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Development & Analysis of a Multiple-Technique VR Locomotion System for Comfortable Traversal of Diverse Environments

by

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Abstract

Virtual reality technology is becoming commonplace in industries spanning from healthcare, defence, consumer entertainment and scientific research amongst various others. Despite a widespread potential for applications in these industries, many challenges still await an optimal solution. This paper presents development and a feasibility study to address the issues of traversing large, complex virtual environments, from the confines of the room-scale area in which the user is physically bound. The method, developed and evaluated, focusses on the HTC Vive hardware, using multiple semi-natural locomotion techniques, achieved using only the controllers and headset for tracking. The developed system allows the user to dynamically imitate a range of movement in the virtual environment (VE), such as walking through to running, climbing and swimming. The resulting technique used is based upon the environmental context in which the user and VR rig are presented. From a limited comparative study against well-established VR locomotion methods, participants generally had little to no discomfort when using the developed system and found that it improved the immersion and enjoyment of their VR experience.

Contents

1 Introduction

1.1 Background to locomotion in commercial virtual reality

Current VR technology has progressed where full room-scale tracking is provided as standard. This allows the user's movements to be accurately scaled and applied to their virtual counterpart in the environment. This allows a reasonable degree of freedom from within the confines of their tracked area. The issue arises when the user wishes to traverse an environment which exceeds the size of their "play-space". Two years have elapsed since the launch of the first consumer-grade HTC Vive units; as we approach the next generation of hardware, the VR experiences now offered are far richer and more immersive, although there is still an absence of a suitable general-purpose locomotion system.

A traditional approach to VR locomotion, explored with games like SUPERHOT VR (SUPERHOT Team, 2016), involves placing the user in a static location against waves of enemies, which upon defeat will allow the user to teleport to the next designated area within the virtual environment (VE). This design choice was primarily due to tracking limitations on the initial consumer VR release platform, the Oculus Rift CV1. The lack of artificial acceleration benefits the game design is this example as it results in minimal discomfort for the user, but still offers a fast-paced experience.

Figure 1:
Static combat depicted in SUPERHOT VR.
SUPERHOT VR (SUPERHOT Team, 2016)

Developers of current VR titles, which offer large environments, such as Doom VFR (id Software, 2017), primarily opt for using variations of teleportation and touchpad locomotion as their primary method of navigation, with the addition of a complementary secondary technique. These games will generally offer a choice to the user regarding the primary locomotion method. The primary methods tend to be adapted to the game's context which can enhance or add gameplay mechanics, such as with Doom VFR, where teleporting allows the target to snap to an enemy, which in turn triggers a unique cinematic attack. Doom VFR also incorporates a secondary "dash" locomotion alongside the teleportation and touchpad methods, which allows the user to quickly move a short distance in a relative direction, as well as reorient themselves by 180°. Although the inclusion of a secondary locomotion technique addresses the expected fast gameplay of the Doom franchise, the primary trade-off is comfort, where an increase in motion sickness and disorientation is probable for many users through the perception of unnaturally fast or unexpected changes in acceleration as outlined in the Oculus Best Practises (Oculus, 2017). When presented with uncomfortable acceleration, longer exposure will generally result in more severe symptoms of motion sickness. To mitigate issues with discomfort in VR, a choice of locomotion methods focussed on comfort has become more prevalent in current large-scale VR games and

Figure 2:
Teleport locomotion snapping to an enemy.
Doom VFR (id Software, 2017)

experiences. This is seen in the case of Fallout 4 VR (Bethesda Game Studios, 2017), where considerations were made to improve comfort in both motion and gameplay respectively. These options include "vignette settings to make smooth locomotion even more comfortable", as well as "for maximum comfort, you can display the Pip-Boy as a projected menu for even easier access." Despite efforts to improve comfort, touchpad-based locomotion was found to invoke symptoms of motion sickness in some users, providing a need for a comfortable alternative. This was summarised in a review by C. Hunt (2017) which outlined the general consensus that "Many enjoy standard locomotion [through a touchpad]— the kind that simulates regular walking and running — while many others enjoy teleportation thanks to it being less nausea-inducing."


Figure 3:
HMD vignette when moving.
Fallout 4 VR (Bethesda Game Studios, 2017)

The use of teleportation as a comfort locomotion method has become widely adopted due to the ease of use and comfort it provides when navigating a large environment. Other comfortable methods of locomotion have also been developed and evaluated, which translate natural motion of the user's VR hardware to in-game movement, such examples include "Arm Swinger" (Electric Night Owl, 2016), which uses the change in controller position to derive a relative forward force. The motion is achieved by the user swinging their arms in a similar manner to that of walking. Another method, "RIPMotion" (Sullivan, R. 2016) tracks the vertical change of the headset position. The effect is achieved by runing on the spot, which provides the change in position for the vertical axis. The use of natural and semi-natural locomotion methods usually results in a comfortable experience, however there are some drawbacks. The main concern is that the methods cause too much physical exertion and as such, are not suitable for every scenario, although in some, it can improve user immersion in the experience. Additionally, the issue of "uncanny valley" can become apparent in regards to the movement. In this context, it presents itself as a phenomenon where the movement represented in VR is just dissimilar enough from the real movement made by the user, which can cause a disconnect between the expected and resulting motion. This can cause symptoms of sickness and instability. Despite these considerations, adoption rates of natural and semi-natural locomotion methods have seen increases with developers producing plug-ins for the purpose of integration with existing games, to provide greater immersion and comfort. One example of such a plug-in is "Natural Locomotion" (Myou, 2018), an application available through Steam that hooks into a game's executable to override the default locomotion method. "Natural Locomotion" uses a modified variant of the "ArmSwinger" method, and subsequently allows the usage of that method in any game that supports conventional touchpad locomotion.

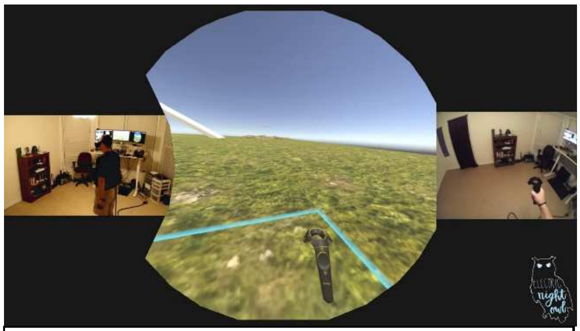


Figure 4:
Demonstration of swinging arms to move.
ArmSwinger (Electric Night Owl, 2016)


Figure 5:
Demonstration of running in place to move.
RIPMotion (Sullivan, R. 2016)

This project takes the existing foundation for natural and semi-natural locomotion methods to develop and combine multiple specialised locomotion techniques into one system. This allows a full range of exploration within the virtual environment with minimal discomfort or loss of immersion; critical to the success of the developed system. The locomotion system is used in the context of a natural open world to facilitate full use of the methods developed. The world contains a variety of terrain to evaluate the ease, comfort and immersion of navigating the environment. Flat and angled ground is to assess walking and running, climbable objects such as mountains and grass ridges are used to assess navigating terrain with height by climbing, and a large body of water is used to assess water navigability through swimming. For the purposes of evaluation, modified teleportation and touchpad methods were implemented into separate builds of the experience. The separate builds were then assessed in a comparative study using a simulator sickness questionnaire, based upon the paper put forth by Kennedy et al. (1993). The questionnaire was modified and adapted for this study to focus on nausea and also provide a subjective evaluation of the experience using each locomotion system.

1.2 Aims of the project

- The primary aim is to develop and fully evaluate a comfortable and immersive locomotion system, using natural methods to achieve walking (through to running), climbing, and swimming.

- The secondary aim is to design a diverse open environment to fully demonstrate and evaluate the capabilities of the locomotion system.

- The tertiary aim is to implement a simple mini-game to add context to the experience and provide a consistent evaluation procedure.

1.3 Objectives

- ➢ Primary Objectives

    - Use preliminary research and evaluation of natural locomotion techniques to define the most suitable algorithms for the system.

    - Implement locomotion techniques, refactoring and modifying the algorithms as assessed.

    - Test and evaluate the locomotion system using a preliminary environment to improve and iterate upon the system.

    - Identify issues and make iterative improvements to the locomotion system until behaviour is fully realised.

    - Implement and adapt existing touchpad and teleportation locomotion methods for comparative evaluation.

- Secondary Objectives

  - Expand the themes used for preliminary testing to design a natural environment using a low-poly aesthetic.
  - Evaluate the environmental components using the developed locomotion system to identify and implement improvements where necessary.
  - Assess viability of the environmental components, emphasising comfort and enjoyment.
  - Optimise environmental performance and refine baked lighting.

- Tertiary Objectives

  - Develop a simple minigame premise to facilitate a range of motion for the evaluation of the study.
  - Implement the minigame and evaluate the length and suitability.
  - Assess completion of the minigame using the developed system, teleportation and touchpad locomotion to ensure evaluation consistency

2 Literature Review

2.1 Established and novel natural locomotion interfaces

Figure 6:
Walking in the Virtusphere
Virtusphere (Virtusphere Inc, 2013)

Current solutions to naturally traverse large-scale virtual environments predominantly involve additional hardware to track and orient the player in the virtual space, each with varying degrees of interaction fidelity, practicality, and comfort. Interfaces such as the Virtusphere (Virtusphere, 2013) consist of a hollow sphere placed on a platform, with rollers to allow the user to freely walk and run inside of the sphere, as well as collect sensor data. Rolling-sphere based interfaces have been shown to provide a semi-natural experience in virtual environments, however as discussed by Nabiyouni et al. (2015 a), they exhibit a lower accuracy of movement than real walking and gamepad methods of locomotion. Although it was recorded that once a steady rate of walking had commenced, "perceived precision and ease of walking were not significantly different when comparing real walking and the Virtusphere". The momentum of the sphere forces the user to make corrective adjustments to their trajectory after changing direction. In addition, a small unexpected backwards force is experienced upon reduction of the user's velocity. Medina et al. (2008) came to a similar conclusion with their early study focussing on the feasibility of the Virtusphere interface, where "Walking in the open area was perceived as the easiest task", however, "walking around the flag poles in a zigzag manner [was the most difficult task].", which would imply the change in directional velocity is difficult to accurately control. This is corroborated by the results of a study conducted by Skopp et al. (2013) where "some participants noted the need to make slow, deliberate movements or expressed concerns about stability and falling in the VirtuSphere.". Skopp also found discussed that "most participants reported small decreases in both presence and satisfaction during VirtuSphere use, relative to [game controller] use, but these differences were small and negligible.", however the study did not provide an accurate assessment of simulator sickness, as participants with susceptibility to motion sickness were excluded. In another study by Nabiyouni et al (2015 b), it was found that using a visual aid to represent the Virtusphere in the virtual environment provided more stability for participants and resulted in less participant falls.

Figure 7:
A user stood on the Torus Treadmill
Torus Treadmill (Iwata, H. 1999)

Another solution to natural traversal involves using active omni-directional treadmills to orient the player, following the work by Hiroo Iwata (1999). Active treadmill interfaces have been shown to present a far lower learning curve than examples with other locomotion interfaces, such as the Virtusphere, with Iwata stating "We accepted 82 visitors in my lab. None of them wore a safety harness. They didn't suffer from instability while walking or changing direction." Modern iterations of these devices, such as the Infinadeck (Infinadeck, 2018) use the relative position of the user on the device to calculate movement. In the video "The Infinadeck Omnidirectional Treadmill – Smarter Every Day" by Destin Sandlin (2018), the creator of the Infinadeck, George Burger, clarifies how movement is calculated relative to the centre of the device to provide the resulting acceleration in the virtual environment. Burger then continues to explain how the interface attempts to reorient the user to the centre of the device using the active two-dimensional treadmill. D. Sandlin (2018) expressed that as "there is inertia in the rollers" the acceleration from central reorientation can still be slightly unexpected when walking has ceased. The Infinadeck device has received numerous iterations since its unveiling in 2014, addressing the main concerns facing this interface method, being positional detection and reorientation of the user. The initial Infinadeck concept lacked positional tracking and directional correction, instead, as noted in a review by B. Lang (2014), "Burger manually controlled [speed and direction] using two makeshift dials." The next iteration unveiled in 2016 improved comfort and natural motion through a tracking harness which dynamically adjusted the treadmill direction and velocity based upon physical motion recorded from the user. Revisiting the Infinadeck interface in April 2018, B. Lang (2018) reported that the latest prototype has replaced the movement detection harness with HTC Vive tracking pucks to allow low-latency, precise positional tracking through the SteamVR lighthouse tracking system. Lang stated that "the company has moved from physical motion detection to using a Vive Tracker mounted on the waist to precisely sense the location of the user with very low latency. "The previous tracking implementation evaluated the position of a device connected via a pole to a tracking harness on the user. This method incurred latency as well as only providing approximations of position, whereas the lighthouse system used with the HTC Vive has been proven by O. Kreylos (2016) to be accurate to an average of 1.5mm as well as offering a worst-case scenario of 4ms latency, assuming HTC Vive tracking pucks update their pose at the same rate as the controllers. Regarding comfort and natural motion, Lang (2018) expressed that "Thanks to the fact that the surface is physically moving below you, your walking gait is very natural." Active omni-directional treadmills appear to offer the most natural interface for VR locomotion, through the convincing resistance of the treadmills and freedom of movement they offer. When using the Infinadeck for movement in VR, the user exhibits very little discomfort, with the primary concern being the acceleration that results from centring the user on the device.

Figure 8:
A user stood in the centre of the Infinadeck
Infinadeck (Infinadeck, 2018)

Despite the benefits of active natural locomotion interfaces, the largest drawback is the size, weight, and cost of the devices, with the initial Infinadeck prototypes weighing in excess of 1000 lbs (Lang, B. 2014) and the release edition expecting to cost upwards of £7,000. Passive natural locomotion interfaces compromise to massively reduce cost, weight and size footprint. The Virtuix Omni (Goetgeluk, J. 2013) is a $699 crowdfunded solution based upon low-friction harnessed walking (Robertson, A. 2015). This style of interface follows the work set out by H. Iwata and T. Fujii (1996) in their study titled "VIRTUAL PERAMBULATOR: A Novel Interface Device for Locomotion in Virtual Environment".

Figure 9:
Walking in the Virtuix Omni at CES 2015
Virtuix Omni (Goetgeluk, 2015)

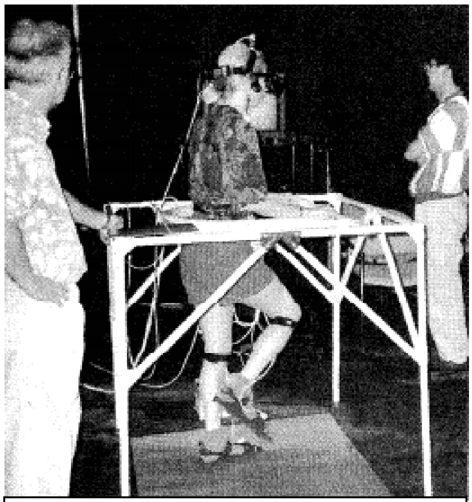


Figure 10:
Locomotion demo at SIGGRAPH '95
Virtual Perambulator
(Iwata, H. Fujii, T. 1996)

In this study Iwata and Fujii developed multiple prototypes which harnessed the user and provided an intermediate layer between the foot and surface to reduce friction. The initial prototypes used casters that allowed two dimensions of movement, the final subsequent revision used a low friction surface on a specialised sandal. A hoop frame was used to secure the user within the designated area. The study involved 235 novice participants at SIGGRAPH '95, of which only 6% (13 participants) were unable to navigate the virtual environment with the interface. The remaining 94% (222 participants) were successfully able to walk within the environment and a subsequent 8% (18 participants) could run spontaneously. Building from this concept the Virtuix Omni uses both a low-friction concave surface and shoes with low-friction material used for the soles. Similar to the device by Iwata and Fujii, the interface also securely harnesses the user within a loop. The Virtuix omni has been met with largely mixed reviews, Robertson (2015) stated "I didn't feel any motion sickness at all, despite playing a fast-paced VR shooting demo that would have turned my stomach while sitting down" although also noted that is requires a "weird gait" as "you have to throw your weight forward just enough to gain momentum, but not so much that your legs slide out from under you". In an article by Carbotte (2016) for Tom's Hardware, editor Seth Colaner expressed a similar experience where "you have to keep your legs pumping and throw your weight into the harness in the direction you want to move" followed by stating "It's a counter-intuitive way to change directions, but it's not awful." These assessments of the Virtuix Omni interface could corroborate with the study performed by Akiduki et al. (2003), where results suggested that "the preceding symptoms associated with motion sickness are the cause of postural instability" as well noting that "[visual vestibular conflict] induced by VR was sufficient to induce motion sickness and postural instability.". This could suggest in the context of the Virtuix Omni, and indeed other locomotion interfaces and methods, that an unnatural walking gait may not directly impact motion sickness and instability alone. It also suggests that as long as the interface can provide a convincing interaction method for the user, visual vestibular conflict, and as such, symptoms of motion sickness and instability can be reduced to insignificant levels.

2.2 Key considerations for avoidance of simulator sickness

Simulator sickness has been a constant issue for virtual reality and other highly immersive experiences. The book "Virtual Reality: Scientific and Technological Challenges" (National Research Council, 1995) outlined key considerations to be made when designing virtual reality experiences, as to avoid discomfort for the user. Many of these practises are still standardised design and operation considerations, such as reduction in latency and awareness of user acceleration, as set out in a 2017 paper outlining design guidelines to reduce simulation sickness in HMDs (Porcino et al. 2017). It has been found that in many cases, the primary cause of motion sickness can be attributed to visual-vestibular conflict, which can be exacerbated in VR applications, as discussed by Akiduki et al. (2003). Visual-Vestibular conflict is the disparity in motion expected by the vestibular system (a fluid-based balance mechanism located in the inner ear), when compared to the visual motion perceived through the eyes, which is commonly associated with motion sickness. The study by Akiduki at al. (2003) concluded that as visual vestibular conflict was induced further, the severity of the postural instability, and by extension motion sickness also increased. The National Research Council (1995) also outlined potential issues with visual-vestibular conflict stating "VE systems that embody mismatches between patterns of visual flow and activity associated with locomotion can be expected to distort the perception of body displacement and of voluntary activity." Following this, they noted that "the degree of which motion sickness is evoked may be relatively minor when visual motion is coupled to voluntary activity" which is supported by the observation that "Interestingly, when individuals walk at a constant speed on the treadmill during conditions of constant flow (regardless of whether the flow is appropriate in direction or magnitude for the actual stepping movements being made), they experience relatively few motion sickness symptoms. By contrast, individuals who are seated and exposed to the same visual flow patterns will report symptoms within a few minutes." This would suggest that convincing movement when walking provides the user of a virtual environment either, greater immersion, and as such would prove more convincing that the motion is occurring, or alternatively a further disconnect from the environment, where the user's motion is too dissimilar from the visual input received. In a recent study by Davis et al. (2015) where subjects viewed two rollercoaster simulations, one low fidelity and one high. The study found that both experiences caused symptoms of nausea, however the high-fidelity simulation with faster flow caused a greater feeling of nausea and at an increased rate. This also corresponds with the National Research Council's (1995) observation that participants who were seated experienced motion sickness though visual-vestibular conflict. Current HMDs experience slight variations to previously identified challenges relating to simulator sickness, with updated guidelines and studies devised to establish the fundamental processes that should be adhered to when developing such applications. Porcino et al (2017) built from Oculus (2017) to highlight essential practises for the purpose of comfort. Similar to the studies reviewed that examine visual vestibular conflict (Akiduki 2003; National Research Council 1995; Davis et al. 2015), primary considerations for VR and HMDs involve the degree of control the user has over their movements. This is in reference to both unwanted changes in acceleration and movement of the player, specifically the camera representing view for the eyes. Another large consideration is field of view (FOV) within the HMD. Lin et al. (2002) performed a study to determine whether any correlation occurred between FOV within a CAVE based virtual environment and enjoyment, presence in the VE, memory retention or simulator sickness. The study found that "with increasing FOV, subjects reported more SS [(simulator sickness)] as well as increased E2i [(presence and memory retention)] scores." The study could not determine an enjoyment scale, as when FOV increased, simulator sickness also increased, which in turn caused enjoyment to reduce. from 140° to 180° FOV, average enjoyment increased, where average simulation sickness scores levelled out. The expected next generation of HMDs is expanding the current 110° FOV to 140° shown with prototypes such as the Oculus "Half Dome" (Hayden, S. 2018). Although this is a sought-after improvement, higher fields of view will incur a greater susceptibility to cause simulator sickness through increased presence, as summarised by Nilsson et al. (2014). With a current lack of standardised locomotion methods offering an ideal technique to navigate diverse environments, the issue of compromising immersion over comfort in fast-paced experiences will exacerbate, until development, or adoption, of one or more natural locomotion interfaces or methods.

2.3 Challenges facing the development of immersive VR locomotion

As discussed, visual vestibular conflict can be attributed as a primary cause of motion sickness in virtual environments, with novel locomotion interface devices, such as the Infinadeck, setting out to provide a semi, to fully, natural walking gait. The benefit of which allows accurate reproduction of the user's action in the virtual environment, generally resulting in the most comfortable and natural experiences. Natural locomotion methods using only consumer HMDs and controllers as the locomotion interface have also been developed, offering similar results to the dedicated interfaces summarised previously. Boletsis (2017) analysed current VR locomotion solutions to propose a typology to help categorise the methods into distinct types: Motion-based, roomscale-based, controller-based, and teleportation-based.

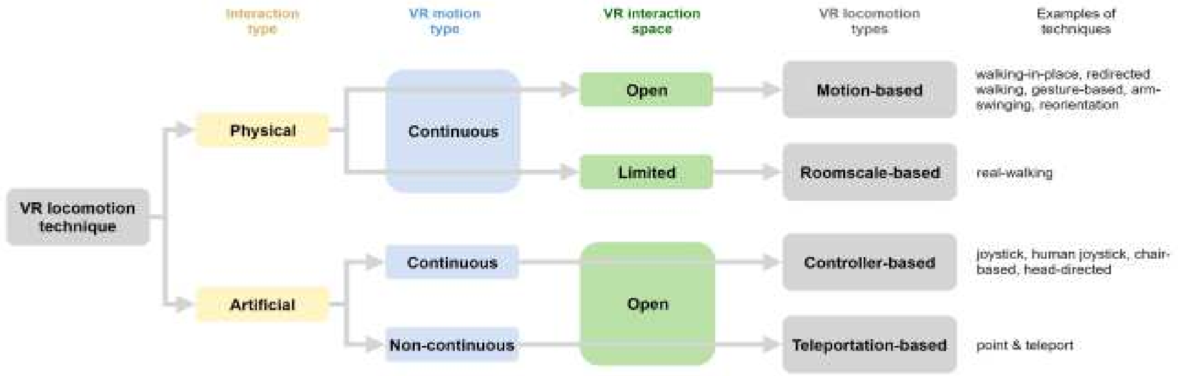


Figure 11:
Proposed VR locomotion typology to assist classification.
Locomotion Typology (Boletsis, C. 2017)

The largest number of locomotion variants appear to conform to motion-based input, indicating a push towards experimentation with versatile, natural methods, capable of exploring large environments. Such methods include walking-in-place, redirected walking and arm-swinging. Other room-scale techniques have been developed to allow real-walking, however experiences are very limited, where the virtual environment adapts to the scale of the real-world area available to provide a continuous experience. Unfortunately, real-walking techniques are unsuitable for large-scale virtual environments, although motion-based techniques to imitate walking are shown to provide versatility in scale and application. A study by Wilson et al. (2016) investigated the viability of using natural locomotion methods in comparison to real-walking. The results, measuring turning error, response time and distance judgement, concluded that both, walk-in-place and arm-swinger techniques produced similar responses to real-walking. The walk-in-place method was shown to outperform arm-swinger, following a closer trend to real-walking. In the study by Wilson et al., motion input for the locomotion methods were captured using Myo armbands, units that capture 9-axis of measurement through an accelerometer, gyroscope and magnetometer. This is not as accurate and provides less fidelity than exact positional tracking, however even through this implementation, semi-natural interpretations of acceleration were shown to provide a comparable experience to real-walking.

Figure 12:
Redirected walking concept using jointed paths.
Application of redirected walking (Langbehn et al. 2017)

Redirected walking is another natural method of locomotion for VR, with an approach and potential applications explored by Langbehn et al. (2017). This technique relies on either providing the user a curved path to follow, as explored in the study, or to coerce the user into a curved path where rotational walking is translated to a forward motion in the virtual environment. The first option presents the most natural method of implementing redirected walking, however this in turn limits the design of the virtual environment, where paths have to be decided ahead of time, as opposed to allowing free and open movement within the environment. Bruder et al. (2012) performed a feasibility study in long-distance redirected walking and found that the methods used “provided users with near-natural vestibular and proprioceptive feedback from actually moving in the real world.” This also corresponded with the participants expressing lower average scores on the simulator sickness questionnaire by Kennedy et al. (1993). Kunz at al. (2016) also showed that using circular-based redirected walking with HMDs could achieve large-scale locomotion around the factory setting used for the virtual environment.

Interaction fidelity is a commonly occurring factor in designing natural locomotion systems for VR applications, McMahan et al. (2016) discussed how interaction fidelity can directly impact locomotion performance in the same manner that the phenomenon “uncanny valley” presents itself in robotics. As interaction fidelity increases, performance increases until a middle range, at which point a sharp decrease in performance is observed until a higher fidelity is reached that closely resembles the target action. This is a larger problem for middle-fidelity techniques that don’t correlate to the real-world counterpart. McMahan et al. put forward that “Given the uncanny valley phenomenon related to interaction [-] we suggest that interaction designers should avoid developing mid-fidelity, semi-natural interaction techniques that lack overall similarities to [-] common real-world actions.” The evaluation by McMahan et al. (2016) correlates with the fidelity study by Nabiyouni et al. (2015 a) which found that low fidelity interaction methods such as an analogue gamepad provided similar performance metrics to the high-fidelity real-walking (albeit with increased discomfort), where a semi-natural locomotion interface, the Virtusphere, caused more discomfort, and performed significantly worse than the low and high-fidelity input techniques. Bozgeyikli et al. (2016) explored the use of teleportation in virtual reality and discovered that users will generally prefer the easiest locomotion method when provided the option. The experiment showed that teleportation allowed a greater accuracy of movement, with walk-in-place second and joystick last, although enjoyment of the walk-in-place method was less than both others, expected due to the higher reported levels of tiredness. Users reported that the teleportation was seen as a “superpower” and more suitable for a game context. More so, a separate experiment was conducted alongside to evaluate the reception of a modified teleportation method, which provided directional control of the final position. Users found that with increased control, the method had a higher difficulty of use and generally provided less enjoyment than teleportation alone. In addition, the added directional component incurred more cognitive load and symptoms of simulator sickness, with participants complaining of dizziness and disorientation in the virtual environment.

2.4 Mitigating discomfort and sickness in locomotion methods

Key considerations were previously discussed to aid in avoiding symptoms simulator sickness. When developing natural and semi-natural locomotion methods for VR, there are additional techniques and factors which can mitigate the onset of motion sickness, primarily focussing on visual vestibular conflict. As seen in the Fallout 4 VR comfort options, a vignette can be applied to the HMD view to reduce the effective field of view. Reductions in field of view are shown to mitigate the symptoms of simulator sickness, as shown by Lin et al. (2002), although this also compromises on immersion through presence in the virtual environment, corroborated in direct relation to HMDs by Porcino et al. (2017). Porcino also advises that locomotion methods avoid movements which are not necessarily made by the player, for example jumping, where there is a lack of movement from the user “can bring serious disparity”. The effects of acceleration can also be mitigated through the use of corresponding motions. Generally, as with most comfort considerations, acceleration should not be induced without the user invoking the action and when invoking movement, the resulting acceleration should be proportional. So et al. (2001) found that higher accelerations cause greater levels of simulation sickness, which can be exacerbated by more than six times with longer exposures. So et al. also found that the largest sickness scores occurred between three and ten meters per second, after which they stabilised. This could indicate that in human walking through to running speeds, motion sickness is more prevalent, requiring additional considerations to ensure a vestibular component is present to the locomotion method. Alternatively, for gamepad-based locomotion and other artificial techniques, reducing the speed to velocities under 3m/s may present the most comfortable compromise, where physical motion is unavailable to compensate for the flow. Motion cues could be used in this case, where a movement is required to be made in the virtual environment. In another study by Lin et al. (2004) it was shown that if motion cues are provided prior to a change in direction, scored symptoms of simulator sickness are generally reduced. In addition, the expected motion provided greater presence in the virtual environment which proved more enjoyable. This is similar to the study previously mentioned by Nabiyouni et al. (2015 b) where visual aids representing the Virtusphere provided greater stability for the user and resulted in less participants falling inside the device upon changes in direction and velocity, as well as providing a higher presence in the environment. Another primary factor to consider when applying mechanisms to mitigate discomfort, is not to additional incur tasks performed by the user, where Bozgeyikli et al. (2016) found that additional cognitive load in a modified teleportation method reduced the overall enjoyment of the experience. This can be due to users misunderstanding the mechanics of the method, which ultimately results in the locomotion method being used inappropriately and inefficiently. Bozgeyikli et al. also found that natural locomotion methods i.e. walk-in-place incurred a greater difficulty in understanding and operation, although implementation-specific factors could affect to the overall experience, such as detection sensitivity, positional tracking accuracy, and locomotion trigger mechanisms. Fundamentally, ease of use and high-fidelity motion should allow natural and comfortable experiences.

3 Methodology

3.1 Development methodology

With VR locomotion occupying a nuanced and specialised area of development, this project applied concepts from behavioural driven development (BDD) to approach the tasks undertaken. As highlighted by C. Solís and X. Wang (2011), there is no clear definition of BDD, however a BDD approach will generally base the acceptance of a system from contextualised accounts which define the behaviour of the given system. The BDD methodology approached uses a template to write scenarios that encapsulate the behaviour expected. The template requires a context of where the behaviour occurs, the event of which occurs in the specified context, and the resulting outcome of the event. The advantages of this approach for locomotion development are due to the clear definition of the behaviour and expected outcomes, as it can prove challenging to define software-based testing criteria for translating physical human motion to a virtual environment. This project also followed practises for Agile software development, first outlined by The Agile Alliance (2001), where 17 individuals representing "Extreme programming, Scrum, Dynamic systems development method, Adaptive software development, Crystal, Feature-Driven Development, pragmatic programming, and others" discussed a new methodology which was titled "Manifesto for Agile Software Development". The paper outlines a foundation of practises for adaptive software development, delivered by key representatives of pragmatic development methodologies. Agile, like BDD, builds from extreme programming practises, as outlined by K. Beck (1999), where larger user stories are broken into smaller tasks. The tasks are then developed and iteratively tested throughout. The completed task is then integrated into the base system where all unit tests are run on the system. Extreme programming practises allow for defects to be quickly identified and resolved through testing with each iteration. Agile development practises focus on developing simple effective solutions so that modification and refactoring is easier, reducing the overall time consumed through iterative improvements. For this reason, Agile development relies on competent design and quality in the implementation. J. Highsmith and A. Cockburn (2001) published a document further detailing Agile development practises, following the discussion published by Beck et al. (2001). The paper discusses practises and their advantages, such as dynamic prioritisation of features, where feature sets can be adapted, added, or removed at the end of each task to allow a pragmatic approach which delivers the most necessary features in the final product. Fundamentally, as described by Highsmith and Cockburn, “Agile practices encourage change rather than discourage it” which was evidenced throughout the development of this project. Using behavioural driven development and Agile methodologies, the locomotion methods were able to be clearly defined which provided a milestone where iterative improvements could be evaluated whether they fulfil the outlined behaviour. With these clear definitions, agile practises encouraged simplification of development, the understandable base for each system allowed modification where necessary in each iteration. Constant testing of the base system for each locomotion method under development ensured that the behaviour was conforming further to the desired outcome.

3.2 Platform overview

Unity 3D 2017.3 was decided as the platform of choice for this project as it allowed for rapid development through the use of scripting and component interfaces, as well as providing deep support for the HTC Vive through the SteamVR plugin maintained by Valve (2015). The VR setup used is an original HTC Vive. The Vive (Vive 2018) offers a 2160x1200 resolution with 1080x1200 pixels per eye at 90hz, a 110° field of view, and as discussed previously, highly accurate positional tracking. The HTC Vive was chosen as it objectively provides the best consumer VR experience available, primarily due to the lighthouse tracking system. The virtual environment designed for this project adheres to a 1 metre per Unity unit rule, this allows an easier representation of objects in the environment and allows accelerations and velocities to be measured in meters per second. For optimisation considerations, baked lightmaps were used throughout, in place of real-time lighting to minimise performance impact and to ensure the experience was capable of holding a consistent 90FPS framerate. Final performance metrics of the experience show a consistent and stable 90FPS (using an Intel i7 4720HQ CPU and Nvidia GTX 980M GPU).

3.3 Implementation details

Research was conducted through first-party analysis of popular locomotion methods used in a range of current VR games. Through these games, experiences, and demonstrations, a number of locomotion methods were identified and analysed to determine a few key factors for their suitability in the project. These factors were used to subjectively contract the number of discovered methods to a few ideal solutions that could be considered for further investigation. Basis for the acceptance of a locomotion method was tied to comfort, ease of use, and interaction fidelity, where the objective of the final developed system is to use natural motion entirely for the traversal of the virtual environment. Comfort was assessed by noting whether the locomotion technique caused sensations of vection, motion sickness or disorientation. Ease of use was evaluated by determining the number of operations or considerations had to be made by the user. If the method induced unnecessary cognitive load then it was deemed less suitable. Interaction fidelity was subjectively assessed by comparing the motion performed, to the motion expected, for example one locomotion method involved the user nodding their head to induce forward motion. This could be considered a low interaction fidelity when compared to the action of walking, where other natural methods, such as the variants of ArmSwinger could be seen as providing a medium-high interaction fidelity through the association of the gesture to walking. Both swimming and climbing locomotion methods saw very few interactive examples developed, with swimming providing the smallest amount of reference material, with only a video demonstration of an experience titled “Mermaid Cove” (Anon. 2017) to determine a relevant algorithm. Climbing experiences such as “The Climb” (Crytek, 2016) and “Climbey” (Lindenhof, B. 2016) proved invaluable, as they offered a natural and immersive climbing experience which provided a detailed insight into the mechanics used.

3.3.1 Walking Locomotion

$$M = \sum_{i=0}^{(Ph > S)}$$

$$Pr = Po + Dh \cdot (F(M \cdot C))$$

Figure 13:
The initial equation derived for run in place locomotion position.

The technique decided upon for natural walking was inspired the work set out by R. Sullivan (2016) named RIPMotion. The initial algorithm developed for this implementation of run-in-place sampled the position of the user's headset to determine if the Y-axis threshold had been reached, which was defined as the user's height at the start of the last set of data, plus a small sensitivity value. The number of frames where the headset position remained above the sensitivity threshold was used to determine the speed of the user. This value was multiplied by a coefficient to provide a resulting magnitude. This is used to determine a position ahead of the player where slope can be calculated and a linear interpolation applied between the positions, over an adjustable amount of time. The equation depicted is a representation of the first algorithm developed, where *M*, as the magnitude of movement, is the number of frames of the headset position *Ph* is above the sensitivity threshold *S*. The resulting position of the user is *Pr* derived from the original position *Po* + the direction of the user *Dh* multiplied by the magnitude. The magnitude is obtained by taking the default force *F* and multiplying that by the result of *M* by the movement coefficient *C*. Once the behaviour was mostly realised for the overall system this algorithm was modified and refactored to base movement upon the delta head position instead of the number of frames above a threshold. The position for the HMD is constantly sampled over the last 10 frames and an average of the delta positions is used to derive a magnitude. The second algorithm shown highlights this change, where *N* is the number of sampled frames, of which the sum of change in the head position *Ph* is averaged to provide the magnitude of movement. This improvement allowed for a greater degree of intuitive dynamic control, where small movements by the user coud now invoke a small translation in the virtual environment. Initial investigations in this project's study found that deriving the direction from the controller caused increased cognitive load and disorientation, however this could be assisted with better instuction. This was expected, with the research by Bozgeyikli et al. (2016) showing that increased control over a technique can cause improper and inefficient operation, and as such a toggle was included in the implementation to allow a switch from controller-directed movement to head-directed movement. The only user control for the run-in-place method is now through the grip buttons, where the user invokes the system to sample their movement and in turn provide forward acceleration.

$$M = \frac{\sum_{i=0}^{N} \Delta Ph}{N}$$

Figure 14:
The final equation used to derive step magnitude from the user's HMD

3.3.2 Climbing Locomotion

$$Pr = Po + (P1 - P0)$$

Figure 15:
The equations derived to achieve climbing position and velocity.

Using "The Climb" (Crytek 2016) and "Climbey" (Lindenhof, B. 2016) as inspiration for developing a natural climbing mechanic, two simple algorithms were defined to achieve both climbing and to apply a small amount of velocity to emulate pushing off from surfaces. The first algorithm calculates the resulting position of the player by taking the original player position and adding the delta position of the controller that is grabbing the climbable surface. This results in an exact translation from the real-life movement to the virtual representation. The equation depicted is the simple representation used to achieve climbing in the experience, where Pr is the resulting position, Po is the original player position, P1 and P0 are new and old controller positions respectively. F is the resulting force where C is the coefficient applied to the delta controller position. An additional layer was developed to the climbing locomotion method to detach the controller model and the tracked movement. This was to allow the controller model to ‘snap’ to climbable surfaces when near, but still allow full positional tracking for the controllers despite their appearance of being attached to the surface. This improvement allowed more freedom when climbing and in conjunction with haptic feedback, provided obvious cues both that a surface was climbable and that the controller was positioned in the correct way to allow gripping of the surface. The user will use the triggers to, in effect, anchor their hands to the surface No major issues were found in the evaluation of climbing, with it even promoting unprovoked inquisitive exploration of the virtual environment.

3.3.3 Swimming Locomotion

From analysing the “Mermaid Cove” demonstration (Anon. 2017), a simple approach was devised, based upon the force calculation used for climbing. The delta controller position is multiplied by a coefficient and applied as a force to the player. For simplicity in the implementation, gravity is disabled when in water and water-resistance is applied as a damping effect to the velocity of the player. Initial investigation showed that a value near 1.0, for example 0.995, provided an adequate damping to the residual acceleration experienced in water. The equation to calculate the force applied *Fa* to the player is shown, where as with climbing, the change in position from the current controller position *P1* and the previous position *P0* is multiplied by a coefficient *C* to provide a directional force. The resulting force *Fr* the user experiences is the damping coefficient *Cd* multiplied by the current player force *Fp*. Unlike the climbing method, the movement force is applied to the user on each physics update, where the player has activated the method through the use of the controller triggers. One issue noted by participants is that the swimming movement felt unnaturally slow although this is a simple revision for future iterations, where the force coefficient *C* and the clamp on the maximum force and can be increased.

$$Fa = C(P1 - P0)$$

$$Fr = Cd \cdot Fp$$

Figure 16:
The equation derived to achieve swimming velocity and damping.

3.3.4 Locomotion management

A central system manages the various aspects of the multiple locomotion methods. This system evaluates and provides contextual information about to player for example, whether they are grounded, in water or climbing. A smaller and separate management system for the controllers exists alongside the locomotion manager. This is to allow controller state queries such as the current virtual object the user is touching, the position of the controller in space, and the button context. The locomotion manager also uses ray-casts to obtain the surface of the floor to determine if the rig is grounded, as well as dynamically adjusting a collider that represents the height of the player. The dynamic collider adjustment allows players to crouch to move under low objects, where if the player is stood vertically, the movement will fail due to collision.

3.4 Testing methodology and design

A standardised simulator sickness questionnaire (SSQ) was developed by Kennedy et al. (1993) to address concerns in existing motion sickness questionnaires, where certain factors were only experienced in limited circumstances. The purpose of the questionnaire, as stated by Kennedy et al. is "to provide a more valid index of overall simulator sickness severity as distinguished from motion sickness", "to provide subscale scores that are more diagnostic of the locus of simulator sickness in a particular simulator for which overall severity was shown to be a problem" and "to provide a scoring approach to make monitoring and cumulative tracking relatively straightforward." The use of this questionnaire and variants building from it, such as the "Revised SSQ" (Kim et al. 2004) and "SSQ: Twenty Years Later" (Balk et al. 2013) have been widespread in studies focussing on simulator, and indeed virtual reality comfort, in such discussed studies as Lin et al. (2002; 2004), Medina et al. (2008) and Skopp et al. (2013). The approach employed by Balk et al. (2013), identified the least and most significant factors of simulator sickness, following the questionnaire outlined by Kennedy et al. (1993). This was achieved through the analysis of results from 530 participants, where 72 "experienced simulator sickness symptoms strong enough to terminate participation in the research study". The results were then analysed to determine the symptoms that contribute the greatest amount to participant dropout. The results found that the symptoms that assess nausea contribute the most to participant dropout rate.

The evaluation for this project chose to follow the work set out by Balk et al. (2013), as their findings provide a concise and directed approach to assess the most significant causes pertaining to simulator sickness. This study uses every factor outlined by Balk et al. shown to directly contribute to nausea. The factors assessed in "Part A" are nausea, general discomfort, stomach awareness, sweating, increased salivation, and vertigo. Participants assess these factors from 0-3, none, slight, moderate, and severe, which will provide an overall nausea score for comparison. This is performed alongside a separate comfort and immersion evaluation in an attempt to gauge subjective opinions of the locomotion systems. "Part B" is evaluated by participants providing a 1-5 score relative to their agreement with each statement presented. The locomotion method for the participant is randomised to ensure no bias can form from the order of the methods.

The study is conducted as part of a minigame, where the user is tasked with exploring the virtual environment to recover 4 pieces of their spacecraft. The craft pieces are located in areas of the environment depicted in the orthographic representation below. The location of the pieces ensures that participants explore multiple sections of the environment and have to encounter varied terrain. Piece A is to acclimate the user to flat ground and basic movement. Piece B introduces uneven ground and a small amount of elevation through climbing. Piece C provides a mildly challenging climb. Finally, piece D which exposes the participant to using multiple locomotion methods effectively, where swimming is met with climbing to exit the body of water, followed by running to the goal. This minigame is repeated three times, once for each locomotion method tested, natural movement, teleportation, and touchpad. Following the completion of the minigame, the participant enters their feedback into the questionnaire which is kept separate for each method. The questionnaire is hosted using Google forms as results can be automatically compiled into a spreadsheet. This method provides easier data collection and evaluation, as well as ensuring security of the results. Please see the appendices to view the questionnaire used for data collection in this study.

Figure 17:
The environment designed for the study, with points of interest marked.

Figure 18:
The test environment, left. A participant running using the natural locomotion system, right.
Single picture taken with explicit participant consent and blurred for anonymity.

4 Results of the study

4.1 First-party evaluation and hypothesis

The developed locomotion system adheres to using natural motion cues which allow dynamic walking through to running, climbing, and swimming, fulfilling the primary aim set out for the project. The resulting motion presented by the locomotion system appears intuitive and adaptable, where the system proves to be fully capable of navigating the diverse environment developed for its evaluation. The prediction for the study is that participants will find little to no discomfort, however the amount of activity required by the natural locomotion method may prove its downfall. The expectation is that participants will also find the natural system more immersive, with a greater presence in the environment, potentially also due to the physical effort required. It's probable that teleportation will deliver the most comfortable experience for participants, however the belief is that the natural locomotion method will provide similar results, although with greater presence and immersion.

4.2 Results

This section will summarise the statistically significant results found through the comparative study of the three locomotion methods evaluated. The study had a limited turnout in regards to participants, due to the difficulty in securing an adequate testing environment. In the resulting experiment, 6 participants of perfect health trialled the experience using each locomotion method to complete the mini-game. Results were recorded after each round of experimentation. This is directly following the participant's completion of the challenge with each respective method. Despite limited participation, the study obtained 198 values across 18 questionnaires, where 3 questionnaires are administered per participant, pertaining to each locomotion method. An additional comments section also allowed participants to note any comments they had about the experience. Participants were encouraged to provide qualitative feedback regarding the movement of each experience, although the nature of the feedback is open to any observation made. This qualitative information provided useful context to the scores received, where one participant noted that they have a slight sensitivity to motion sickness.

4.2.1 Simulator sickness nausea results

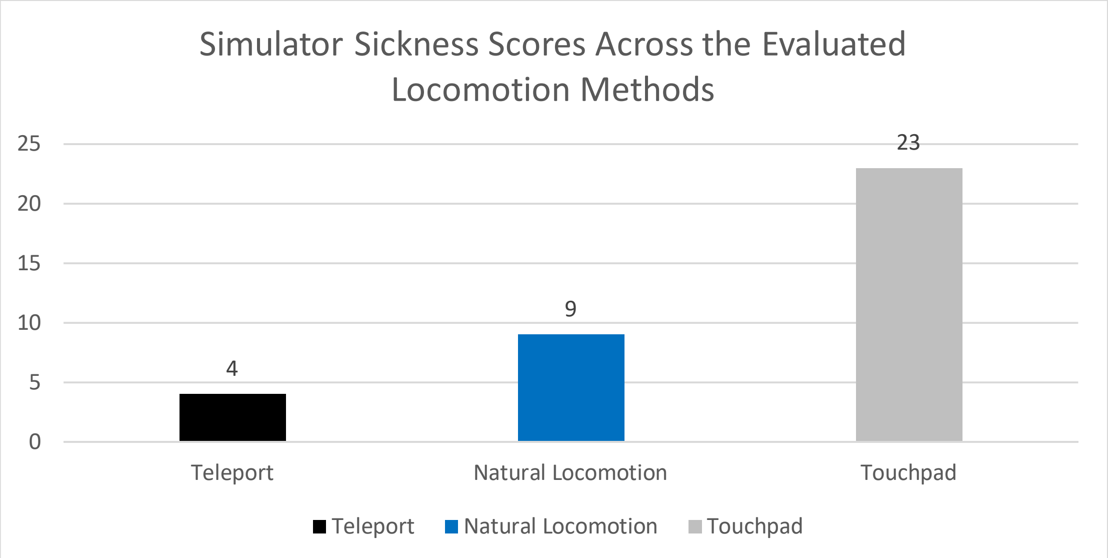
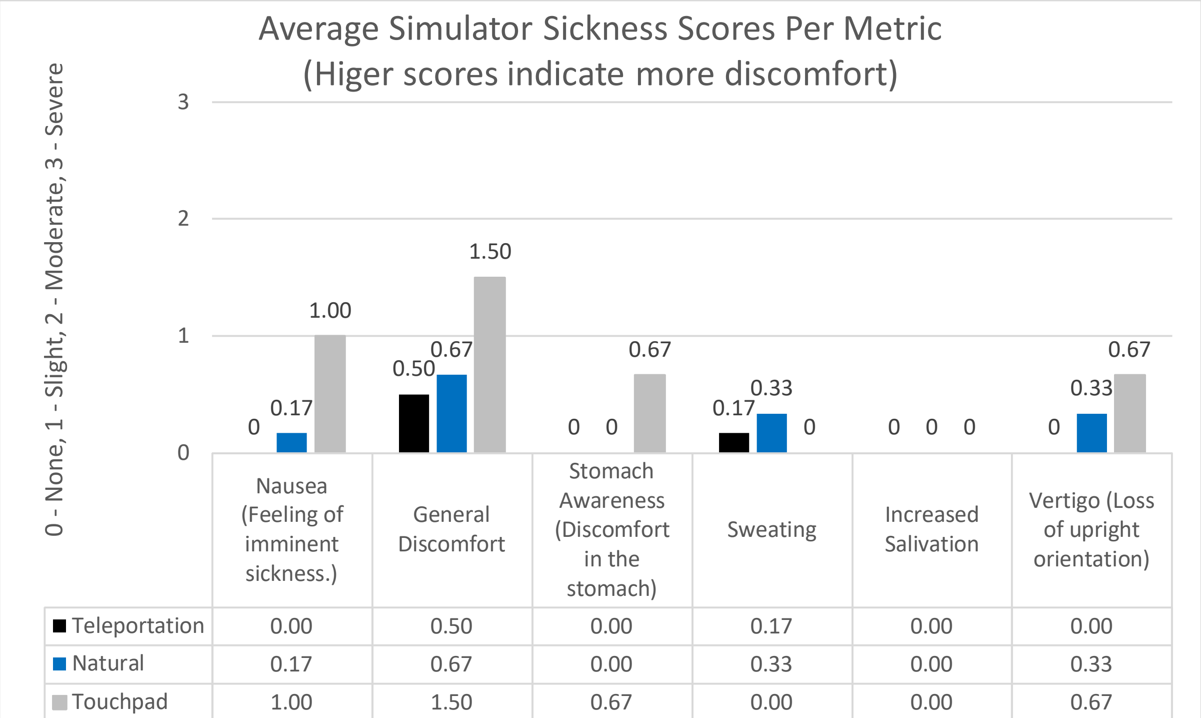


Figure 19:
A bar chart outlining the totalled scores for the modified simulator sickness questionnaire, focussed on nausea

Figure 19 outlines the scores totalled across all participants. These scores provide a relative representation of the onset of simulator sickness across the locomotion methods. As evidenced through the results, teleportation and natural locomotion performed similarly in terms of reducing symptoms of simulator sickness, where teleportation showed to incur slightly less discomfort than the natural method. Touchpad locomotion performed significantly worse, scoring more than three-times the reported simulator sickened values of natural locomotion.

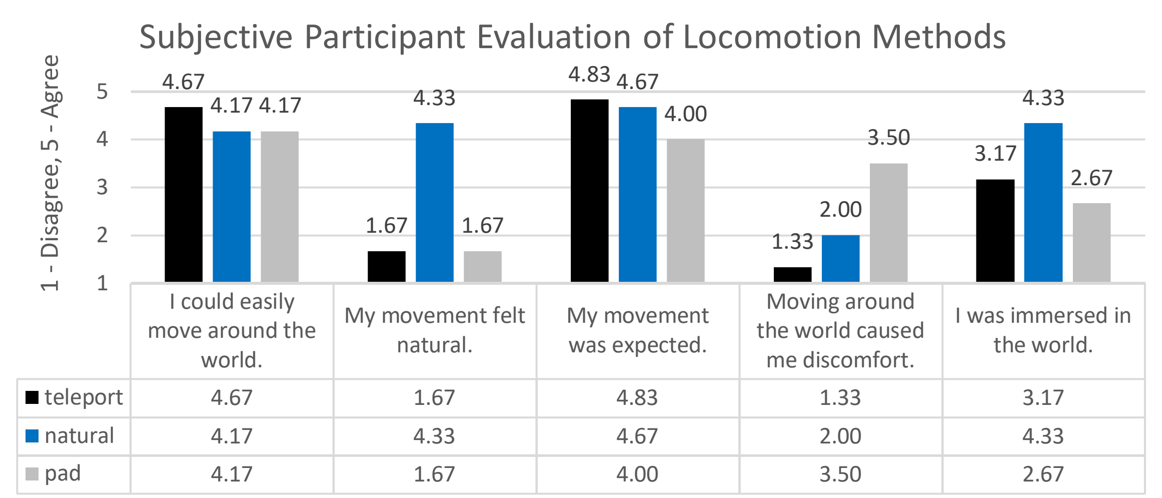


	Nausea (Feeling of imminent sickness.)	General Discomfort	Stomach Awareness (Discomfort in the stomach)	Sweating	Increased Salivation	Vertigo (Loss of upright orientation)
■ Teleportation	0.00	0.50	0.00	0.17	0.00	0.00
■ Natural	0.17	0.67	0.00	0.33	0.00	0.33
■ Touchpad	1.00	1.50	0.67	0.00	0.00	0.67

Figure 20:
A bar chart detailing the average simulator sickness scores across the nausea categorisation

Figure 20 highlights the specific metrics used to evaluate simulator sickness in this study. Across the varied metrics, touchpad locomotion scores worse than the other locomotion methods tested. Touchpad locomotion shows next to no indication of simulator sickness, where no individual marker presents even a slight overall indicator of discomfort. Natural locomotion shows very slight signs of discomfort, however again, these values present little sign of simulator sickness.

4.2.2 Subjective comfort and immersion results



	I could easily move around the world.	My movement felt natural.	My movement was expected.	Moving around the world caused me discomfort.	I was immersed in the world.
■ teleport	4.67	1.67	4.83	1.33	3.17
■ natural	4.17	4.33	4.67	2.00	4.33
■ pad	4.17	1.67	4.00	3.50	2.67

Figure 21:
A bar chart outlining the average scores for each comfort and immersion metric.

Figure 21 provides the average figures recorded for each subjective metric. The chart represents the overall participant reception of the locomotion methods. Participants found little difference in the ease of use of the locomotion methods, with teleportation again showing a slight increase in ease of use. The natural locomotion method was found to feel significantly more natural than both teleportation and touchpad locomotion methods. There was no significant difference between the expectation of movement from each method, although touchpad locomotion appears to score slightly worse. Discomfort scores prove varied between the methods, where teleportation displays almost no signs of discomfort when moving, and touchpad locomotion scores suggest a significant difference in the amount of discomfort. Natural locomotion was shown to cause a mild amount of discomfort when navigating the environment, however scores remain much closer to the values recorded for teleportation. Natural locomotion shows a clear lead in the subjective immersion metric, where touchpad and teleportation methods showed only moderate immersion in the experience.

5 Analysis of results and conclusions

5.1 Analysis and discussion of results

The outcome of the study suggests similar findings to Akiduki at al. (2003) and National Research Council (1995), where the inclusion of a suitable natural motion cue alongside acceleration and movement provide mitigating effects to the symptoms of motion sickness, through reduction of visual-vestibular conflict experienced by the user. Touchpad locomotion caused the most discomfort for participants, which could be expected due to the acceleration experienced without an accompanying physical action. Teleportation was the most comfortable method observed by the participants, where no acceleration occurred, although interestingly the natural locomotion method provided comparable results, incurring only a fractional increase in discomfort. The natural method proved to be both comfortable and immersive, with the only concern raised, being that it required much more effort than the other methods evaluated. Corroborating with this point, one participant noted “Movement is too realistic so effort was required to achieve basic movement.” The natural method was enjoyed by participants and found to provide greater presence and satisfaction from only their interaction with the environment. Participants stated “I enjoyed the choice of movements i.e. walking, climbing and swimming and being able to easily transition between the three” as well as “I really enjoyed the swimming and climbing, it was very entertaining”. This would correspond with the higher immersion scores as comments for the other methods noted “The teleportation made the game feel less realistic due to the unusual movement mechanics. This aspect also made the game too easy and not entertaining as a result”, in addition to “I found the [touchpad] movement very easy, however the actual movement in game made me very uncomfortable due to my sensitivity to motion sickness.” These comments would suggest that unnatural locomotion methods make large compromises in immersion or comfort to provide a simple movement interface. The natural locomotion method didn’t provide a significant challenge to participants, where one participant noted “It took a minute or two to work out all the controls but it was fun when I got the hang of it.” This suggests that the learning curve is relatively low for this implementation. This could be due to the system conforming to high fidelity interaction, where Nabiyouni et al. (2015) and McMahan et al. (2016) found that if a system exhibits a high enough interaction fidelity, the performance generally corresponds. Performance can be severely impacted if the fidelity falls below the threshold for moderate-high fidelity interaction.

5.2 Evaluation of the developed system

The developed natural locomotion system fulfils the desired objectives of this project. The system successfully allows the user to navigate through a diverse environment, through natural walking, climbing and swimming. The results of the limited study provide a reasonable basis to continue development into natural locomotion systems comprised of multiple sub-techniques. Small concerns were expressed through the study expressing that swimming and running techniques could be improved if they allowed faster movement, however this would have to be fully evaluated as a change in acceleration may invoke nausea in some users. The main additional concern raised is that the effort required for the natural locomotion system may not be suitable for every scenario, as some users prefer less active games. For immersive experiences where user presence is paramount, the use of a natural locomotion system, such as the example developed for this project, would offer an effective solution. When compared to the two most common methods of locomotion in VR experiences, the natural method developed, offers similar comfort to teleportation, alongside natural immersive interaction with the virtual environment. Some minor issues still persist, where collision detection can fail. This has the potential to cause disorientation, as it would be highly unexpected from the user’s perspective.

5.3 Conclusions and future work

The work set out in this paper shows the potential of achieving high-fidelity movement and interaction in VR applications. Although not applicable to every VR context, this study shows evidence that using high-fidelity techniques in a contextually appropriate manner can enhance a user's experience and offers an alternative to traditional teleportation-based locomotion where comfort is concerned. The demonstration provides an application where natural locomotion can excel, offering the user interesting methods of navigating the virtual environment. The system shows factors which could benefit from additional testing, such as re-evaluation of the speeds experienced during walking and swimming, where participants suggested that an increased speed in these areas would improve the experience. An approach could also be made to assess the correlation between degree of activity used for a locomotion system, and its comfort. This would directly address the concern that the locomotion system developed requires "strenuous" activity as noted by participants. The system itself could be refactored to use clearly defined locomotion states. This could allow the easy integration of multiple techniques, to provide the user complete control over their movement in every context. Overall the project proved successful, fulfilling the aims set out for acceptance of the resulting artefact. The locomotion system was developed and evaluated to a reasonable degree and allows the user to navigate using natural motion alone through the use of the HTC Vive HMD and controllers. The environment was designed using low-poly assets to fully encapsulate the capabilities of the developed system, adhering to optimisation practises to ensure there were as few differentiating factors affecting the results of the study. The mini-game provided consistency which ensured that the experiment was repeatable and the results accurate. In conclusion, although the study lacked a significant number of participants, the results follow a clear trend and differentiate the locomotion methods used, where the comfort and immersion metrics demonstrate a predictable outcome for each locomotion method. A follow-up study would be useful to assess numerous natural locomotion methods and interfaces, where a combination of dedicated locomotion interfaces and specialised methods could be assessed relative this developed system.

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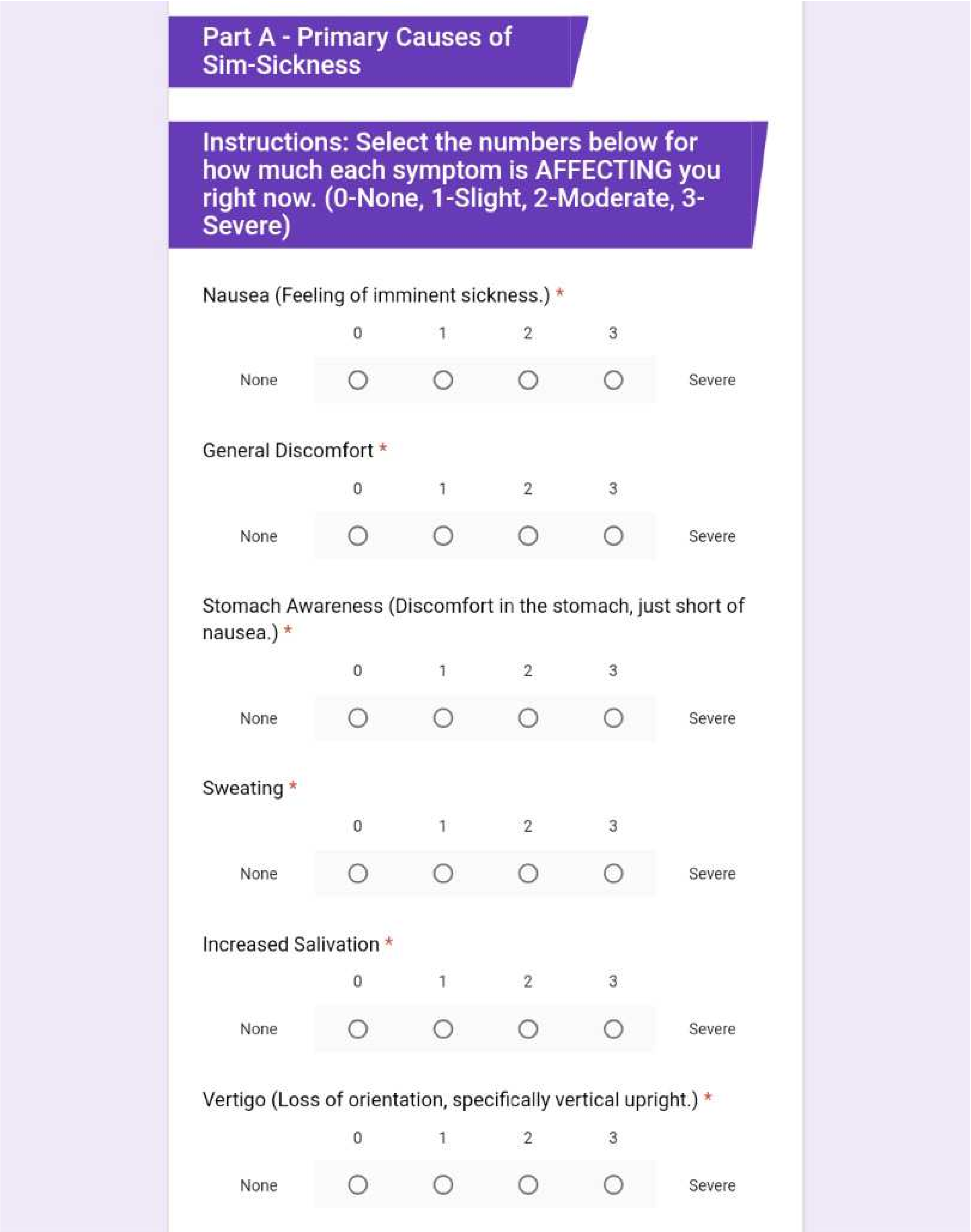
6.3 Appendices

6.3.1 Simulator sickness questionnaire



Part A - Primary Causes of Sim-Sickness

Instructions: Select the numbers below for how much each symptom is AFFECTING you right now. (0-None, 1-Slight, 2-Moderate, 3-Severe)

Nausea (Feeling of imminent sickness.) *

	0	1	2	3	
None	○	○	○	○	Severe

General Discomfort *

	0	1	2	3	
None	○	○	○	○	Severe

Stomach Awareness (Discomfort in the stomach, just short of nausea.) *

	0	1	2	3	
None	○	○	○	○	Severe

Sweating *

	0	1	2	3	
None	○	○	○	○	Severe

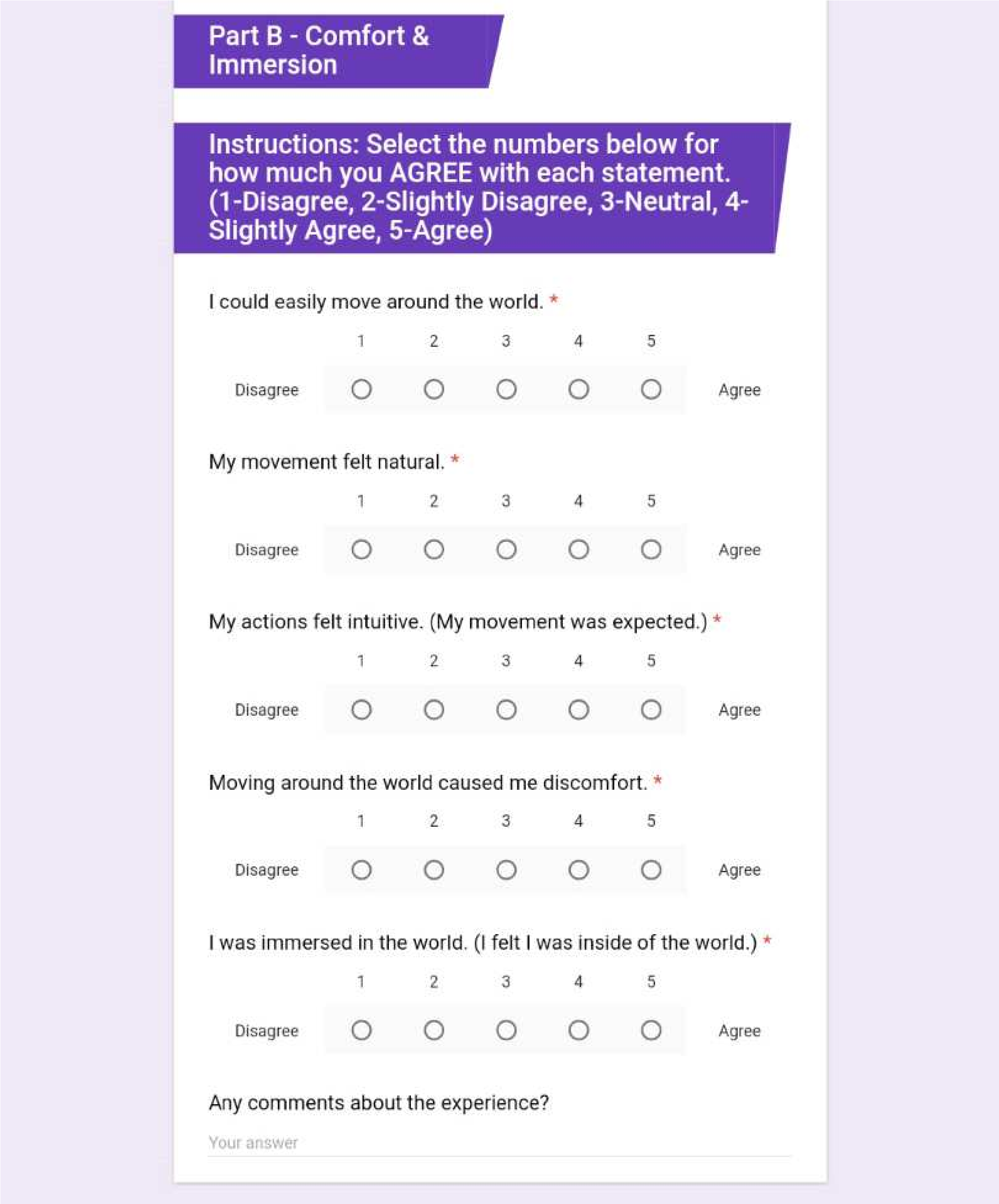
Increased Salivation *

	0	1	2	3	
None	○	○	○	○	Severe

Vertigo (Loss of orientation, specifically vertical upright.) *

	0	1	2	3	
None	○	○	○	○	Severe

6.3.2 Comfort and immersion questionnaire



Part B - Comfort & Immersion

Instructions: Select the numbers below for how much you AGREE with each statement. (1-Disagree, 2-Slightly Disagree, 3-Neutral, 4-Slightly Agree, 5-Agree)

I could easily move around the world. *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

My movement felt natural. *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

My actions felt intuitive. (My movement was expected.) *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Moving around the world caused me discomfort. *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

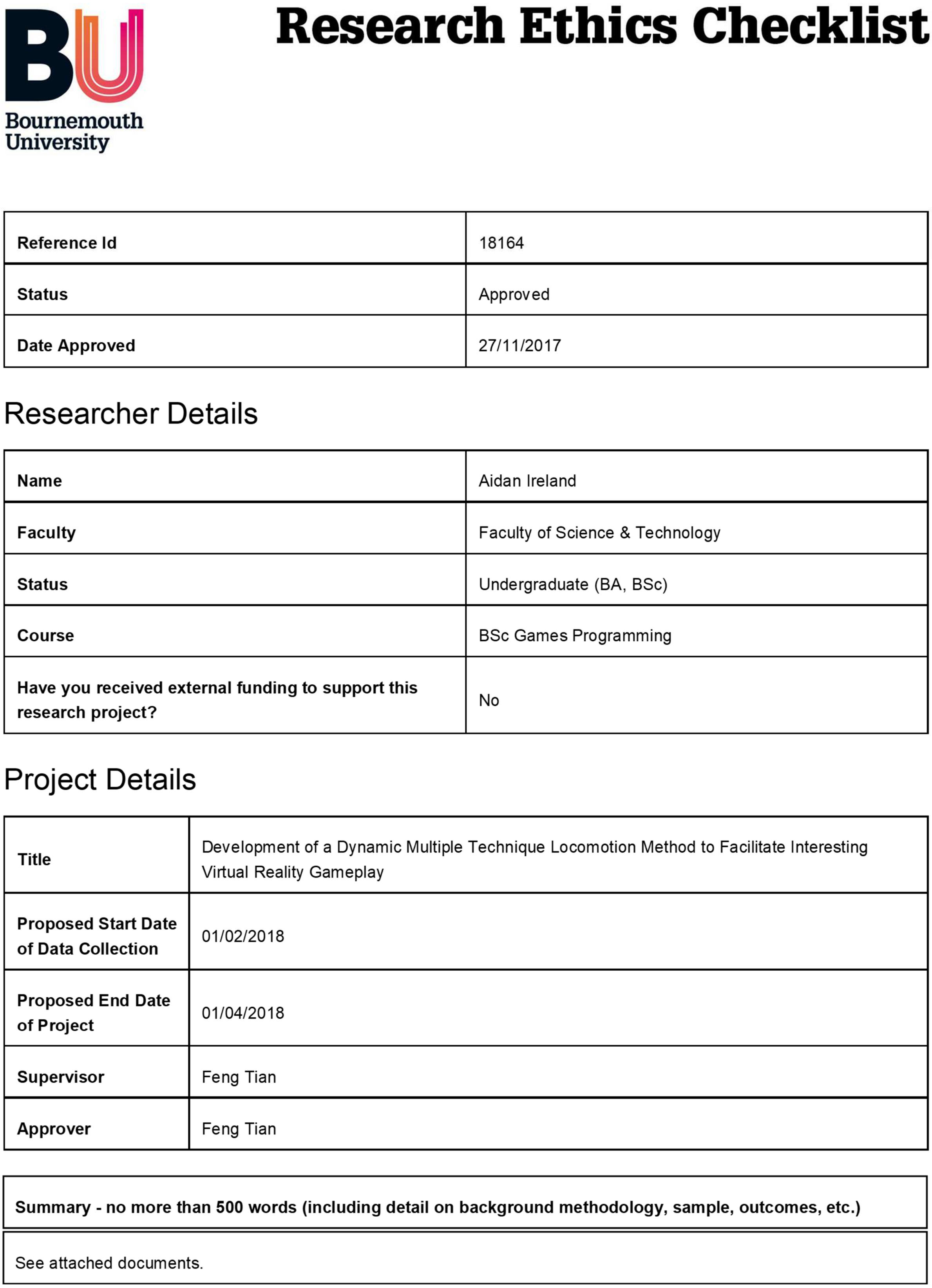
I was immersed in the world. (I felt I was inside of the world.) *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Any comments about the experience?

Your answer

6.3.3 Ethics approval



Bournemouth University

Research Ethics Checklist

Reference Id	18164
Status	Approved
Date Approved	27/11/2017

Researcher Details

Name	Aidan Ireland
Faculty	Faculty of Science & Technology
Status	Undergraduate (BA, BSc)
Course	BSc Games Programming
Have you received external funding to support this research project?	No

Project Details

Title	Development of a Dynamic Multiple Technique Locomotion Method to Facilitate Interesting Virtual Reality Gameplay
Proposed Start Date of Data Collection	01/02/2018
Proposed End Date of Project	01/04/2018
Supervisor	Feng Tian
Approver	Feng Tian

Summary - no more than 500 words (including detail on background methodology, sample, outcomes, etc.)
See attached documents.

External Ethics Review

Does your research require external review through the NHS National Research Ethics Service (NRES) or through another external Ethics Committee?	No

Research Literature

Is your research solely literature based?	No

Human Participants

Will your research project involve interaction with human participants as primary sources of data (e.g. interview, observation, original survey)?	Yes
Does your research specifically involve participants who are considered vulnerable (i.e. children, those with cognitive impairment, those in unequal relationships—such as your own students, prison inmates, etc.)?	No
Does the study involve participants age 16 or over who are unable to give informed consent (i.e. people with learning disabilities)? NOTE: All research that falls under the auspices of the Mental Capacity Act 2005 must be reviewed by NHS NRES.	No
Will the study require the co-operation of a gatekeeper for initial access to the groups or individuals to be recruited? (i.e. students at school, members of self-help group, residents of Nursing home?)	No
Will it be necessary for participants to take part in your study without their knowledge and consent at the time (i.e. covert observation of people in non-public places)?	No
Will the study involve discussion of sensitive topics (i.e. sexual activity, drug use, criminal activity)?	No

Are drugs, placebos or other substances (i.e. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	No

Will tissue samples (including blood) be obtained from participants? Note: If the answer to this question is 'yes' you will need to be aware of obligations under the Human Tissue Act 2004.	No

Could your research induce psychological stress or anxiety, cause harm or have negative consequences for the participant or researcher (beyond the risks encountered in normal life)?	No
Will your research involve prolonged or repetitive testing?	No
Will the research involve the collection of audio materials?	No

Will your research involve the collection of photographic or video materials?	No
Will financial or other inducements (other than reasonable expenses and compensation for time) be offered to participants?	No

Please give a summary of the ethical issues and any action that will be taken to address these. Explain how you will obtain informed consent (and from whom) and how you will inform the participant about the research project (i.e. participant information sheet).
A publicly available information sheet will be displayed around Bournemouth University, offering the opportunity to test a VR experience, where the participants will provide feedback on the developed VR motion system. Potential participants are able to make contact through my university email, provided on the information sheet. The potential participant will be instructed on the nature of the study and can then make the informed decision to consent in participation.

Final Review

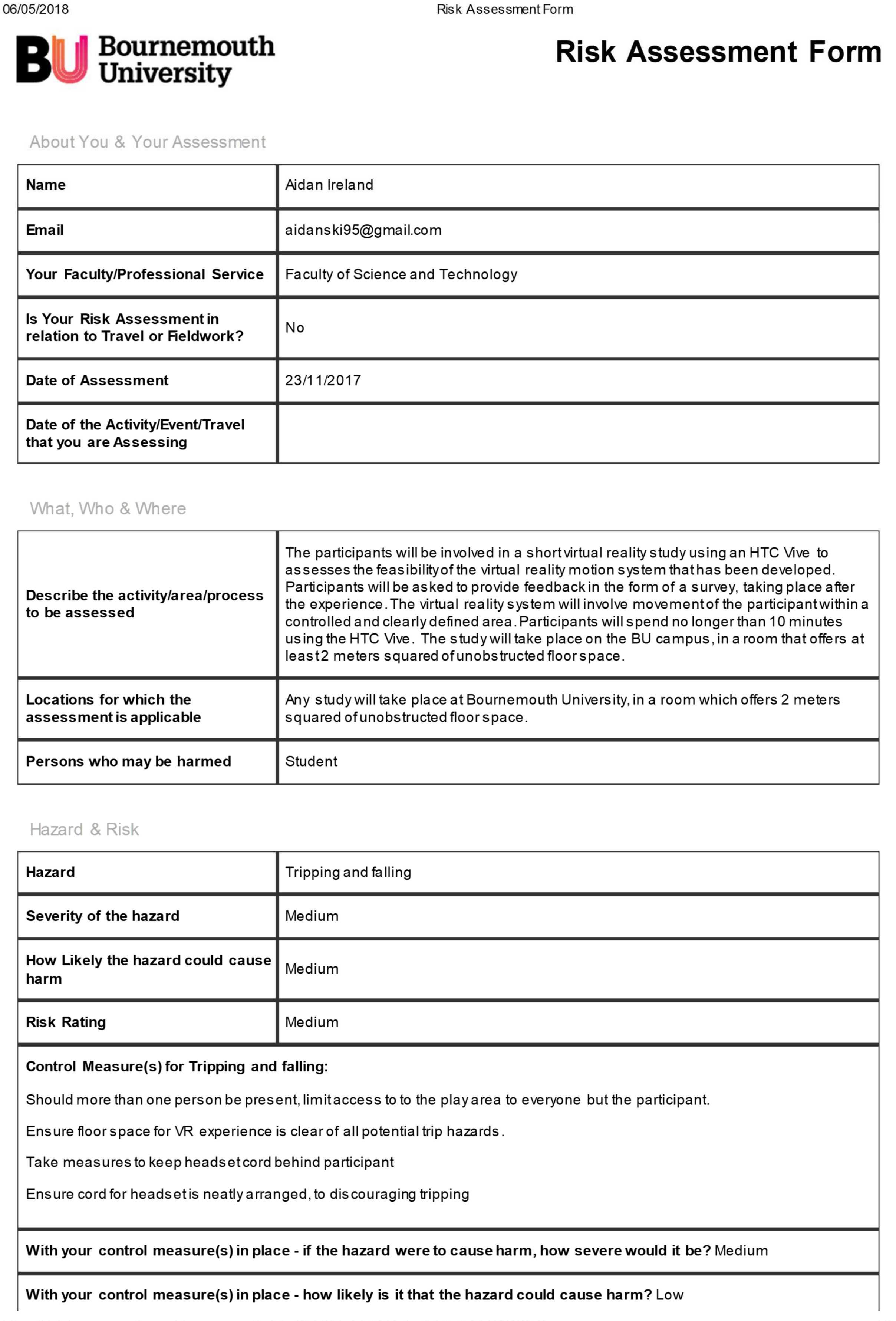
Will you have access to personal data that allows you to identify individuals OR access to confidential corporate or company data (that is not covered by confidentiality terms within an agreement or by a separate confidentiality agreement)?	No
Will your research involve experimentation on any of the following: animals, animal tissue, genetically modified organisms?	No
Will your research take place outside the UK (including any and all stages of research: collection, storage, analysis, etc.)?	No

Please use the below text box to highlight any other ethical concerns or risks that may arise during your research that have not been covered in this form.

Researcher Statement

JOURNALISM / BROADCAST RESEARCHERS: I confirm that I have consulted and understand the Research Ethics Supplementary Guide: For Reference by Researchers Undertaking Journalism and Media Production Projects (available on the Research Ethics page)	Yes

6.3.4 Risk assessment



Bournemouth University

Risk Assessment Form

About You & Your Assessment

Name	Aidan Ireland
Email	aidanski95@gmail.com
Your Faculty/Professional Service	Faculty of Science and Technology
Is Your Risk Assessment in relation to Travel or Fieldwork?	No
Date of Assessment	23/11/2017
Date of the Activity/Event/Travel that you are Assessing	

What, Who & Where

Describe the activity/area/process to be assessed	The participants will be involved in a short virtual reality study using an HTC Vive to assesses the feasibility of the virtual reality motion system that has been developed. Participants will be asked to provide feedback in the form of a survey, taking place after the experience. The virtual reality system will involve movement of the participant within a controlled and clearly defined area. Participants will spend no longer than 10 minutes using the HTC Vive. The study will take place on the BU campus, in a room that offers at least 2 meters squared of unobstructed floor space.
Locations for which the assessment is applicable	Any study will take place at Bournemouth University, in a room which offers 2 meters squared of unobstructed floor space.
Persons who may be harmed	Student

Hazard & Risk

Hazard	Tripping and falling
Severity of the hazard	Medium
How Likely the hazard could cause harm	Medium
Risk Rating	Medium

Control Measure(s) for Tripping and falling:

Should more than one person be present, limit access to to the play area to everyone but the participant.

Ensure floor space for VR experience is clear of all potential trip hazards.

Take measures to keep headset cord behind participant

Ensure cord for headset is neatly arranged, to discouraging tripping

With your control measure(s) in place - if the hazard were to cause harm, how severe would it be? Medium

With your control measure(s) in place - how likely is it that the hazard could cause harm? Low

The residual risk rating is calculated as: Low

Hazard	Photosensitive epilepsy and other disorders
Severity of the hazard	High
How Likely the hazard could cause harm	Low
Risk Rating	Medium

Control Measure(s) for Photosensitive epilepsy and other disorders:

Ensure have no previous records of photosensitive epilepsy or other disorders which could be induced or exacerbated with exposure to VR

Fully inform all participants of the potential risks associated with the use of VR

With your control measure(s) in place - if the hazard were to cause harm, how severe would it be? Medium

With your control measure(s) in place - how likely is it that the hazard could cause harm? Low

The residual risk rating is calculated as: Low

Hazard	Motion sickness & Vection using VR
Severity of the hazard	Medium
How Likely the hazard could cause harm	Medium
Risk Rating	Medium

Control Measure(s) for Motion sickness & Vection using VR:

Encourage immediate removal of the headset, should motion sickness symptoms arise.

Move all hard objects that could injure the participant, should they lose balance, clearly out of range.

Limit time using VR headset to 10 minutes.

With your control measure(s) in place - if the hazard were to cause harm, how severe would it be? Medium

With your control measure(s) in place - how likely is it that the hazard could cause harm? Low

The residual risk rating is calculated as: Low

Hazard	Walking outside play area
Severity of the hazard	Medium
How Likely the hazard could cause harm	Low
Risk Rating	Low

Control Measure(s) for Walking outside play area:

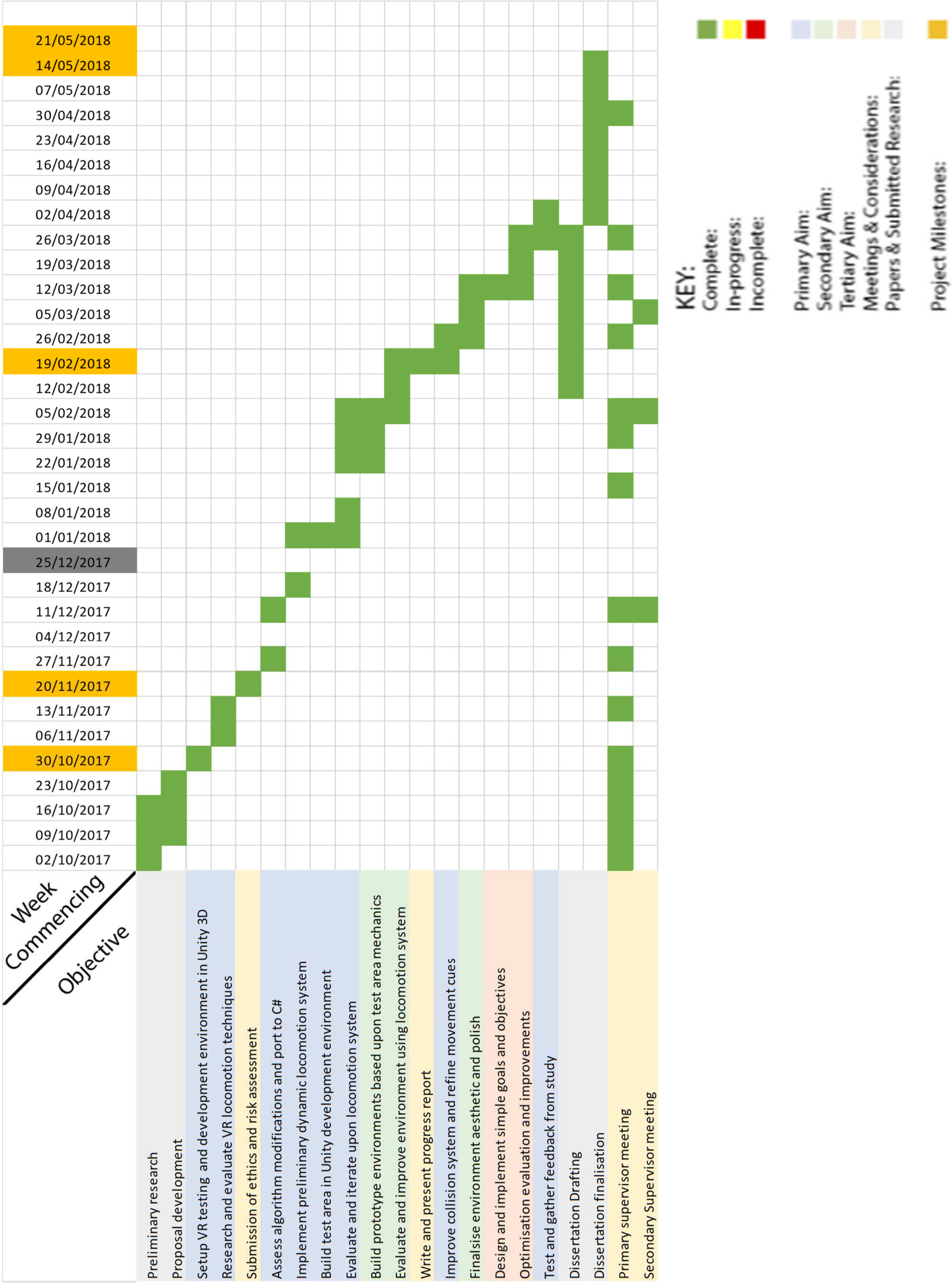
Use the SteamVR chaperone feature (overlays the real-world play area in the game world) to inform the participant of their location in relation to play area

Assist participant in orienting themselves in the centre of the play area. Allow for a clear space outside the play area so that, should the participant overstep the play area they still have an allocated buffer of floor space
With your control measure(s) in place - if the hazard were to cause harm, how severe would it be? Low
With your control measure(s) in place - how likely is it that the hazard could cause harm? Low
The residual risk rating is calculated as: Low

Review & Approval

Any notes or further information you wish to add about the assessment	
Names of persons who have contributed	
Approver Name	Auto Approved by Aidan Ireland
Approver Job Title	[Not Applicable]
Approver Email	Auto Approved by aidanski95@gmail.com
Review Date	01/02/2018

6.3.5 Simplified Gantt chart to provide estimated scale and tasks



Week Commencing / Objective	Preliminary research	Proposal development	Setup VR testing and development environment in Unity 3D	Research and evaluate VR locomotion techniques	Submission of ethics and risk assessment	Assess algorithm modifications and port to C#	Implement preliminary dynamic locomotion system	Build test area in Unity development environment	Evaluate and iterate upon locomotion system	Build prototype environments based upon test area mechanics	Evaluate and improve environment using locomotion system	Write and present progress report	Improve collision system and refine movement cues	Finalise environment aesthetic and polish	Design and implement simple goals and objectives	Optimisation evaluation and improvements	Test and gather feedback from study	Dissertation Drafting	Dissertation finalisation	Primary supervisor meeting	Secondary Supervisor meeting
21/05/2018 🟧																					
14/05/2018 🟧																			🟩		
07/05/2018																			🟩		
30/04/2018																			🟩	🟩	
23/04/2018																			🟩		
16/04/2018																			🟩		
09/04/2018																			🟩		
02/04/2018																	🟩		🟩		
26/03/2018																🟩	🟩	🟩		🟩	
19/03/2018																🟩		🟩			
12/03/2018														🟩	🟩	🟩		🟩		🟩	
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05/02/2018									🟩	🟩	🟩									🟩	🟩
29/01/2018									🟩	🟩										🟩	
22/01/2018									🟩	🟩											
15/01/2018																				🟩	
08/01/2018									🟩												
01/01/2018							🟩	🟩	🟩												
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27/11/2017						🟩														🟩	
20/11/2017 🟧					🟩																
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23/10/2017		🟩																		🟩	
16/10/2017	🟩	🟩																		🟩	
09/10/2017	🟩	🟩																		🟩	
02/10/2017	🟩																			🟩	

KEY:
Complete: 🟩
In-progress: 🟨
Incomplete: 🟥

Primary Aim: 🟦
Secondary Aim: 🟩
Tertiary Aim: 🟧
Meetings & Considerations: 🟨
Papers & Submitted Research: ⬜

Project Milestones: 🟧

6.3.6 Raw participant results and comments

Nausea (Feeling of imminent sickness.)	General Discomfort	Stomach Awareness (Discomfort in the stomach)	Sweating	Increased Salivation	Vertigo (Loss of upright orientation)	I could easily move around the world.	My movement felt natural.	My actions felt intuitive. (My movement was expected.)	Moving around the world caused me discomfort.	I was immersed in the world. (I felt I was inside of the world.)
Natural										
	0	0	0	0	1	4	4	4	2	4
0	0	0	0	0	0	4	4	5	1	5
1	2	0	1	0	1	4	4	5	3	4
0	1	0	0	0	0	4	5	4	2	4
0	1	0	0	0	0	5	4	5	2	5
0	0	0	1	0	0	4	5	5	2	4
0.17	0.67	0.00	0.33	0.00	0.33	4.17	4.33	4.67	2.00	4.33
Teleportation										
0	1	0	1	0	0	3	3	5	2	3
0	0	0	0	0	0	5	1	4	1	2
0	0	0	0	0	0	5	1	5	1	3
0	1	0	0	0	0	5	1	5	2	3
0	0	0	0	0	0	5	2	5	1	4
0	1	0	0	0	0	5	2	5	1	4
0.00	0.50	0.00	0.17	0.00	0.00	4.67	1.67	4.83	1.33	3.17
Touchpad										
1	1	0	0	0	0	3	2	3	4	2
0	0	0	0	0	0	5	3	5	2	4
2	3	2	0	0	0	5	1	5	5	2
1	2	1	0	0	1	5	1	4	4	2
1	1	1	0	0	2	3	1	3	3	3
1	2	0	0	0	1	4	2	4	3	3
1.00	1.50	0.67	0.00	0.00	0.67	4.17	1.67	4.00	3.50	2.67

Natural

Only part that felt generally unnatural was the swimming
Movement is to realistic so effort was required to achieve basic movement. would prefer a less strenuous game in my downtime. Additionally, the controller input was annoying because of the button placement. I really enjoyed the swimming and climbing, it was very entertaining and made me more interested in VR. I also enjoyed the gameplay aspects of the demo, and would enjoy seeing this developed further
I enjoyed the choice of movements e.i walking, climbing and swimming and being able to easily transition between the three. however i found it uncomfortable at times due to my slight sensitivity to motion sickness.
I liked climbing the most. swimming and running felt a bit slow though. It was a fun game and I only felt uncomfortable when I fell climbing.
This was also really fun. Teleportation was interesting, but I really enjoyed how naturally I could move. It took a minute or two to work out all the controls but it was fun when I got the hang of it.
this was more fun than the others but took longer

Teleportation

The teleportation made the game feel less realistic due to the unusual movement mechanics. This aspect also made the game too easy and not entertaining as a result. This style of gameplay could become boring after a while.
I had great fun with the power like feel of teleporting around the world. although this method of movement is very unrealistic it was still easy to lose yourself in the game.
Teleporting around the game was easy and was a lot smoother than the other touch moving. Teleporting too fast made me lose balance once.
This was really fun. I haven't tried virtual reality before and I expected it to be different, but using teleportation was really easy.
teleporting was easy but i still felt a tiny bit queasy from the last go

Touchpad

Some issues with scaling verticle objects
Music would make the game more immersive. The movement felt easy to achieve however it would have been better to incorporate some more complex actions for climbing and swimming. Similar to these methods in the other demo example with more active movements.
i found the movement very easy, however the actual movement in game made me very uncomfortable due to my sensitivity to motion sickness.
Moving was easy but felt disorientating. I wouldn't want to use this for a long time because it felt uncomfortable at the end.
This was not as enjoyable as the first time. Moving made me feel slightly unwell, especially when jumping off cliffs.
i lost my balance a few times but it wasn't too bad