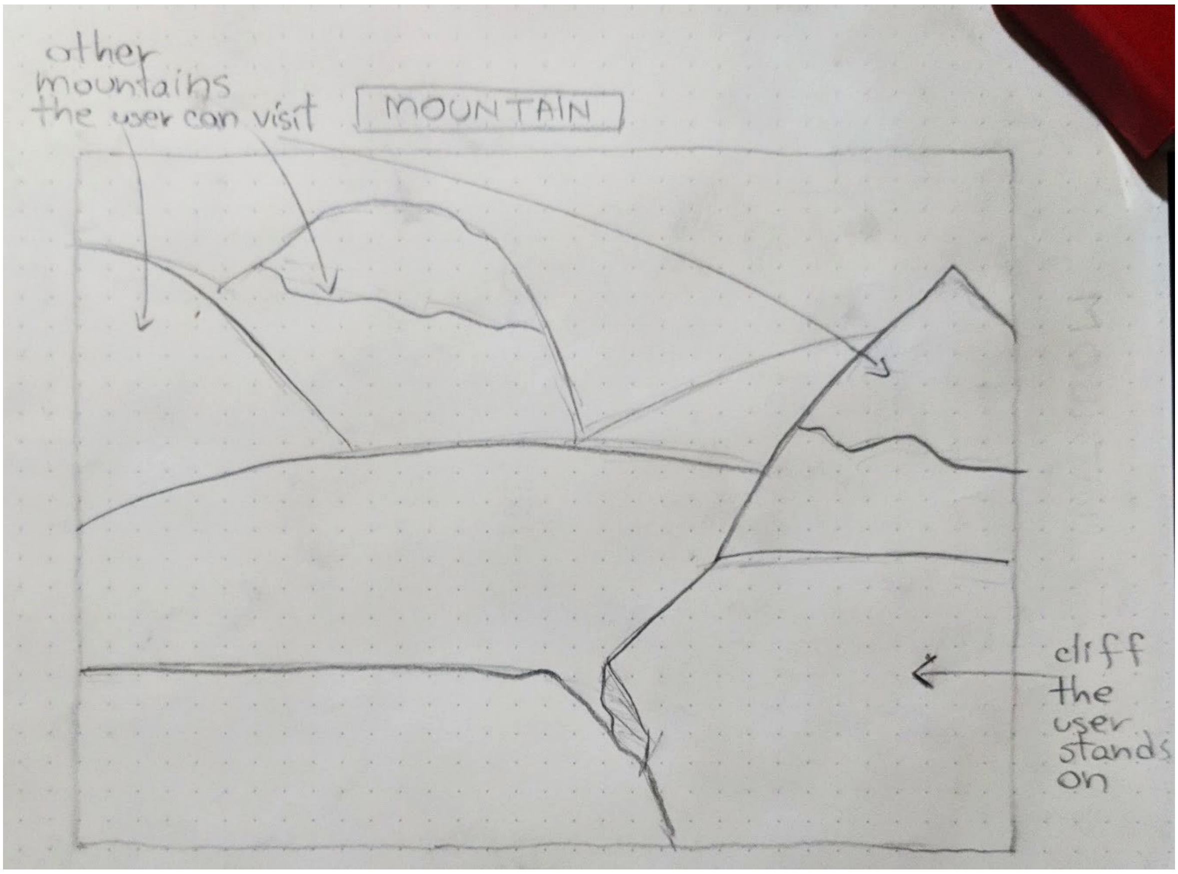

Fig 10. Initial sketch of "Mountain" scene design;
User's view in the starting position

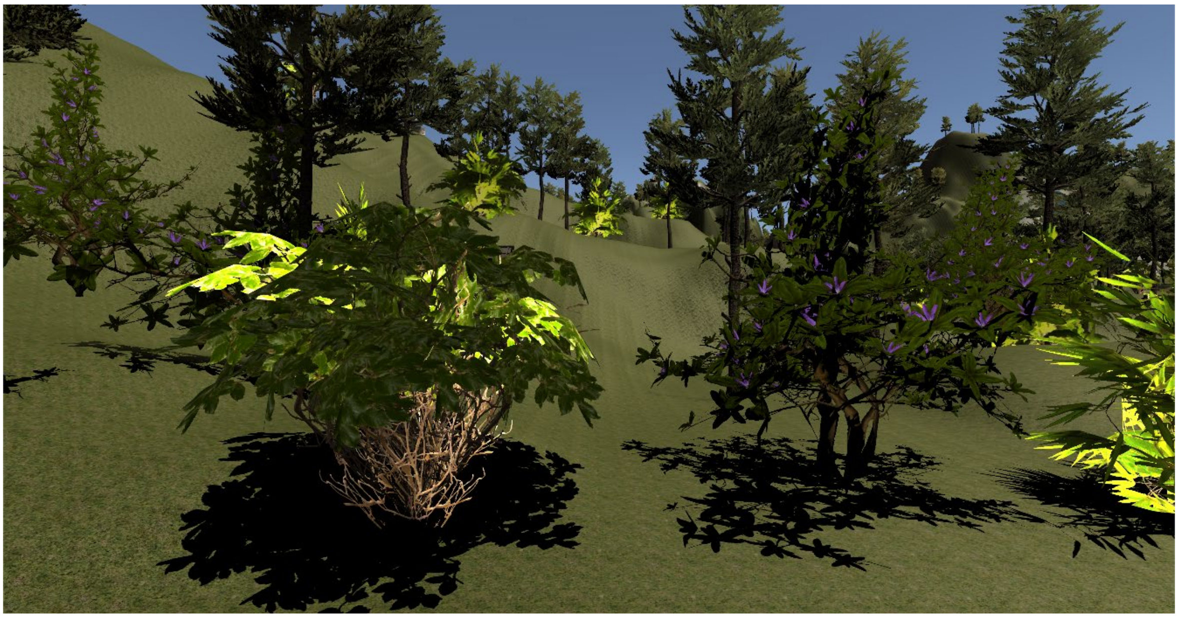

Fig 11. Final design of "Mountain" scene;
User's view in the starting position

7. Implementation

7.1 Mobile application

The system was built using the Unity game engine version 2018.3.4f1 and Microsoft Visual Studio 2017 for C# development of scripts. In addition to these products, the Android and Google VR (version 1.190.1, released on 16th of January 2019) software developer kits (SDK) have been imported into the project in order to develop a mobile VR application. This version of Unity supports the development of VR projects on mobile platforms, specifically for Cardboard and Daydream. Online documentation of the Google VR SDK provided an insightful guide to developing for this medium, along with the Unity development documentation and forums. In particular, the Google Daydream documentation has been a source of inspiration for the development of the Teleport and Tunnelling steps (Google VR Developers, 2018b, c, e).

The prototypes were tested via the Unity Editor and connected to the smartphone device with the Instant Preview Daydream application (Google VR Developers, 2018f). For the experiment phase, the built version of the application was used, consisting of a Gradle Project (extension of file: .apk) installed on the device.

As mentioned in section 6.1, the movement techniques scripts are attached to the "Player" object (see Figure 12), which is formed by the user's camera view ("Main Camera"), the visual model of the Daydream controller ("GvrControllerPointer") and the area with instructions for step dynamics ("Step_instructions") (see Figures 13, 14). In detail, the Camera object contains a black shape to act as a cover in the Blink step and a black frame to act as the frame in Tunnelling vision (see Figure 15).

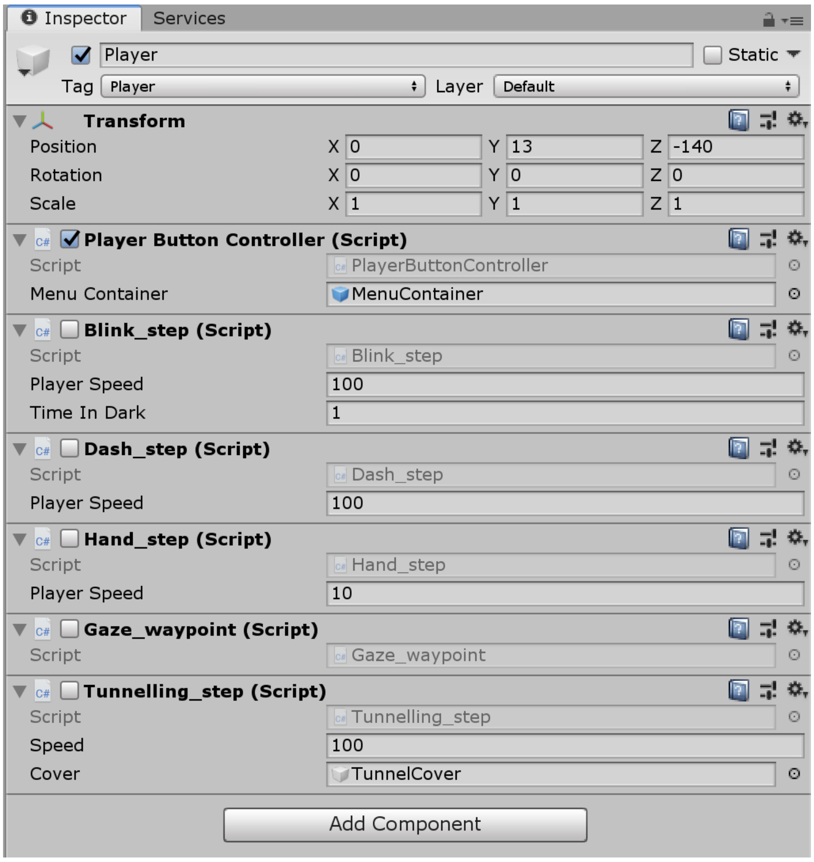

Fig 12. "Player" object components list

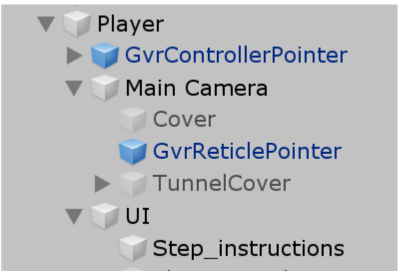

Fig 13. "Player" object hierarchy

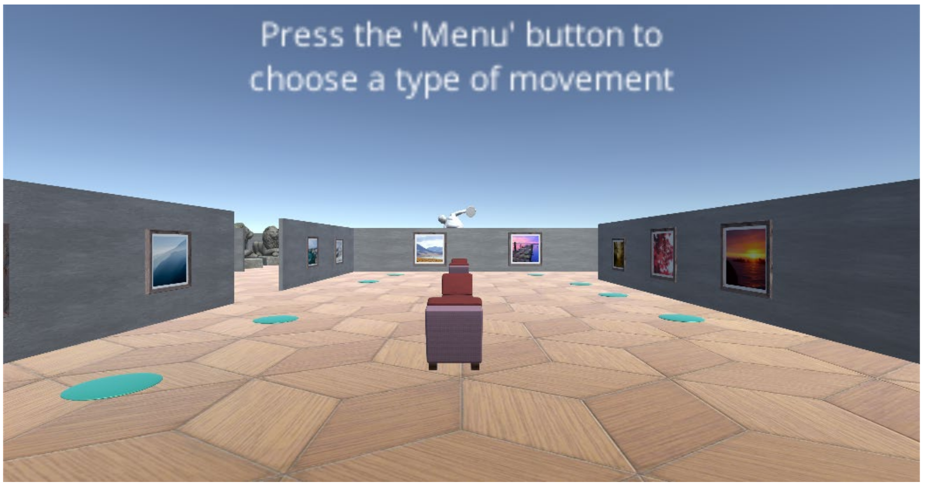

Fig 14. Screenshot of area of instructions

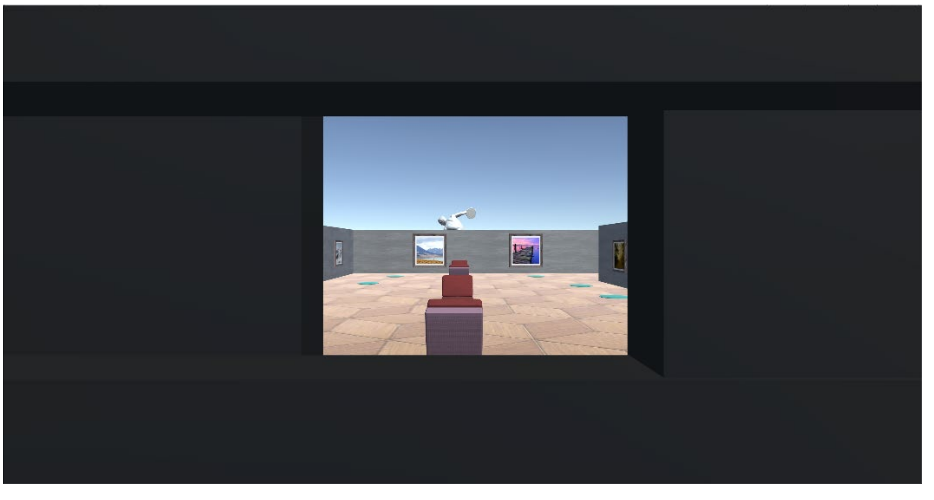

Fig 15. Screenshot of Tunnelling vision frame

From the user's perspective, to start the experience they must choose a movement technique from the menu (see Figure 16) accessible by pressing the App button on the controller. The "MenuContainer" object (see Figure 17) encapsulates the elements of the interface and acts as a manager for the buttons' dynamics through the "MenuController" class.

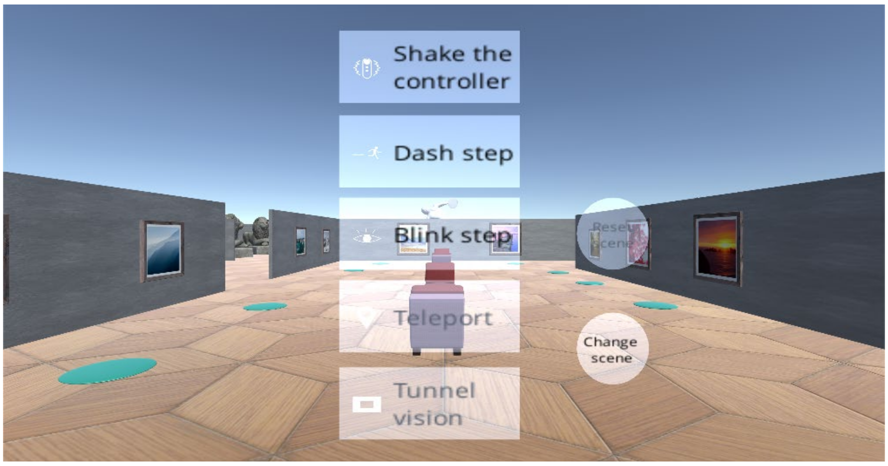

Fig 16. Screenshot of the menu containing buttons for five different steps

Fig 17. "MenuContainer" object hierarchy

In Unity development, the functions Start() and Update() are basic methods for implementing the dynamics of game objects. The former is called only on the frame the class is activated, while the latter is called every frame afterwards (Unity Documentation, 2018a, b). Thus, most steps are implemented within these two methods: Dash (see Figure 18), Shake the controller (see Figure 19) and Tunnelling (see Figure 20). These check for user interaction in every frame, and change the position of the user ("transform.position") for a set distance ("playerSpeed"/"speed") per frame.

The latter variable can be changed via the Unity platform too, as it is declared as public. For the Tunnelling step, the method looks for an active cover ("isHover"), in order to allow advancement by tracking the user's finger position between frames ("controller.ToushPos != previousPos"). Blink step follows the same incremental advancement as Dash step (see Figure 21), and adding a given amount of time of darkness ("_timeInDark") for the blinking effect.

```
// Update is called once per frame
void Update()
{

    if (controller.GetButtonDown(GvrControllerButton.TouchPadButton))
        transform.position = transform.position +
        Camera.main.transform.forward * playerSpeed * Time.deltaTime;
}
```

Fig 18. Code snippet of Dash step implementation

```
// Update is called once per frame
void Update()
{
    if (transform.position.y > 0 && transform.position.y < 300)
    {
        //if the controller's position is changed:
        if (controller.Accel.x > 5 || controller.Accel.y > 5)
            transform.position = transform.position + cmr.transform.forward
            * playerSpeed * Time.deltaTime;
    }
    else
        transform.position = startpos;
}
```

Fig 19. Code snippet of Shake the controller implementation

```
void Update()
{
    //turning cover on/off
    if (controller.GetButtonDown(GvrControllerButton.TouchPadButton))
    {
        isHover = !isHover;
        cover.SetActive(isHover);
    }

    //move camera
    if(isHover == true)
    {
        if(controller.TouchPos != previousPos)
            transform.position = transform.position +
            Camera.main.transform.forward * speed * Time.deltaTime;
    }

    previousPos = controller.TouchPos;
}
```

Fig 20. Code snippet of Tunneling implementation

```
// Update is called once per frame
void Update()
{
    if (controller.GetButtonDown(GvrControllerButton.TouchPadButton))
    {
        StartCoroutine(Blink());
    }
}

private IEnumerator Blink()
{
    cover.SetActive(true);//screen is covered

    //change position
    transform.position = transform.position + Camera.main.transform.forward
    * playerSpeed * Time.deltaTime;
    yield return new WaitForSeconds(_timeInDark); // wait in the dark

    cover.SetActive(false);//cover dissappears
}
```

Fig 21. Code snippet of Blink step implementation

Lastly, the Teleport implementation is parted between the "Player" object and the "Waypoints", objects situated around the maps, acting as teleport destinations. The user places the "ReticlePointer" on the "Waypoint" object and upon pressing the TouchPad button their position changes to its location. This is reflected by assigning the "Gaze_waypoint" script to the "Player" object, which awaits the "ReticlePointer" to hit a "Waypoint" (see Figure 22). Due to the high amount of tree assets in the Mountain scene, an added functionality changed the implementation of this class to aid the user in finding the "Waypoints" around them (see Figure 23). In particular, the methods “PointerEnter” (see Figure 24) and “PointerExit” (see Figure 25), are responsible for displaying the “Teleport here” guiding text. Along with changing the position of the user (see Figure 26), these methods are assigned to every “Waypoint” in both scenes, thus concluding the second half of the Teleport process.

```
// Update is called once per frame
void Update()
{
    Ray ray = cmr.ViewportPointToRay(new Vector3(0.5f, 0.5f, 0f));

    if (Physics.Raycast(ray, out hitObj, distanceOfRay))
    {
        if (hitObj.transform.gameObject.CompareTag("Waypoint"))
            if
            (controller.GetButtonDown(GvrControllerButton.TouchPadButton))
            {
                hitObj.transform.gameObject.GetComponent<Teleport_v2>().Tele
                portPlayer();
                hitObj.transform.gameObject.GetComponent<Teleport_v2>().Poin
                terExit();
            }
            else
                hitObj.transform.gameObject.GetComponent<Teleport_v2>().Poin
                terEnter();
        else
            for (int i = 0; i < waypoints.Length; i++)
                for(int j = 0; j < waypoints[i].transform.childCount; j++)
                    waypoints[i].transform.GetChild(j).gameObject.GetCompone
                    nt<Teleport_v2>().PointerExit();
    }
}
```

Fig 22. Code snippet of the “Gaze_waypoint” class implementation

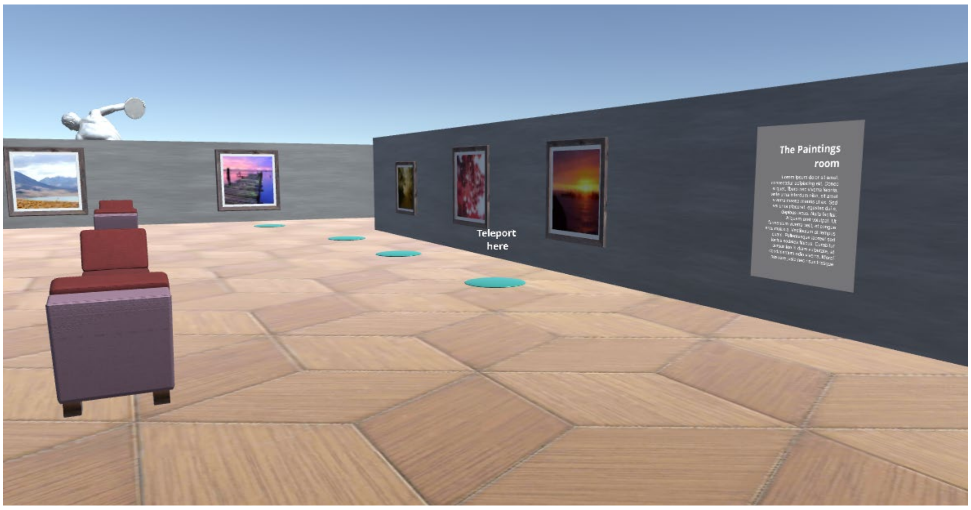

Fig 23. Screenshot of “Teleport here” guide, active when the user aligns their centre of view to a “Waypoint”

```
public void PointerEnter()
{
    if (transform.parent.name == "Benches")
    {

        transform.GetChild(7).transform.eulerAngles = new
        Vector3(0,cmr.transform.eulerAngles.y, 0);
        transform.GetChild(7).gameObject.SetActive(true);
    }
    else
    {
        transform.GetChild(0).transform.eulerAngles = new Vector3(0,
        cmr.transform.eulerAngles.y, 0);
        transform.GetChild(0).gameObject.SetActive(true);
    }
}
```

Fig 24. Code snippet of "PointerEnter" method, responsible for displaying the guiding text when the user looks at a "Waypoint"

```
public void PointerExit()
{
    if (transform.parent.name == "Benches")
        transform.GetChild(7).gameObject.SetActive(false);
    else
        transform.GetChild(0).gameObject.SetActive(false);
}
```

Fig 25. Code snippet of "PointerExit" method, responsible for hiding the "Teleport here" guiding text

```
public void TeleportPlayer()
{
    player.transform.position = new Vector3(transform.position.x,
    transform.position.y + 10, transform.position.z);
}
```

Fig 26. Code snippet of the Teleport method responsible for changing the user's position

7.2 Challenges faced

Virtual Reality development is still considered a new subject to be taught in higher education and is subject to lecturer's willingness to modify their course content between academic years to include it. Thus, for this project the Udacity Nanodegree in VR development (Udacity, 2019) was attended during the summer preceding the academic year. This online course provided an insightful look into developing with the Unity engine for Google Cardboard and understanding the foundations of

VR development. However, this project focuses on Daydream development which, in comparison with Cardboard, includes the controller required for this study. There is little to no tutorials on developing for Daydream online, most of them being focused on Cardboard development, which is a platform more accessible to developers due to the company's efforts to distribute as many to the public as possible at no price (Singer, 2015; Ledger, 2016). Thus, during the implementation phase the Daydream documentation was consulted, to understand the structure of the Google SDK.

However, using the online documentation proved to be quite problematic as a beginner in mobile VR development. For instance, working with Unity events (for example, developing button interaction) was counter-intuitive, as the use of trigger events attached to game objects (which behaves as expected when developing for Cardboard) do not perform as intended. This is due to the Google SDK's own Event System, separate of Unity's, which is required for mobile VR development. Its implementation lacks flexibility in modifying it manually, as the entire SDK is overly-complex for what its classes do. This issue has been raised a year ago by the GitHub user Warwick Molloy, and it is still due for rectification (Molloy, 2018). As he pointed out, the only work-around for this problem is developing the functionality manually. Within this study's application this is reflected in every movement technique script, by listening to any interaction with the controller's buttons in every frame (in the Update() method, instead of a separate method) in order to advance. Having five steps, the menu, the buttons and the player listening for controller interaction at every single frame, performance issues can arise due to the number of checks performed during one session. To accommodate for this, the "MenuController" class contains the "ClearSelection()" method, which is called every time a new instance of the menu is invoked by the user, to disable all movement scripts before they choose one. This was also implemented to ensure the user can try only one movement technique at a given time.

Moreover, modifications in the Google VR SDK structure from one release to another proved to be laborious. Specifically, the classes responsible for controller development from version 1.150.0 (released on 4th of July 2018) were duplicated with new names to support a Beta feature for the upcoming Daydream headset. Despite the originals being deprecated within the same release, they were still available to develop with by version 1.190.1 (released on 16th of January 2019). Visual Studio only reflected this change after the latter release, which affected the progress of this study's application. For instance, the class "GvrControllerInput" (Google VR Developers, 2018g) contained properties and methods to access the controller's hardware for user input. The duplicated class to be used instead became "GvrControllerInputDevice" (Google VR Developers, 2018h), with no other difference other than the added word at the end of the class name.

For example, to check whether the user pressed the TouchPad button, the initial implementation required accessing only one property of one class:

```
if (GvrControllerInput.ClickButtonDown)
```

in comparison with the new implementation, which requires a new variable to store the controller (highlighted in orange), accessing a method of its type class and referring to the button (highlighted in green) as a property of a controller's buttons class:

```
private GvrControllerInputDevice controller;
controller =
GvrControllerInput.GetDevice(GvrControllerHand.Dominant);

if (controller.GetButtonDown(GvrControllerButton.TouchPadButton))
```

This change in the SDK's codebase is due to support an upcoming Mirage Solo headset (Hayden, 2018b), which will offer 6DOF (compared to the current one, of 3DOF) and the capability to develop for multiple controllers. This forces the development on any platform beside the Mirage Solo (which has no release date as of April 2019, two years after its announcement) to abide by this structure, despite the rest of them (Cardboard, Daydream, Samsung Gear VR) supporting none or only one controller.

Furthermore, during the implementation phase of this study the documentation of the SDK structure was insufficiently written for fundamental classes such as GvrPointerGraphicRaycaster (responsible for identifying user interaction between the "ReticlePointer" and any given game object in the scene). However, as of the release of version 1.200.0 (2nd of April 2019) of the Google VR SDK, all of the documentation has been appropriately updated to reflect the current structure (Larson, 2019). For example, the previously mentioned GvrControllerInput class now highlights the properties and methods which are deprecated (Google VR Developers, 2018g), while GvrPointerGraphicRaycaster is now thoroughly documented (Google VR Developers, 2018i). Unfortunately, at the time of these corrections this study was conducting its experiments and the application couldn't be modified to reflect them due to time constraints. Nonetheless, this issue heavily influenced the progress of the mobile application at the time of its implementation, since the understanding of these classes was based on their code's interpretations, rather than detailed comments of how they work.

As highlighted in section 7.1, Instant Preview is an Android application for Daydream-ready smartphones, which communicates with the Unity engine in testing the project without building it to the device. This shortens implementation timeline significantly; however, it still remains unstable. Towards the end of developing this study's project, a connection error between the game engine and this application was encountered. This issue has been reported since last year, and after the author of this study contributed to its discussion this year, more users recorded the same behaviour (Minneci, 2018). This bug was overcome by restarting both the smartphone and laptop, however its performance heavily decreased afterwards, and any further testing was instead done by building the application on the device repeatedly. Since building time ranges between 30 and 10 minutes, the experiments phase of this study had to be delayed from end of March to beginning of April, in order to finish implementation successfully.

Lastly, the Unity game engine recommends the use of prefabs, a system which introduces objects as templates which can be instantiated in more than one scene (Unity Manual, 2018). For more clarity, this concept is similar to how Site Master design maintains consistency throughout a website. Nonetheless, in spite of its usefulness in developing the menu, a bug was encountered while working with an asset (Unity Forum, 2018). Namely, in the Museum scenario there are two types of "Waypoints" used for teleporting: green circles placed next to every displayed piece and benches situated in the middle of the rooms. The latter are an asset formed as a prefab which contains individual models of the real-life piece of furniture (see Figure 27). The issue appeared when assigning the "Teleport here" guiding text to this game object, as the hierarchical order of a prefab's children could not be modified. The expected behaviour was for the desired text to be placed on top, in order to reflect the implementation of the Teleport step (see Figure 28). However, it was placed at the bottom of the list, forcing the development of additional testing in the step's implementation to accommodate for this issue (see Figures 24 and 25).

Fig 27. Bench object hierarchy,
with the guiding text as the last child

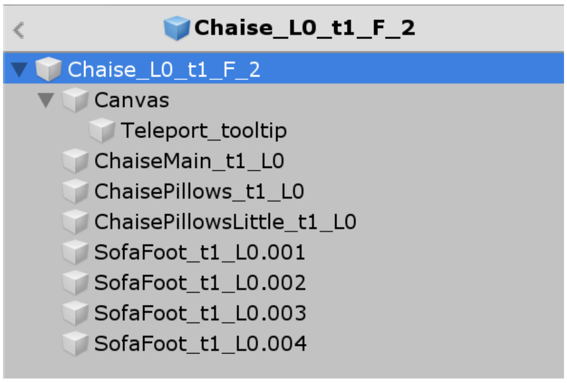

Fig 28. Bench prefab hierarchy,
with the guiding text intended as the first child

7.3 Experiments design

The instruments utilised for the experiment phase of this study are: a Dell XPS 15 laptop with an Intel Core i7-7700HQ processor and 16GB RAM, a Daydream headset (first generation) with its Bluetooth-enabled controller and a Google Pixel XL (first generation) running Android 9 Pie.

The format of one session consists of a 15-minute session in which the participant is immersed in the VR experience to explore both scenes using all five locomotion methods, followed by a 2-3 minutes break to adjust back to the real world and further complete the survey (see Appendix 2). The former allows for an average of 7 minutes exploration time per scene and was adapted per participant according to their previous exposure to VR experience and amount of time they took to test each movement technique. However, as mentioned in section 5.1, due to the smartphone's hardware limitations, the experiment cannot exceed more than 15-20 minutes play time without a significant decrease in performance as a consequence of device overheating.

This has only been encountered with one participant, due to their unfamiliarity with digital immersive experiences. Their exploration time was doubled for the Museum scenario (the first scene performed) to ensure all steps have been tested, but a 10-minute break had to be included before trying the Mountain scene, to cool the device. The participant did not encounter any enhanced symptoms of cybersickness due to the longer exposure and the planned period of time for exploring the second scenario was attained.

In order for the participant to be susceptible to any form of cybersickness, they have to be immersed in the VR experience. Thus, to ensure ecological validity, data gathering was conducted by naturalistic observation and note taking. To limit any interference the presence of the experimenter may cause to the level of immersiveness experienced by the participant, the location of the session took place in an environment where human observation is expected. Thus, the experiment was conducted indoors, in a communal student place in Queen Anne Court. A cubicle designed for groups of students to work on their coursework was chosen for added privacy. Given the participant is wearing the headset, they cannot see surrounding people, but expect to hear voices around them and attract short curious looks from passers-by.

Moreover, observation allows for an insightful examination of human behaviour (Warren et al., 2013), as participants feel more comfortable than in a lab environment and are more generous in expressing their reactions through body movements. This provided valuable input for note taking, in comparison to video recordings which can prove to be too intrusive for this setting (Warren et al., 2013). Additional coding was applied to the field notes, measuring the symptoms encountered before, during and after the given time for experiencing the application. The notes were time sampled every 2 minutes, to maintain the immersiveness perceived by the participant. This allowed the experimenter to observe body movements denoting reactions to the experience.

On another hand, to avoid selection bias due to previous exposure to VR experiences, the survey takes into account the frequency and different platforms the participants could have tried before this study. Moreover, recording the age of the participants ensures consistency over the perceived cybersickness (Wolfe, 2000).

8. Data Analysis

8.1 Data processing

Measuring cybersickness entails a subjective experience which is influenced by age, gender and level of previous exposure to the technology in question or similar ones to it. Personal views, meanings and reactions cannot be quantified, as this study does not focus on relationships between variables, but on exploring and describing qualities of phenomena. Thus, the following piece of qualitative research concentrates on the experience of the participants, studied in their natural environment, to identify trends and any deviant data points that may arise.

The technology used in this study is mobile VR, considering the vast adoption of smartphone devices worldwide, and the hardware availability their recent releases provides to VR experiences. Moreover, VR headsets for smartphones are cheap and easy to build, thus being financially accessible to their owners. However, this assumes the user is comfortable in trying this technology and it is desirable for the interface of VR experiences to facilitate for every level of technological proficiency. In detail, the context of usage by an user is mostly formed of the comfort of their own home, the room varying according to personal preference, as mobile VR does not require a dedicated floor space in order to be experienced.

Due to the small size of this study and limited amount of resources, non-probability sampling was applied to select participants. Specifically, convenience sampling applied within the university environment provided six participants for the experiments, while quota sampling accommodated for another four. These two methods were used in order to reach a better population validity (see Figure 29), as participants from the former group are within their twenties. This was prone to leaving a great segment of the population with access to mobile VR outside of this study's discussion, hence the use of age-based quota sampling to diversify the data points.

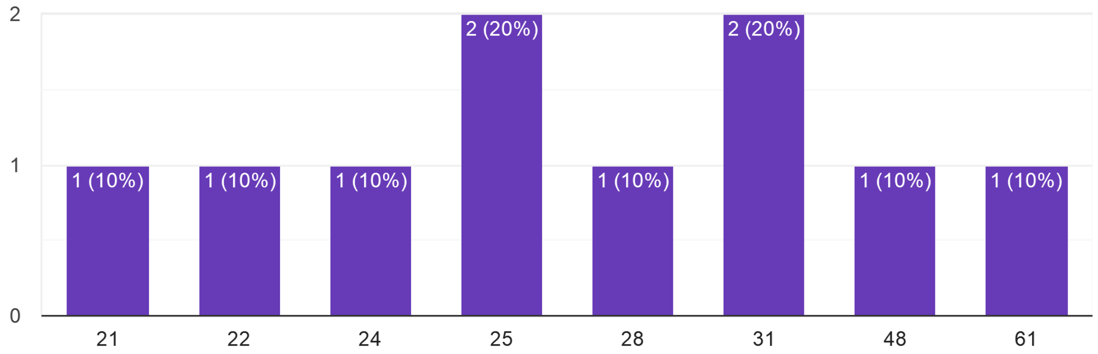

Fig. 29 Chart of this study's participants' age (horizontal axis), number of participants with a particular age (vertical axis), along with percentage applied to the total number of participants

The emphasis on participant age comes as a guide to the level of cybersickness they may encounter, as older people may be more susceptible to experiencing it. However, the results indicate no such relationship between age and cybersickness encountered, but frequency of VR use (see Figure 30) influenced the overall experience of this study's application.

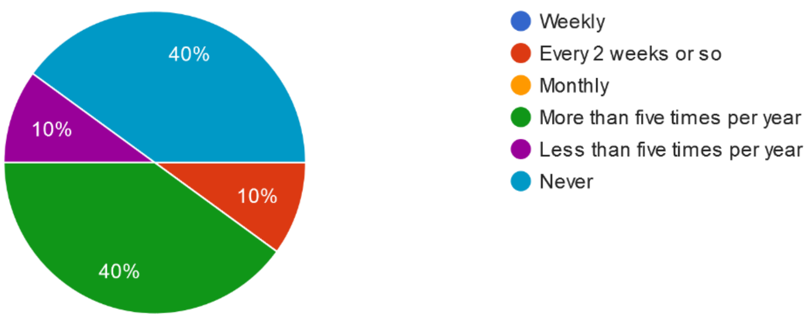

Fig. 30 Participants' frequency of VR use (colour coded), shown as percentages applied to the total of number of participants

For data analysis, survey data and field notes are coded at a first order descriptive level, categorised by the five locomotion techniques used. This organisation of data allows for a structured thematic analysis (see Section 8.2) with minimal biased interpretation.

8.2 Results discussion

The sample group used in this study contained in equal parts (see Figure 30) frequent users of VR as well as participants who have not used the technology outside of isolated cases (such as this study or a once-shared 360 video from friends). These rare occurrences were too distant to be considered by the participants within a yearly basis, as the survey question focuses on, hence the "Never" option was chosen to reflect that. After experiencing this study's mobile application, these participants presented a greater excitement than the rest of the participants, especially while giving positive feedback over the content displayed in both scenes explored. This was influenced by their prior understanding and guessed expectations of how they would perceive a VR experience, which were heavily based on pop culture illustrations, such as the "Ready Player One" novel by Ernest Cline published in 2011. Moreover, the hardware limitations discussed in section 7.2 influenced the cybersickness perceived by the participants with no prior VR experience, which is due to their unfamiliarity with the artificial look of virtual worlds. Thus, common complaints encountered in this aspect were directed towards quality of assets and unrealistic layout of the Mountain scene, along with expressed disappointment over level of detail in certain assets in the Museum scene. Following the discussion in section 2.4, establishing vection within a VR experience as a technique to enhance immersiveness can be easily influenced by the feeling of presence and the level of naturalism a virtual world provides. However, this was only encountered by the older participants with no prior VR experience and was overcome by shifting their attention to the content present in the given scene.

On the other hand, the explored potential of Tunnel Vision in section 2.3 was confirmed by the participants, as its dynamic was regarded more fluid in comparison to the incremental advancement practised by the other locomotion techniques. The use of finger movement over the touchpad button was perceived as an intuitive and comfortable way of navigation, while having a "funny helmet on", as one of the participants commented. Tunnel vision was regarded the preferred means of exploration in the Mountain scenario by half of the participants (see Figure 31), due to the cover's capability to reduce sickness induced by peripheral vision movement while exploring with great speed. Still, it was regarded as nauseous by nearly half of the participants (see Figure 33) and induced all tracked symptoms of this study.

Second and very close to Tunnel Vision in the Mountain scenario was the "Shake the controller" locomotion technique (referenced as "Using your arms" in Figure 31), which monitors the position of the controller in order to mimic real-life arm swinging while walking. This attempt to simulate real-life walking was "like driving" for the eldest participant, as involving their body to achieve movement was equivalent to the feeling of using a tool for the same goal. Moreover, the lack of an implemented height-limit for navigation often led to using this method for "flying", hence its common preference for exploring the mountain. However, two participants experienced dizziness over the continuous movement it provides (thus proving the necessity for the cover in Tunnel vision) and only one occurrence of vertigo and ataxia (see Figure 33).

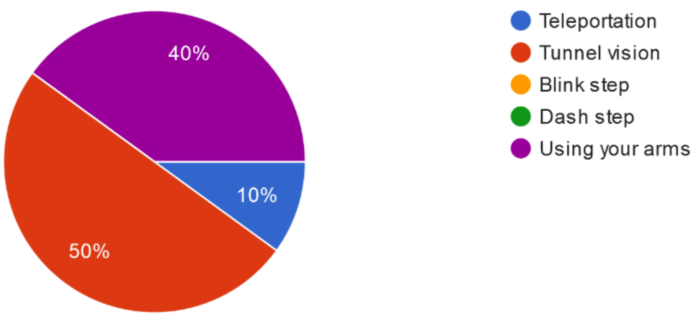

Fig. 31 Participants' preference (expressed in percentages applied to the total number of participants) for a locomotion technique (colour coded) in the Mountain scenario

For a storytelling experience such as the Museum scenario, Teleportation was found by most participants as a great way to explore the displayed content (see Figure 32). Specifically, the placement of "Waypoints" next to every point of interest provided an intuitive transition from asset to asset, offering the opprtunity to explore greater details by using Dash step. The benches placed in the middle of the rooms were greatly appreciated by participants in terms of establishing the museum atmosphere. However, the lack of an avatar body underneath the user's view position (which would sit on the bench) was disorientating for the eldest participant. Upon ensuring them that their view is placed at the height of 1.8 meters (thus real-life eye-level is respected in the virtual world), the participant was more content in continuing to use this movement method and got used to the absence of a virtual body representation for the rest of the experiment. In comparison with the Mountain scenario, Teleporting was perceived as disorientating, due to added difficulty in finding the "Waypoints" through the trees and bushes surrounding the user.

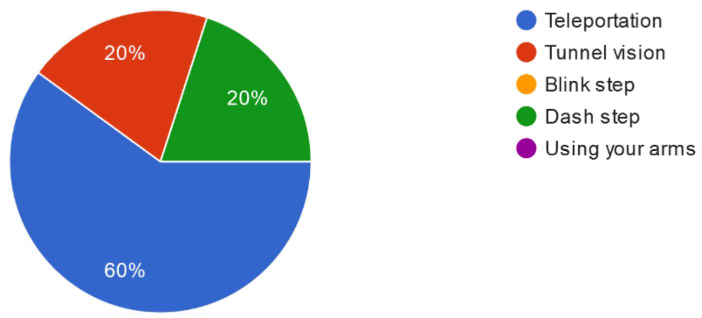

Fig. 32 Participants' preference (expressed in percentages applied to the total number of participants) for a locomotion technique (colour coded) in the Museum scenario

A contrasting find to what has been discussed in section 2.3 is the comparison between Dash step and Blink step. While the former was regarded as more likely to cause motion sickness than the former, this study's experiments proved the opposite. Beside an overall complaint over slowness of navigation for both steps, the blink visualisation (screen is blank for one frame) was taking too much time out of exploration than the rest of locomotion techniques. Having this in mind, Dash step also was perceived as an obstacle for exploration, as one of the participants compared the experience to viewing stop motion animation, but slower or watching online entertainment but shifting from pause to play in every frame. Nevertheless, Blink step was regarded as disorienting and eye strain inducing by nearly half of the participants (see Figure 33), while Dash step had one occurrence of each of the headache, disorientation and eye strain symptoms.

Another common theme observed in the field notes is about developing the locomotion techniques to use head orientation as direction of movement. While participants with significant amount of video gaming experience found it counterintuitive, the participant with mountain hiking experience appreciated it. The former voiced the preference to use the controller as an indicator of their desired destination, while the latter enjoyed the dependency on it which imposes the user to explore the map around them. However, no other participants commented on this matter, therefore no conclusions can be formed from this limited amount of data.

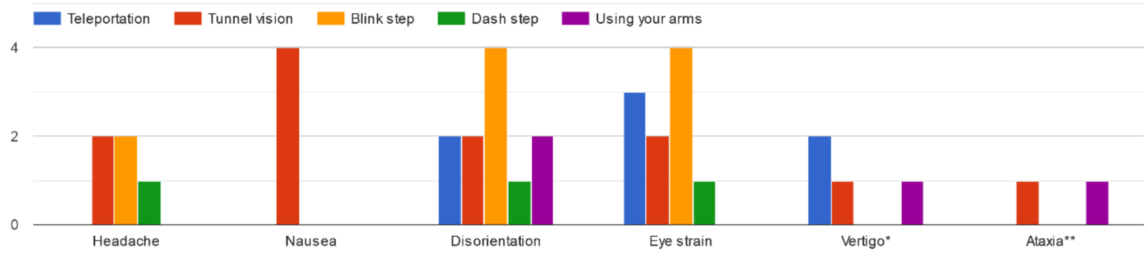

Fig. 33 Number of times (vertical axis) the expected symptoms (horizontal axis) were encountered by participants in using the locomotion techniques (colour coded)

Lastly, in comparison to the expected user journeys discussed in section 6.2, three participants deviated from the anticipated path in the Mountain scenario, being interested in the overseeing horse statue (which can be seen from every point on the map) or discovering a shortcut to the Settlement ruins (see Figure 9). In the Museum scene, only two participants chose to continue their exploration firstly with the “Warfare” room (see Figure 4), in comparison with the rest choosing the room on their left. This behaviour was expected, as the starting point view of this map (see Figure 7) offers visual cues indicating points of interest located at the user’s left, while access to the right room is not clearly signposted.

9. Evaluation

The final product of this study implemented all essential requirements established in section 5.2, along with the development of two distinct scenarios and user instructions to facilitate usability. However, there is potential for further improvements to track participant data and test a wider variety of locomotion techniques for cybersickness induced. The final version of the locomotion techniques reflects the behaviour encountered within commercial products currently on the market, as explored in section 5.1. Conversely, due to lack of VR development prior to this study, the visual effects accompanying these movement methods are due for future improvement. Above all, the ability to reset the user’s position at any given time proved to be beneficial to managing any inconsistencies risen by the steps’ development, maintaining control over the user’s position at all times.

On another hand, the application prioritised movement functionalities over gamifying the experience, to maintain the flexibility of the project’s management over the second half of the second academic term. This study’s application purpose is for research progress and not commercial use. Therefore, the layout of the two maps (Museum and Mountain) was arranged to facilitate for data gathering and not for open world exploration. This provided enough time to address the development challenges discussed in section 7.2 and complete most of the requirements set in section 5.2. Completing the Literature Review before the second academic term proved to be ideal for managing the study’s workload, in parallel with university coursework.

On a personal level, the subject of this study provided a great opportunity to exercise user-centred design thinking, learn VR development and understand the implications of a research paper. Started in the Summer of 2018 with attending an online course on implementing for this technology, the learning curve stationed for most of the first academic term due to literature research and increased drastically during the development phase. Specifically, having to explore the structure of the Google VR SDK in order to achieve the ideal behaviour had the most impact in implementation progress, and offered an insightful look into how mobile VR is performed. Learning and experiencing the different issues Daydream developers have to face within a project's lifecycle is mind-opening towards the rate new technologies are adopted by big corporations such as Alphabet Inc..

10. Future development

A factor determining the preference of participants towards a specific locomotion method is the travelling distance between two frames of that particular technique. Hence, Dash step and Blink step were developed for small incremental advancements, while the rest proved ideal for open world exploration and storytelling. This led to participants favouring the latter over the former. Thus, the development of an interface component, such as a slider, is considered for future development, as the perceived speed (distance travelled between two frames) can be subjective to the user. While shorter increments facilitate for indoor environments navigation, a faster relocation is preferred for open world exploration, to mimic real-life behaviour.

Moreover, due to time constraints the data logging requirements are not implemented completely, as saving the corresponding files to the device proved to be too challenging to delay the experiment phase of this study. The steps tracking logic is commented out of the application for future improvements, and is present in the codebase within the "MenuButtonClick" class, responsible for the management of menu buttons interaction.

Finally, implementing the Teleport functionality by projecting an arc originating in the virtual model of the controller was difficult to develop manually with no previous experience in Unity development. The current version opts for a waypoint-based system, in which the user is given a number of objects they can choose to teleport to, which mirrors the behaviour present in Cardboard experiences. Nevertheless, future development has to change the dynamics of this step, to encourage the use of the controller provided by the headset and not the user's head direction.

11. Conclusion

One of the goals set at the beginning of this study was to explore different locomotion techniques in order to find the one inducing the least amount of cybersickness within the given scenarios. However, the findings show that Dash step, the movement method which induced the least amount of symptoms, was also the most critiqued due to its slow advancement. In contrast, Tunnelling vision was the most preferred way of exploring the Mountain scene, despite it producing a great amount of cybersickness symptoms.

On the other hand, the locomotion technique that didn't simulate in any form real-life walking, Teleport, was considered the best navigational means for the Museum scene, which was expected from a storytelling point of view. However, the lack of virtual body representation of the user and its transition from a point of interest to another often times induced eye strain.

Therefore, the main outcome of this study is that cybersickness is encountered subjectively and is heavily influenced by frequency of usage of the technology given. More experienced participants enjoyed exploring around the scenes without real-life constraints, while beginners had greater surprise whenever their view advanced through walls, hills or trees.

Nevertheless, due to the small size of the sampled group, further research is required to form any further conclusions in regard to this subject. In particular, future development discussed in section 10 and updating the mobile application to the latest release of the Google VR SDK are the most noticeable factors in improving the results of this study.

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13. Appendices

13.1. Appendix 1 - Project Proposal

COMP1682 Project Proposal

Cybersickness induced by movement within virtual reality on a mobile platform

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1. Overview

The question of cybersickness induced by locomotion inside a virtual environment (VE) is broadly explored for desktop head-mounted displays(HMD) such as Oculus Rift or HTC Vive (Regan 1995, Mon-Williams et al. 1993, Dennison & D'Zmura 2018), but not as much for the mobile phone based platform.

Locomotion in this project is defined here as the ability to move from one place to another by feet, and "movement" will be often times used as a synonym. Cybersickness is a newly founded term denoting a sense of nausea and disorientation similar to sea sickness or car sickness, produced by a disbalance between what the inner ear of the user perceives and what the visual cues observe (Davis et al. 2014). Mobile platforms here refer to the combination of a smartphone compatible with virtual reality (VR) and an enclosure containing 2 lenses directed to a dedicated space for the phone.

Desktop HMDs track the movements of the user's headset and controllers by using room-scale sensors (Waller et al. 2007). Moreover, they have the computing power of the desktop computer they are connected to in terms of graphics performance. The best VR hardware available on mobile platforms is incapable of reaching the major headsets' performances and it lacks in creating visual feedback about the real world to the user (Fang et al. 2017). For this study, the Daydream VR headset for smartphones is used, which provides a small Bluetooth-connected controller. Hence it allows VR developers with more possibilities of implementing movement, compared to any other mobile headset.

This project will be facing the movement challenges of mobile virtual reality experiences based on mobile platforms, by testing empirically five different ways of locomotion (teleportation, tunnel vision, blink step, dash step and swinging the controller) within a given virtual space (climbing/hiking on a mountain and walking/reading in a museum). Exploring a mountain requires a more goal-directed approach in User Experience (UX), while the other relies on storytelling. The experiment will consist of a mobile application encompassing the two scenarios and five locomotion techniques followed by a survey to quantify the participants' feedback. The application will be developed in Unity and its scripts written in C#. A statistics significance test will be used to evaluate the findings of the experiment.

Keywords: cybersickness, locomotion, mobile platform, movement, virtual reality

2. Aim

The experiment will examine and evaluate the cybersickness effects of 5 different commonly used locomotion types within the context of two scenarios.

3. Objectives

3.1 Research report

- Research cybersickness causes and effects in virtual reality (1-2 days)
- Research locomotion techniques used by head-mounted displays experiences and mobile platforms (3-5 days)
- Research user experience studies in mobile virtual reality for exploration scenarios (2-3 days)
- Write Introduction Chapter (2-3 days)
- Write Literature review Chapter (3-5 days)

3.2 Design documentation

- Research user interface guidelines used in virtual reality interfaces (2-3 days)
- Read leading industry companies' blogs from their research departments on virtual reality projects (1 day)
- Write Product Design chapter (3 days)

3.3 Product implementation

- Develop wireframes (2-3 days)
- Create interface prototype (1 day)
- Build five locomotion techniques to be used by the product (2-3 days)
- Build Mountain scenario of product (2-3 days)
- Build Museum scenario of product (2-3 days)
- Refine the product for research use (1 day)
- Write Product Implementation Chapter (2-3 days)

3.4 Experiment

- Create survey questions (1-2 days)
- Conduct 15-20mins long experiments in campus (up to 5 days, depending on number of participants)
- Interpret and analyse the data (1-2 days)
- Write Results & Discussion Chapter (3-4 days)

3.5 Evaluation and reflection

- Evaluation of final project (1 day)
- Write Reflection Chapter (1-2 days)
- Present in report future plans for improvement (1 day)
- Write Conclusion Chapter (1-2 days)

4. Legal, Social, Ethical and Professional

The experiment for this project will be conducted as a 15 minutes long period of time given to the participant, in which they explore the features of a mobile virtual reality application, the product of this project.

The data will be gathered digitally under the form of a survey completed by the participants after the allocated 15 minutes. The only personal information that is being recorded are their gender and age. This information is crucial for the deduction of the research question and will be used only for this study alone. The final report and project presentation will include this information and it will be erased after the completion of this project. All data gathered during this project is anonymous, as no name or identification is requested of the participants.

The participants can refuse to take part of the experiment at any time. While focusing on the virtual reality (VR) application, participants are likely to be prone to any of the following cybersickness: dizziness, eye strain, nausea, headaches or ataxia*. Whenever they feel uncomfortable they can take the headset off, either take a break or leave the experiment. Since the participants will not be aware of their surroundings while immersed in VR, the experimenter will be monitoring the space around them for any obstacles. Moreover, the experiment will be conducted in safe and quiet indoor space. Two rooms in the maritime university campus will be chosen to conduct the experiment, one in Dreadnought building and the other on first floor of Queen Anne Court.

*postural disequilibrium or a lack of coordination

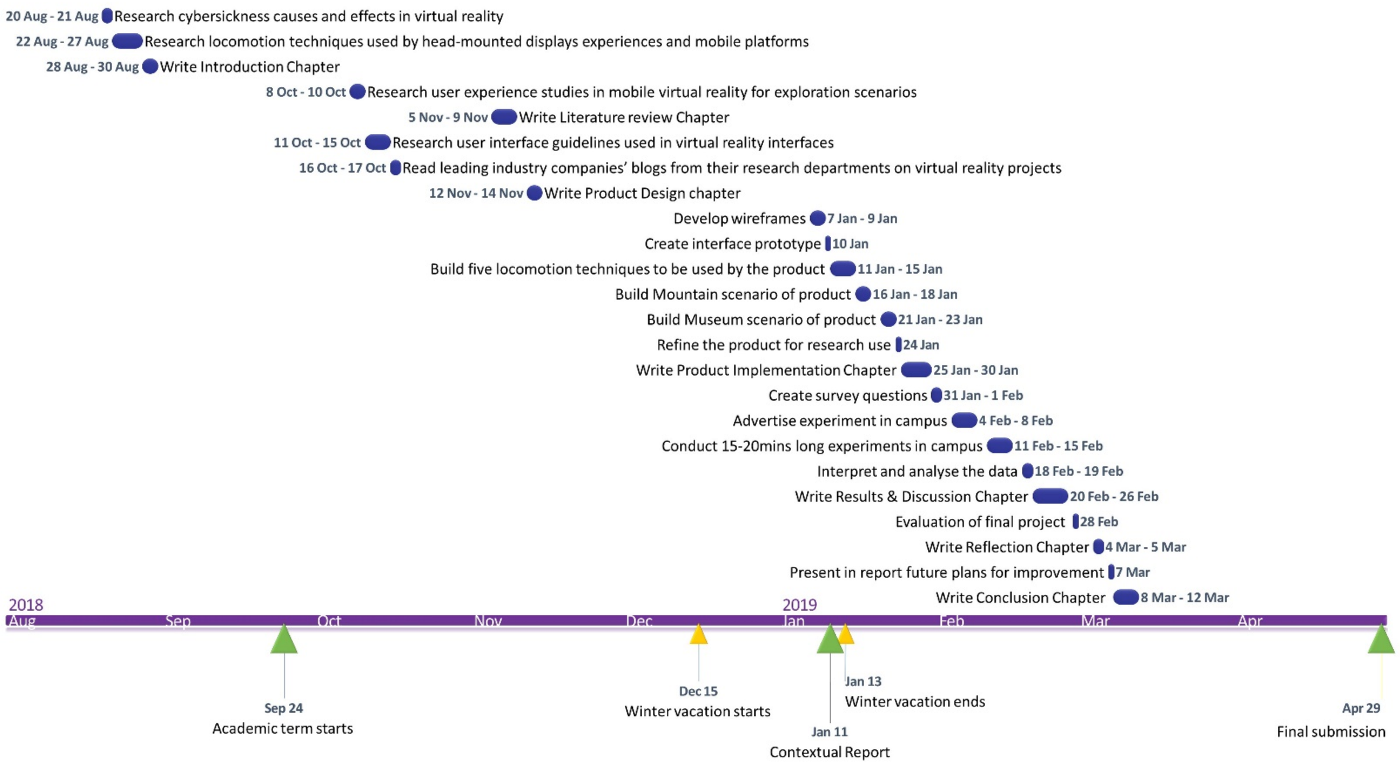
5. Planning

Kanban is a Lean methodology heavily used in today's leading digital organisations in developing software products (Anderson 2010). Its incremental (but not iterative) nature allows a steady and focused development of the project, given the objectives defined at point 3 and the timeline containing hard deadlines in January and April. The Work In progress (WIP) limitations structure the different objectives within the lifecycle, and maintains focus on the task at hand, making sure every deadline is met in advance (Kniberg & Skarin 2010).

During the course of first semester, I would be initiating my research in how locomotion techniques have been approached in the major headsets, how Daydream proposes to be conducted and new ways of achieving re-location. Moreover, I will study the approaches researchers took in compensating for all types of discomfort in the virtual reality experience. The prototyping and building of case scenarios will be done with the Unity engine and programmed in C# using Microsoft Visual Studio.

In the second semester I will conduct my research, by user testing on a Google Pixel XL phone with a Daydream VR headset and controller. In April, the results will be analysed and the findings will complete the project.

5.1 Gantt Chart



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13.2. Appendix 2 - Survey

Survey - Cybersickness induced by movement within virtual reality on a mobile platform

The purpose of this paper is to user-test several ways of movement within a virtual space available for the mobile hardware and measure the level of cybersickness induced by each.

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*Required

1. **Gender:** *

Mark only one oval.

- ◯ Female
- ◯ Male
- ◯ Prefer not to say
- ◯ Other:

2. **Age:** *

____

3. **How often do you interact with Virtual reality devices?** *

Mark only one oval.

- ◯ Weekly
- ◯ Every 2 weeks or so
- ◯ Monthly
- ◯ Less than five times per year
- ◯ Never
- ◯ Other:

4. If you have experienced Virtual Reality, please choose which platform

We refer as "experiences" to any type of virtual reality project, be it a game, a video or a dashboard screen. *Tick all that apply.*

- ☐ 360 video (e.g. Facebook post, Youtube video)
- ☐ Google Cardboard
- ☐ Google DayDream
- ☐ HTC Vive/Oculus Rift
- ☐ Samsung Gear VR
- ☐ Magic Leap
- ☐ Oculus Go
- ☐ Microsoft Hololens
- ☐ Other:

5. What symptoms have you encountered during this study's experience?

* a disordered state where the individuals surroundings appear to swirl dizzily;

** postural disequilibrium or a lack of coordination; *Tick all that apply.*

	Teleportation	Tunnel vision	Blink step	Dash step	Using your arms
Headache	☐	☐	☐	☐	☐
Nausea	☐	☐	☐	☐	☐
Disorientation	☐	☐	☐	☐	☐
Eye strain	☐	☐	☐	☐	☐
Vertigo*	☐	☐	☐	☐	☐
Ataxia**	☐	☐	☐	☐	☐
Others	☐	☐	☐	☐	☐

6. If you ticked "Others", please specify below:

7. Which type of movement did you enjoy the most for the Museum scenario? *

Please tick which one applies to you

Mark only one oval.

- Teleportation
- Tunnel vision
- Blink step
- Dash step
- Using your arms

8. Which type of movement did you enjoy the most for the Mountain range scenario? *

Please tick which one applies to you

Mark only one oval.

- Teleportation
- Tunnel vision
- Blink step
- Dash step
- Using your arms