Comparison of teleportation locomotion methods for efficient wayfinding in virtual reality environments

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Declaration

This dissertation is submitted to the University of Bath in accordance with the requirements of the degree of Computer Science in the Department of Computer Science. No portion of the work in this dissertation has been submitted in support of an application for any other degree or qualification of this or any other university or institution of learning. Except where specifically acknowledged, it is the work of the author.

Abstract

A challenge of teleportation locomotion techniques in virtual reality (VR) environments is that the primary benefit of teleportation - the ability to traverse large travel distances quickly – is also one of its biggest drawbacks: teleporting users do not see much of the virtual environment they are travelling across. This results in poor user spatial awareness that negatively affects their ability to wayfind efficiently. Despite the importance of locomotion methods in VR, there have been no comparisons of teleportation methods within a virtual environment utilising modern 3D graphics on modern consumer VR hardware. Of the studies conducted, they have either focused on specific elements of locomotion or spatial awareness without consideration of the larger picture or have significant limitations resulting in findings not generalising well to consumer hardware.

To address these problems this study conducted an experiment on the currently best-selling consumer VR headset, the Meta Quest 2. Four different locomotion methods were compared, with evaluations of wayfinding efficiency achieved by comparing participant performance when navigational visual aids were enabled and disabled for a given route. This report presents the experiment's findings and provides recommendations for VR researchers and developers with the goal of encouraging better VR software and experiences for consumers.

Whilst the study failed to reject all null hypotheses and found no clear best-performing teleportation method, findings limited to the sample suggest that the point and teleport technique performs better for efficient wayfinding only when users have prior knowledge of an environment or have access to visual aids. Alternatives such as dash teleport and step teleport appear to perform better than point and teleport when UI aids are not present. Feelings of motion sickness were low for all forms of locomotion, although some techniques can result in increased feelings of motion sickness compared to others.

With no clear best-performing method, recommendations for VR researchers and developers include being aware that the advantage of one teleportation method in a particular context may be a disadvantage in another context. Providing a range of locomotion methods and software visual aids for users to choose from depending on their needs and preferences appears the best approach to ensure teleportation remains useful and accessible for the best possible consumer VR experience.

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1 Introduction

The purpose of the project is to conduct an experiment using software to compare different teleportation locomotion techniques and their effect on wayfinding efficiency in a virtual reality (VR) environment. The study was conducted across 2022-2023 as part of an MSc Computer Science degree within the field of Human Computer Interaction (HCI) at the University of Bath.

1.1 Problem description

Locomotion is considered one of the most important elements of VR interaction (Christou et al., 2016). It enables users to travel to a destination, a common task in VR environments, and influences user spatial awareness and their ability to wayfind (Bozgeyikli et al., 2016; Sarupuri et al., 2017). These are essential components for ensuring a user understands their current location in relation to their destination and can decide which route to take to reach it. Artificial methods of locomotion such as teleportation provide users with ever faster methods of travel and have become popular with users due to the improved hardware capabilities such as gesture tracking now found in modern consumer VR hardware and the high level of immersion these techniques provide (Boletsis, 2017).

Despite teleportation and its effect on spatial awareness being the subject of many studies over the decades, many of these studies have been conducted with various limitations, from the technology-constrained systems of the late 1990s (Bowman et al., 1997; Bakker et al, 2003) to studies conducted either on hardware unrepresentative of the devices available to typical consumers, such as a CAVE system (Christou et al., 2016) or on highly limited mobile devices (Bhandari et al., 2018) that do not offer a complete VR experience. Other limitations have prevented prior study findings generalising to modern VR hardware and software, either due to the use of simplistic graphics that don’t reflect the modern 3D environments consumers experience today or because these studies have focused on very specific elements of locomotion without considering spatial awareness or wayfinding (Cherep et al., 2020).

The problem this study seeks to address is twofold: firstly, no single study has incorporated all the elements a consumer experiences when moving inside a virtual environment on modern VR hardware. Secondly, of the studies conducted, there is no consensus on which teleportation techniques perform best, making it difficult to make an informed choice on which technique provides the most advantages without compromising on wayfinding and spatial awareness.

1.2 Aims

The study seeks to overcome the outlined problem by achieving two aims:

1. **Measure and compare the effect of different teleportation locomotion methods on wayfinding using modern consumer VR hardware.**

   Three different teleportation locomotion techniques and one controller joystick locomotion technique will be evaluated. Participants will complete routes assigned to each technique twice, once with visual aids enabled and once with visual aids disabled. Qualitative participant data and quantitative measurements of duration, travel distance, deviation from each route's optimum path and movement route traces will be used to evaluate and compare the efficiency of each technique.

2. **Recommend teleportation locomotion methods for efficient VR wayfinding.**

   Once the results are analysed, recommendations will be provided for HCI and VR researchers and developers to incorporate into their own software. VR is at the frontier of new hardware and software interfaces within the field of HCI, providing new tools and experiences for users. Understanding how tools such as teleportation locomotion affect users is essential to maximising VR's potential and ensuring users continue to use it. Recommending the best teleportation locomotion methods for wayfinding ensure researchers and developers build the best possible VR experiences.

1.3 Contribution

This report is written for HCI and VR researchers and developers deploying VR software onto consumer VR hardware such as the Meta Quest 2. It presents findings into how different teleportation locomotion methods affect participants and provides recommendations so researchers and developers can build better virtual reality experiences.

Overall findings suggest there was no single best-performing teleportation technique of the three compared in this study. Where users already know the environment or have appropriate UI aids to direct them, point and teleport performed most efficiently, although alternatives such as dash teleport and step teleport allowed users to build up spatial awareness, allowing them to more efficiently wayfind when UI aids were disabled. Some teleportation methods appear to cause higher user error rates in wayfinding despite being mechanically similar. Feelings of motion sickness were low for all forms of locomotion with only minor variations between methods. The study recommends that VR software should provide a range of locomotion options for users to choose from according to the needs of the user and the priorities of the software, whilst being aware that the advantage of one teleportation method in a particular context may be a significant drawback in another context.

1.4 Report structure

Chapter 1 (Introduction) introduces the study's aims and the problem it is trying to solve. The current state of virtual reality locomotion methods and wayfinding research in virtual reality environments are reviewed and discussed in **Chapter 2 (Literature and Technology Review). Chapter 3 (Design of the Experiment)** outlines the requirements of the software built for the study, and the design of the experiment conducted using this software. The experiment is analysed in **Chapter 4 (Results and Analysis)** along with a discussion of its findings and their implications. **Chapter 5 (Conclusion)** concludes the report and outlines the contribution of the study to the fields of HCI and VR and reflects upon its limitations and possible future work.

2 Literature and technology review

A literature and technology review was conducted to outline the current state of consumer VR headset technologies and assess recent and key past studies into VR locomotion methods, spatial awareness and wayfinding. Findings from the review were used to identify gaps and requirements that would inform the design of the experiment.

2.1 Background

The availability of affordable consumer virtual reality (VR) head-mounted display (HMD) hardware alongside accessible and attractive software has seen VR explode in popularity in the last decade (Slater, 2018). As adoption by regular users has increased, so too has the number of VR studies. With locomotion methods considered an essential component of VR (Bozgeyikli et al., 2016; Christou et al., 2016) many studies have focused on how users move in VR spaces. As consumer hardware has become capable of supporting gestured-based pointing, one locomotion method, teleportation, has become a 'mainstream' technique for movement in VR (Boletsis, 2017, p.2) due to the benefits of overcoming physical space limitations and minimising motion sickness, but at the cost of reduced spatial awareness and wayfinding capabilities (Sarupuri et al., 2017; Bhandari et al., 2018; Habgood et al., 2018). Spatial awareness influences how users wayfind, long considered of 'great importance' (Bowman et al., 1997, p.54) in gaming and non-gaming virtual environments (Cherep et al., 2020) and both have been the focus of studies over the last few decades.

Despite the number of studies in this area of VR, many have looked at components of teleportation and spatial awareness in isolation, used specialist hardware or limited methodologies. Many comparisons of locomotion techniques do not assess their impact on spatial awareness (Frommel et al., 2017; Coomer et al., 2018), whilst studies investigating teleportation and spatial awareness together use simpler methodologies such as object location (Xu et al., 2017) or pointing back to the start (Bakker et al., 2003; Weißker et al., 2018) that don't mirror how users wayfind when moving. Where wayfinding has been studied within larger virtual environments they utilised specialist CAVE equipment (Christou et al., 2016) not generally available to consumers or used unrepresentatively sparse virtual environments (Bakker et al., 2003; Bhandari et al., 2018; Cherep et al., 2020). Few studies have been conducted on widely available consumer VR headsets such as the Meta Quest 2. This results in lower ecological validity with findings potentially not generalising to modern VR experiences, whilst studies into how teleportation locomotion techniques affect wayfinding capabilities remain sparse, despite navigation in virtual environments being an essential part of the VR experience.

This review will consider teleportation techniques and their impact on spatial awareness, wayfinding and motion sickness within the field of VR. Together these topics will highlight gaps and opportunities within the current body of research that the study can address in its experimental design and software.

2.2 Current state of virtual reality

VR allows users to experience and interact with 'immersive 3D computer generated virtual environments' (Christou et al., 2016, p.1). It has existed since the 1970s (Sharp et al., 2019) and began to look like something we would recognise today in the 1980s (Slater, 2018). However, despite showing 'great promise' during this period (Seibert and Shafer, 2018, p.79) it wasn't until the 2010s when affordable consumer HMD hardware along with improvements in graphics and CPU capabilities made VR accessible and attractive enough to general consumers rather than just researchers (Frommel et al., 2017; Slater, 2018). The 2013 release of the Oculus[1] Rift Development Kit was considered a 'significant milestone' for VR (Boletsis, 2017, p.1) and allowed software developers to reuse skills in existing popular 3D development tools such as Unreal Engine and Unity, further improving the availability of the technology.

VR HMDs provide visual feedback via a pair of screens mounted in front of a user's eyes. Many HMDs track head and hand positions via the headset component, with handset controllers incorporating buttons and joysticks for direct input by users. Consumer HMDs such as the Meta Quest 2 are widely available and offer an all-in-one integrated hardware and software solution. They require no specialist knowledge to set up or use, are entirely cable-free for regular use and incorporate app stores that make accessing software straightforward.

VR has attracted the attention of researchers over the last four decades despite its early software and hardware limitations. Two widely studied and closely related components of VR relevant to this study's topics are realism and locomotion. Realism is a key feature and attraction of VR and enables users to respond to simulations of realistic environments as though they are real (Seibert and Shafer, 2018) despite users knowing subconsciously that it is an illusion (Slater, 2018). Realism stems from two elements: immersion - objective fidelity offered by a VR system - and presence - a user's subjective response to a VR system (Bowman and McMahan, 2007). Different combinations of immersion and presence can build or break VR's illusion, and locomotion is one element essential to upholding the illusion. Locomotion allows users to move in the virtual environment often via techniques analogous to how users move in physical environments. It is required, alongside spatial awareness and wayfinding, for the successful navigation of virtual environments (Christou et al., 2016). Unwieldy or disorientating locomotion methods can prevent a user from spatially understanding the virtual environment around them, preventing them from navigating successfully and thus detract from a user's immersion (Slater, 2018). To provide a realistic experience in VR that users want to participate in it is necessary to understand how different methods of locomotion effect users.

2.3 Methods of locomotion

Locomotion is the method by which users move between points in physical and virtual environments. It is 'one of the most important considerations' in VR interaction due to its impact on spatial awareness, navigation and immersion (Christou et al., 2016, p.1; Bozgeyikli et al., 2016; Sarupuri et al., 2017). A comparison of locomotion methods was first studied by Bowman et al. (1997) and refreshed two decades later by Boletsis (2017). Attention to specific locomotion methods has altered over the decades as hardware and software technologies have

[1] Oculus is now known as Meta. Meta and Oculus used interchangeably depending on source material.

changed, but Boletsis (2017) classifies all locomotion into two distinct interaction types: physical and artificial (Appendix O: Figure 24).

This distinction immediately portrays a tension at the core of locomotion within VR: providing locomotion techniques that enable freedom of movement but do not detract from the illusion of VR despite needing to operate within the real physical world with real physical limitations (Bhandari et al., 2018). If a user sees an infinite virtual environment but can't walk further than a few metres before they need to stop in a physical room, their experience of VR will be negative. Because of the constraints of physical locomotion, artificial techniques of locomotion, some of which are impossible in the real-world, have been developed to augment or replace physical locomotion techniques. Whilst many of these new techniques have been successful at overcoming physical limitations, they have introduced new challenges such as spatial disorientation or have exacerbated existing issues such as motion sickness.

2.3.1 Physical locomotion techniques

Boletsis (2017) considers all physical locomotion to be continuous, reflecting the reality that humans cannot instantly move to their destination. Physical locomotion techniques in VR therefore mimic how humans move in the real-world, with walking or motion in-place considered the 'most natural' physical movement in VR (Freitag et al., 2014, p.119). In-place movement can incorporate a wide range of techniques, from treadmills (Boletsis, 2017) and moving tiles (Funk et al., 2019) to positional tracking via cameras (Bhandari et al., 2018) or tracking arm-swings to simulate upper body motion of walking without requiring a user to move their legs (Boletsis, 2017).

Four factors have limited the use of many physical locomotion techniques in consumer VR hardware:

1. They require specialist equipment to safely hold a user in place or track a user's movement or limbs (Liu et al., 2017)
2. Physical locomotion methods can be tiring for users to repeatedly perform. This is typically undesirable to consumers who seek entertainment without being exhausted (Frommel et al., 2017).
3. They are typically unsuitable for users who may want or need to experience VR whilst seated (Sarupuri et al., 2017).
4. Increased feelings of motion sickness caused by the disconnect between what a user feels their body is doing versus what a user sees in the VR display. This conflict between a user's vestibular and visual systems is otherwise known as optical flow (Frommel et al., 2017).

Workarounds have been developed to minimise some of these limitations. Redirected walking algorithms (Bruder et al., 2009), automatic reorientation of a user's virtual self to face a new direction when they reach the physical limits of their real-world space (Freitag et al., 2014) or the use of a physical curved wall a user can touch to provide the illusion they are walking in a straight line in the virtual environment (Bozgeyikli et al., 2016) solve some of the limitations at the cost of additional hardware or increased software complexity to develop and use. However, it was the introduction of consumer HMDs with effective gesture-tracking that enabled artificial alternatives to be developed.

2.3.2 Artificial locomotion techniques

Artificial locomotion techniques can simulate physical continuous motion via the use of controller joysticks or gesture tracking. It also enables non-continuous motion such as instant movement to a destination that is not possible in the real-world (Boletsis, 2017). Artificial techniques have been extensively reviewed and studied (Boletsis, 2017; Frommel et al., 2017; Sarupuri et al., 2017; Bhandari et al., 2018; Coomer et al., 2018; Liu et al., 2018; Funk et al., 2019) and are broadly categorised in Table 1.

Technique	Example	Motion type
Controller input	Input typically from a joystick to initiate motion. Can also include input via touchpad, buttons or triggers.	Continuous
Automated	Typically on-rails motion (occasionally within another moving object such as a vehicle), where a user cannot alter the direction or speed of their movement. Can also be in conjunction with gaze, whereby a user continually moves in the direction they are looking.	Typically continuous
Tracking	Usually gesture-based and requires a user to move their fingers, hands or arms to simulate motion whilst seated.	Typically continuous
Teleportation	Typically translates a user to their destination instantly.	Non-continuous

Table 1. Artificial locomotion techniques in VR.

Artificial techniques can overlap in features and can be combined: trackable gestures might require a user to point at a destination in VR before pressing a controller button to initiate the teleportation. As with physical locomotion methods, techniques such as reorientation after movement can be used to augment artificial locomotion further, and it is common for VR applications to switch between different techniques depending on context: users might explore smaller spaces using continuous techniques via a controller joystick but switch to teleportation to quickly traverse large environments.

Whilst all four techniques can be implemented within VR and desktop 3D environments to varying degrees of success, the introduction of consumer VR hardware such as the HTC Vive and Oculus Rift with support for gaze and gesture tracking helped teleportation become a ‘mainstream’ VR locomotion technique (Boletsis, 2017, p.2) by being both effective as a method of movement and also because it feels more immersive in VR compared to its desktop implementation.

2.3.3 Teleportation locomotion techniques

Teleportation is the act of moving instantly from a user's current virtual location to another virtual location with no discernible motion or delay. Teleportation can be configured in numerous ways (Table 2) and like artificial techniques in general, can also overlap in features and be combined.

Teleportation technique	Alternative names	Technique detail
Free teleport	Also known as 'point and teleport' or 'arc teleport'	User aims a pointer and typically presses a button to trigger the translation to the destination (Frommel et al., 2017). Pointing typically uses an in-display linear or parabolic line to assist the user.
Fixed teleport	Also known as 'fixpoint teleport' or 'node teleport'	Movement between specific pre-determined waypoints or nodes (Frommel et al., 2017; Habgood et al., 2018).
Continuous teleport	Also known as 'steering' or 'indirect'	Uses a controller with a joystick (or other input) to move. This is considered teleportation as continuous movement can be thought of as micro teleportations 'between infinitely close locations' that are reached frame by frame (Weißker et al., 2018, p.98). As this is a broad classification it includes techniques such as trigger-walking (Sarupuri et al., 2017), arm-cycling (Coomer et al., 2018) and point-tugging (Coomer et al., 2018).
Step teleport	Also known as 'jump teleport'	Builds upon free teleportation by teleporting the user in small discrete jumps or steps to their eventual destination (Weißker et al., 2018).
Dash teleport	Also known as 'point-tugging'	Dash combines continuous teleportation with free teleportation, moving a user in a continuous motion towards their chosen destination (Bhandari et al., 2018; Boletsis and Cedergren, 2019).

Table 2. Summary of teleportation locomotion techniques.

Teleportation locomotion in a virtual environment offers two key features: firstly, it allows users to move further, faster and with less effort than they could physically (Rahimi et al., 2020). Secondly, it overcomes the limitations of physical spaces inhibiting freedom of movement (Bhandari et al., 2018). Whilst teleportation offers tangible benefits and unique features versus other locomotion methods there are drawbacks: user spatial awareness can be reduced (Cherep et al., 2020; Habgood et al., 2018) and depending on how teleportation is configured it can increase feelings of motion sickness (Liu et al., 2018; Weißker et al., 2018).

2.3.4 Teleportation locomotion and motion sickness

Many studies conducted on teleportation techniques aim to understand their effect on reducing motion sickness. Considerations of motion sickness even arise in studies where reducing motion sickness is not the primary concern, most likely due to motion sickness being a core issue that is essential to understand and overcome to broaden the appeal of VR. Motion sickness is commonly experienced by continuous locomotion techniques due to optical flow, whereby what a user sees is different to what their body perceives (Frommel et al., 2017).

Studies into teleportation have therefore been attractive as it appears to be a ‘simple solution’ to the problem of motion sickness caused by VR locomotion (Habgood et al., 2018, p.371). However, many studies continue to find overcoming motion sickness a challenge with little consensus as to which methods are best for reducing sickness. Redirection techniques applied to teleportation by Bruder et al. (2009), Freitag et al. (2014), Bhandari et al. (2018) and Liu et al. (2018) found mixed results as to whether it reduced or increased motion sickness. Teleportation specific techniques such as point–tugging, arm-cycling and trigger-walking also saw varying degrees of success: point-tugging was worse for sickness versus a joystick (Coomer et al., 2018) whereas trigger-walking (Sarupuri et al., 2017) and arm-cycling (Coomer et al., 2018) resulted in less sickness.

2.4 Spatial awareness and wayfinding

Spatial awareness is part of a general navigational framework encompassing ‘all the cognitive skills which allow people to orient themselves in a 3D space in order to get from one place to another’ (Christou et al., 2016, p.2). Spatial awareness enables people to make decisions, monitor their location and recognise routes and their destination (Kuliga et al., 2019) both before, during and after travel (Bowman et al., 1997). Whilst spatial awareness is considered ‘critical’ for virtual environments in gaming and non-gaming applications (Cherep et al., 2020, p.481), interest in spatial awareness is not limited to the field of VR: various behavioural and neurobiological studies have been conducted to understand how ‘landmark recognition, heading determination, odometry (distance-measuring), and context recognition’ all interact and play a role in planning and moving through environments (Jeffery et al., 2013, p.523).

Spatial awareness is influenced by the act of teleportation: instantly teleporting a user to their destination is an effective way of reducing optical flow, a common cause of motion sickness. Optical flow is the relative motion of objects in the scene versus the motion of the viewer, and reducing optical flow reduces feelings of motion sickness (Bhandari et al., 2018). However, teleporting interferes with a user’s ‘sense of space’ due to the ‘disorientating effect of changing position without continuity of motion’ (Habgood et al., 2018, p.371). Liu et al. (2018) adds that users not seeing any of the environment they’ve just moved through leads to poor path integration, an integral part of how people track their current orientation and position in relation to their start and end destinations by either continuous vestibular motion or by observing landmarks (Bhandari et al., 2018). If users have not moved their bodies continuously and have teleported so far that they bypassed all of an environment’s landmarks, the user will likely have poor path integration resulting in poor spatial awareness.

Because of the importance of spatial awareness to user wayfinding, and the compromise needed between reducing motion sickness and using teleportation techniques, the effect of teleportation on spatial awareness has been the focus on numerous VR studies over the decades. However, many studies in this area include constraints and limitations that influence how well these studies generalise to current VR hardware and software. Bowman et al. (1997) first observed that free teleportation (referred to as ‘jumping’ in 1997 and ‘point and teleport’ today) reduced user spatial awareness and resulted in users being unable to locate their target. Bakker et al. (2003), using early HMD hardware, concluded similarly. Both studies utilised low-fidelity graphics and outdated hardware compared to modern capabilities, although such limitations are also found in more recent studies. Bhandari et al. (2018) observed that continuous teleportation methods were better than instantaneous (non-continuous) teleportation for reducing optical flow but used a mobile VR headset and a featureless virtual landscape (Rahimi et al., 2020). Low-fidelity graphics, sparse environments and less optimal hardware may mean that these studies’ findings do not hold in more modern virtual environments. In addition, the methodologies used by these and other studies to measure spatial awareness are simplistic and do not truly reflect how users wayfind when moving in a modern, more complex 3D environment: Bakker et al. (2003) required users to point at their starting location (after reaching their destination) by turning a dial on a large handset. Later studies by Xu et al. (2017) and Weißer et al. (2018, p.97) also required users to point ‘back to the start’, although Weißer et al. (2018) does use a larger environment than the other studies, making it more representative of modern 3D environments.

Christou et al. (2016, p.5) appears to be the first study to investigate wayfinding within a 3D environment more representative of the real-world, utilising a large-scale village with buildings that blocked line of sight to destinations within a CAVE system, albeit without consideration of teleportation and instead only used continuous motion techniques. Christou et al. (2016) concluded that decoupling gaze from movement direction in VR, just as humans do in reality, offered better peripheral vision and spatial awareness, resulting in ‘faster travel times, more successful traversals to the destination and greater accuracy in keeping to the center of the paths’. Zhao et al. (2020) used a similarly large-scale populated 3D environment to Christou et al. (2016). Across HMD and desktop, they compared continuous motion (using a joystick) to free teleportation limited to 10m range and concluding similarly: using a joystick did not lead to ‘better spatial learning performance’ than the alternative of teleportation (Zhao et al., 2020, p.328). Zhao et al. (2016) observed that the range-limit may have resulted in users updating their spatial awareness at a frequency closer to that of continuous joystick motion, thus resulting in minimal differences in spatial learning between the two methods (Zhao et al., 2020, p.353). Rahimi et al. (2020, pp.2284) extended Christou et al. (2016) and Zhao et al. (2020) by adding minor modifications to teleportation. Their study observed that ‘gradual animated and pulsed transitions’ during step teleportation improved spatial awareness when teleporting in discrete steps versus instantaneous teleportation. The findings of Rahimi et al. (2020) suggest that reducing some of teleportation’s instantaneity (in this case making users teleport in steps to the destination) doesn’t compromise on the benefits of fast-travel whilst avoiding motion sickness and poor spatial awareness.

It is notable that there is not full consensus on the findings of Christou et al. (2016), Zhao et al. (2020) and Rahimi et al. (2020). Cherep et al. (2020) observes that walking (tracked by the VR headset) offers the best performance versus teleportation for spatial updating, concluding it was due to walking providing body-based (vestibular) cues needed for successful path integration. In addition, Cherep et al. (2020) also observed that the use of landmarks saw no improvement in spatial knowledge compared to an open environment, contrary to findings by

Bowman et al. (1997) and Jeffery et al. (2013), although it must be noted that their study's landmark environment, just as with Bakker et al. (2003) and Bhandari et al. (2018), was still quite sparse and unrepresentative of modern 3D environments. Finally, the recommendation of decoupling gaze from movement direction (Christou et al., 2016) was refuted in a later study by Coomer et al. (2018) who observed it increased feelings of motion sickness.

A lack of 'empirical studies' into teleportation is noted by Boletsis as a gap for future studies to address (2017, p.10), an observation made also by Cherep et al. (2020). Where studies have been conducted, a lack of consensus into teleportation and spatial awareness shows there is opportunity to build upon these studies' methodologies and observations by using more capable hardware, improved virtual environments and more representative measurements of how users understand and wayfind in the environment around them.

2.5 Summary

Teleportation as a locomotion method, along with its effects on motion sickness and its impact on spatial awareness in a VR environment, has been the subject of many studies over the decades. However, no single study has incorporated all the elements of consumer VR hardware, teleportation locomotion techniques, spatial awareness (with a focus on wayfinding) and modern graphical capabilities together.

Studies from Bowman et al. (1997) and Bakker et al. (2003) observed that teleportation affects spatial awareness but used low-fidelity graphics and legacy hardware that doesn't reflect the modern VR experience today, as does a more recent study by Bhandari et al. (2018) with their use of mobile VR. Additionally, methods to measure a user's spatial awareness required users to point back to a starting target or location (Bakker et al., 2003; Xu et al., 2017; Weißer et al., 2018) rather than requiring a user to fully wayfind within the virtual environment, meaning their spatial awareness findings do not generalise well to larger 3D environments navigated by users today. Where studies have utilised large environments they either required specialist equipment such as the CAVE system (Christou et al., 2016), considered wayfinding but not teleportation techniques (Christou et al., 2016) or were only interested in augmenting or comparing teleportation techniques but not their impact on spatial awareness (Frommel et al., 2017; Coomer et al., 2018; Liu et al., 2018; Funk et al., 2019). In addition, there is no clear consensus on which combination of software features should be utilised to enable users to enjoy the benefits of teleportation and reduce motion sickness without compromising on spatial awareness and reduced user immersion, with Christou et al. (2016), Coomer et al. (2018) and Cherep et al. (2020) observing contradictory findings for similar techniques.

3 Design of the experiment

Findings from the literature and technology review were used to determine the aims, success measures and scope of the study. From these, the requirements were defined for the design and build of a VR application that could be deployed onto a consumer VR headset. An experiment was designed that used the VR application and was conducted with participants.

3.1 Findings

The design of the study was primarily drawn from the findings of the literature and technology review. In addition, best practice recommendations from the VR headset's manufacturer along with the researcher's experience designing and building software were also gathered.

3.1.1 Literature and technology review findings

Table 3 shows the findings of the literature and technology review that the study will address.

Finding	Recommendations
Lack of teleportation studies conducted (Boletsis, 2017; Cherep et al., 2020), especially on modern consumer VR hardware.	A teleportation study will be conducted on modern consumer VR hardware – in particular, the Meta Quest 2.
Recall studies within VR have measured spatial awareness by using a limited technique of asking users to point back to their starting position (Bakker et al., 2003; Xu et al., 2017; Weißer et al., 2018). These do not fully reflect how users use spatial awareness to wayfind.	Study will measure spatial awareness by require users to retrace their route using only their memory, a more realistic approach of how users wayfind.
Point and teleport is a popular locomotion technique in VR due to being a standard feature in modern consumer hardware (Boletsis, 2017). Several variants of point and teleport have been developed to overcome its limitations including step teleport and dash teleport (Bhandari et al., 2018; Weißker et al., 2018).	Study will incorporate three different teleportation techniques (point and teleport, step teleport and dash teleport) to compare how they influence a user's spatial awareness and their ability to wayfind.
Continuous movement surpassed teleportation for spatial awareness (Cherep et al. (2020). Additionally, many studies have used continuous movement via controller joystick as a baseline for comparison against other locomotion methods (Sarupuri et al., 2017; Coomer et al., 2018; Zhao et al., 2020).	Incorporate continuous movement via controller joystick as one of the study's locomotion methods to help benchmark teleportation techniques.
Several spatial awareness studies have used large-scale villages with buildings that blocked line of sight to landmarks and destinations, enabling participants to behave like they would	The study's virtual environment will be a reasonably-sized scene for users to explore, with a variety of buildings, landmarks and objects that block line of

in more complex real-world environments (Christou et al., 2016; Zhao et al., 2020).	sight and allow users to build up their spatial awareness of different areas within the environment.
Important early studies in the field of VR used low-fidelity 3D objects and graphics running on legacy hardware that don't reflect modern capabilities (Bowman et al., 1997; Bakker et al, 2003).	The experiment will utilise modern hardware and software that can render recognisable objects in a realistic looking 3D environment.
Decoupling gaze from movement direction in VR offered better peripheral vision and spatial awareness (Christou et al., 2016).	The study will decouple headset gaze direction from movement direction, so the user can look freely in any direction regardless of their movement direction.
Using blink animation when triggering a teleport improved spatial awareness (Rahimi et al., 2020).	Blink animation will be used for all teleportation locomotion.
In addition to data collected during their VR experiments, many studies also used participant questionnaires to evaluate qualitative responses to feelings of sickness, preference for locomotion methods and overall considerations of virtual reality (Bhandari et al., 2018; Rahimi et al., 2020).	Utilise questionnaires to collect motion sickness and user preference data. This is important because a teleportation method that performs well but makes a user experience motion sickness is not practical and does not make VR more attractive to consumers.

Table 3. List of findings from literature and technology review.

3.1.2 Virtual reality best practice findings

Findings were gathered from Meta, the manufacturer of the Quest 2 headset, using their best practice guides to avoid known issues and reduce participant discomfort (Table 4). These findings were important to ensure the study did not unknowingly implement VR poorly and unduly influence the results of the experiment.

Finding	Recommendations
'Minimise sensory mismatches' between vestibular and visual systems to minimise disorientation, eyestrain and nausea (Meta, 2023a).	Adopt manufacturer's recommendations, including ensuring frame rates remain high and preventing users from moving or rotating too quickly.
Ensure participant input is mapped to buttons users expect to use, and to ensure any motion tracking is mapped 1:1 to maintain a 'natural sensory experience' (Meta, 2023b).	Adopt manufacturer's recommendations, including a simple controller button schema and the manufacturer's default motion tracking settings.

Table 4. List of findings from VR manufacturer's best practice.

3.1.3 Experience of researcher

The researcher has a decade of experience designing and building software for end-users. This experience was used to elicit requirements (Table 5) that would result in software suitable for an experiment that was reliable, easy to use and accurate at collecting the data needed by the study.

Finding	Recommendations
Using a tutorial helps users to familiarise themselves with software.	Build a tutorial that allows participants to become familiar with the VR headset, its controllers and the locomotion techniques prior to the main study starting. This can also reduce variance in user experience unduly affecting the study's results.
Reducing UI elements and user choice can minimise feelings of being overwhelmed by the software or not knowing what to do.	Avoid the use of menus and keep instructions as clear and precise as possible. Participants will not be able to configure the software.
Ensure data is not lost even if the software or hardware suffers an unexpected failure.	Device data collection will be automatic and saved to disk in near real-time. Should the application or headset crash, all data up to the point of the crash will be retained.
Ensure participants receive the same software experience and that their data isn't merged with the data of other participants.	When a participant completes the study, all software variables and states will be automatically reset, meaning the study can quickly move onto the next participant and avoid participant data merging.

Table 5. List of findings from experience of researcher.

3.2 Aims

Building upon the findings of the technology and literature review, the following experimental aims were identified prior to designing the software and the experiment. These in turn helped define the study's success measures and its scope.

3.2.1 Experiment aims

1. **Measure and compare the effect of different teleportation locomotion methods on wayfinding using modern consumer VR hardware.** Participants will be required to navigate different routes using different teleportation techniques to determine their effect on wayfinding efficiency.

2. **Recommend teleportation locomotion methods for efficient VR wayfinding.** VR is at the frontier of exploring how new hardware and software interfaces are providing new tools and experiences for users. Understanding how tools such as teleportation techniques affect users is essential to maximising VR's potential. Recommending the best teleportation locomotion methods for wayfinding ensure HCI researchers and VR developers can avoid or overcome issues that prevent users wanting to use VR.

3.2.2 Success measures

The success of the study will be evaluated using the following metrics:

1. Build and deploy software onto VR hardware that meets the study requirements.
2. Design and run an experiment with participants that collects the required data for analysis.
3. Provides recommendations on which teleportation techniques are best for wayfinding in VR.

3.2.3 Study scope

The study is deliberately constrained due to the study's aims, its nature as an experiment (rather than as a full software development project) and the resources of the researcher. It is limited to:

- Using software designed only for the Meta Quest 2 VR hardware.
- A pre-determined set of locomotion methods and routes.
- Experimental procedures suitable for an in-person controlled laboratory experiment.
- Focusing on effects only within VR environments and not real-world analogies.
- No formal documentation of software requirements or user feedback.

3.3 Software requirements

The study's findings and aims defined the software's requirements and the researcher's approach to development to ensure it was appropriately and efficiently designed and built.

3.3.1 Functional and non-functional requirements

Appendix A summarises the functional and non-functional software requirements derived from the findings of the literature and technology review and the aims of the study.

3.3.2 Development and deployment of software

A full list of software (and their versions) used can be found in Appendix B, along with a full list of source code (Appendix C) and a guide to key source code (Appendix D). A list of configurable parameters can be found in Appendix E.

The Meta Quest 2 was chosen for the VR hardware as it is one of the best-selling widely available VR headsets (IDC, 2022), with a well-documented SDK supported by Unity, one of the most widely used 3D/VR development IDEs. Unity[2] supports deploying software onto the Quest 2 hardware from macOS, as well as running the software directly on macOS, meaning the researcher's existing computer equipment could be used for all stages of development, including testing non-VR specific functionality directly on the computer without requiring the VR headset, reducing testing times (Appendix O: Figure 25). Unity also handled optimisation

[2] Tests were also conducted using Unreal Engine 5. As of September 2022, Unreal lacked built-in support for the Meta Quest 2 on macOS and required significant workarounds.

of lighting and assets and could automatically deploy .apk packages onto the Quest 2 as part of the software's build pipeline, meaning prototypes could be rapidly installed and tested on the Quest 2 headset. Combined, these factors reduced technical complexity and meant that deploying new code and features onto the headset could occur within seconds.

Where possible, Unity pre-built packages and plugins were used, allowing VR features to be quickly deployed and tested without building or configuring everything from scratch. Meta's XR plugin for Unity was used to ensure features specific to the headset (such as head tracking) were easily accessed by the researcher. Unity's XR Interaction Toolkit package was utilised to draw lines showing where a handset is pointing and was achieved simply by adding its XR Ray Interactor component to the Meta XR plugin for hand tracking.

Unity's utilisation of the C# language was also beneficial for writing the code needed to build features not provided by Unity or plugins. As C# is an object-oriented language and shares similarities with other languages known by the researcher, development of the software began quickly with a minimal learning curve. All scripts subclassed Unity's MonoBehavior class to easily access methods essential for managing and modifying a 3D environment, such as Unity's built-in per-frame Update() method. Strict use of public and private variables and methods controlled read and write access to improve modularity, reduce difficult to trace errors and speed up development. To reduce duplication of scripts and objects, Unity's prefabs were used for elements that would be reused across the tutorial and study scenes, including for lighting and physics. For objects with scripts attached to them (such as waypoint objects detecting when a user reaches them), scripts were written and debugged used Microsoft Visual Studio, with changes automatically appearing in Unity's Editor.

3.3.3 Software testing and refinement

Initial testing was conducted iteratively using Unity's built-in Game View running on macOS (Appendix O: Figure 26). This allowed very rapid testing of scene and route layouts, locomotion methods, transitions between scenes and to ensure physics (for obstacle detection) and IO (for efficiently writing logs to disk) functioned correctly. Once this functionality was complete, testing of specific hardware features (such as handset pointing and head tracking) was conducted directly on the Quest 2 hardware. After primary testing by the researcher was complete, informal user testing was conducted with family and friends to gather feedback on general usability and identify potential issues (Appendix F). Feedback was considered and issues fixed before software source code was frozen prior to the experiment commencing with participants.

3.4 Experimental design

Combined, the study's findings, aims and its software requirements define the context and parameters the experiment must operate within. In turn the experimental design outlines its hypotheses and measurements, its operational procedures and how it will be conducted ethically and safely.

3.4.1 Overview

The experiment is empirical and requires observable participants performing measurable actions. The primary dependent variable of the study is efficiency and is more concretely formed from wayfinding-specific dependent variables such as measurements of time taken to complete a route, distance travelled to complete a route and user deviation from an optimum path. These are defined in more detail in 3.4.7, along with identification of the contributory independent variables.

As a factorial experiment with several independent variables, to ensure fairness and robustness, the experiment was designed as a within-subjects study, with each participant experiencing the same software, virtual environments, locomotion methods, starting software states and experimental procedures. These are outlined in the following sections. Additional efforts to reduce potential factors causing experimental invalidity are outlined in Appendix G.

3.4.2 Hypotheses

Table 6 outlines the experiment's three hypotheses. There are used to address the study's aims by providing focus for the experiment and the specific configuration of its software.

Hypothesis	Null hypothesis is rejected	Failed to reject null hypothesis
H1. Use of any teleportation locomotion method results in more efficient completion of routes by participants than using continuous motion via controller joystick when waypoints are disabled.	This outcome would support providing recommendations for specific teleportation techniques when software requires efficient traversal of an environment.	No clear best performing teleportation method for efficient route completion.
H2. Using continuous motion via controller joystick for locomotion results in improved spatial awareness versus any teleportation method.	This outcome supports prior findings that spatial awareness improves when users are not teleported and enables providing recommendation of specific methods for improving spatial awareness.	No clear best performing locomotion method for spatial awareness.
H3. Use of continuous motion via controller joystick results in increased feelings of motion sickness versus any teleportation method.	This outcome supports prior findings that spatial awareness improves when users are teleported and enables providing recommendation of specific methods for improving spatial awareness.	No clear best performing locomotion method for reducing motion sickness.

Table 6. List of hypotheses.

3.4.3 Participants

The experiment required volunteer participants to be observed using the VR software whilst wearing the VR headset. In accordance with the University of Bath's ethical requirements, the following check was conducted to screen participants prior to them commencing the experiment:

> **Participants must be aged between 18 and 65.** An age gate was implemented based on the VR manufacturer's recommendation that elderly people should not use the headset, which this study determined as older than 65. Additionally, participants were required to be over 18 to simplify gathering consent and storing data, and ensuring the experiment could be run without parents, guardians or chaperones.

Participants did not need prior experience or knowledge of VR or 3D environments to enter the experiment. Participants were recruited via the researcher's family and friends. It is noted that the study's non-public participant pool risks participants skewing towards a particular demographic, a factor considered during analysis. The study was conducted in April 2023 at the researcher's home in a dedicated room prepared for the experiment. Before joining the study, participants were required to read and sign the Participant Information Sheet (Appendix J) and the Participant Consent Form (Appendix K). Both forms and the questionnaires were approved by the University prior to the study commencing.

3.4.4 Ethics

The University of Bath's *12-Point Ethics Checklist* (Appendix H) was completed and approved by the researcher's supervisor. The checklist raised no significant concerns, however, as the study required human participants and captured motion data from the device participants would be using, it was determined that the University of Bath's *Checklist for Full University Ethics Sub-Committee Review* form (Appendix I) and the department's online *Ethical Implications of Research Activity (EIRA1)* should be completed. Approval was received for all forms prior to the experiment being conducted with participants, although there were two points the study was required to address prior to the experiment starting (Table 7).

Point raised	Addressed by
1. Physical safety of participants whilst wearing and using the headset.	• Conducting study in a controlled environment free of obstructions and trip hazards. • Enabling the Quest 2's built-in 'Guardian' boundary warning functionality. This enabled pass-through imagery on the display if the participant moved too far from the designated safe zone. • The researcher would be present during the experiment to observe the participant and ensure they remained in the safe area whilst using the headset.
2. Ensure no personal information was captured at any	• Ensuring data was limited to only that needed to answer the research question. • All data was anonymised, with no personal data requested or captured.

point during the study.	• Device data was strictly limited to screen recordings or motion data provided by the device and did not include any facial or biometric capture.

Table 7. List of raised ethical points addressed by the study.

3.4.5 Locomotion methods and routes

Locomotion methods and their associated travel routes are independent variables and were carefully controlled to ensure participants behaved as naturally as possible during the experiment and weren't unduly influenced by its design.

To address all three hypotheses, four locomotion methods were chosen based on findings from the literature and technology review, alongside being easy for participants to learn quickly to ensure the experiment could be completed in a reasonable duration. Continuous movement with joystick, as a familiar and popular movement method, was chosen as a baseline to compare the three teleportation locomotion methods against. The three teleportation techniques appear in recent literature and are modern methods to users of VR consumer hardware and software. These range from the well-known non-continuous point and teleport technique where users instantly translate to their destination, bypassing obstacles, to the fully continuous dash teleport, whereby a user is pulled towards their destination within a few seconds. Step teleport is positioned between the two as it instantly teleports a user in small incremental steps towards their destination. Their implementation is detailed in Appendix D.

To support H2, routes that passed landmarks were designed to help participants build spatial awareness and enable measurements of landmark recall by participants. A variety of routes were created to prevent a user's growing familiarity with a route affecting how well a locomotion technique performed. Each locomotion technique was paired to a particular route. Routes were designed to standardise the travel distance, the number of turns and the number of landmarks passed, to reduce the risk of too much variance affecting the study's outcome. Each route had an 'optimum path' variant, defined as following the most direct path between two waypoints whilst avoiding obstacles. Waypoints were enabled once per locomotion technique and appeared in the form of cylindrical visual aids for participants to follow (Figure 2; Figure 5). Waypoints were disabled for the second run through when using the same locomotion technique, with participants required to wayfind without any visual aids.

The following framework (Table 8) was designed to ensure the experiment followed a fair and robust procedure for presenting each locomotion method and route:

Stage	Summary	Detail
1	The software will feature four locomotion methods.	Continuous motion via controller joystick, point and teleport, step teleport, dash teleport.
2	Four routes were created of similar length and containing a similar number of turns and landmarks.	• Each locomotion method was assigned to a specific route that did not change. • Each route has a set start and end point. These differ between routes. • Each route must be completed by

		participants within 90 seconds.
3	Each locomotion method will require participants to complete the assigned route twice: once with waypoints enabled and once with waypoints disabled.	**Waypoint enabled:** • The first time a route is completed, five 3D waypoints will appear at set points (Figure 5), eventually leading to an 3D endpoint designating the end of the route. • From the participant's starting point the first waypoint is always visible. • When the participant reaches the first waypoint using the assigned locomotion method, the first waypoint will disappear and the next waypoint will appear in the scene. The next waypoint will be visible to the user without requiring them to move around. This step repeats until the final waypoint (the endpoint) is displayed (Figure 4). • Upon reaching the endpoint, the participant will be sent to the start of the same route to complete again but with waypoints disabled. **Waypoints disabled:** • Immediately after the waypoint route is completed, participants must complete the route again but without no waypoints visible. The endpoint remains on display but is not visible to the user from the start point. • Without waypoints participants must remember how to wayfind from the start point to the endpoint.
5	On reaching an endpoint when waypoints are disabled.	• The study will move onto the next pairing of locomotion method and route. • If all pairings have been completed, the software experiment is over.

Table 8. Framework used to present each locomotion method and route.

3.4.6 Design of virtual reality environment scenes

The study's findings required the software to build two environments: a tutorial scene to enable participants to practice locomotion techniques and a study scene where the main experiment was conducted. Each scene was visually different with a distinct set of assets, colour palette and object positioning. The scenes shared identical locomotion techniques, user interfaces and instructions (Appendix O: Figure 28, Figure 29), virtual handset assets, and visual identifiers for waypoints. Both scenes are integral to the experiment and are discussed below.

3.4.6.1 Tutorial scene

The tutorial scene was designed to let participants become familiar with how the different locomotion methods function, along with the mechanics of routes and waypoints. This intentional approach was to reduce the effects of VR inexperience on the study's results.

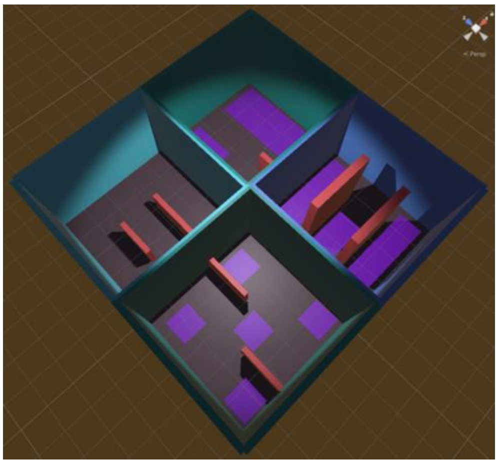

Figure 1. The 4 tutorial rooms from above.

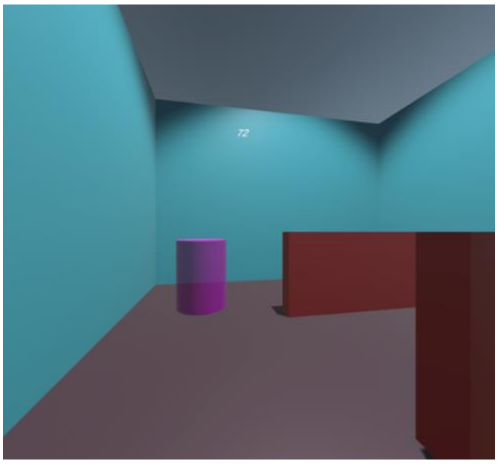

Figure 2. User's perspective inside tutorial with waypoints enabled.

All participants experienced the tutorial scene first. It is visually different to the study scene (described in 3.4.6.2) to prevent participants learning the study scene's environment. The tutorial scene consists of four rooms (Figure 1), each designed for the participant to practice using a specific locomotion method (Figure 2). Obstacles were used to block line of sight to waypoints, forcing participants to scan the room and move around them. The colour palette was designed to visually distinguish the purpose of objects in the room to speed up participant learning. The training scene begins with the continuous joystick locomotion method in a simple mini maze and follows the waypoint/no-waypoint framework outlined in 3.4.5 before repeating in a different room for point and teleport, dash teleport and step teleport. The order of techniques was chosen to allow participants to become comfortable with simpler locomotion methods before moving onto more complex techniques.

3.4.6.2 Study scene

The study scene (Figure 3) is visually different to the tutorial scene and was designed around a rectangular 3x3 grid (Table 9). It was designed to appear open world with familiar objects to encourage participants to act naturally. Each cell includes up to three landmarks of varying size, features and prominence, with a slightly uneven distribution to make the environment feel unstructured. Each object was chosen to mimic likely features found in a suburban neighbourhood containing a mix of houses and open spaces and are used to help participants build their spatial awareness. Obstacles such as fences and trees were placed to prevent users from leaving the study boundaries, block line-of-sight to other landmarks or prevent direct movement to another area, forcing participants to use their spatial awareness to work out how to move around them.

Figure 3. Study environment from above.

House / toy train	Pair of houses / lumber	Rock feature
House	Road junction / statue / house	Rock feature
Statue / rock feature	House / tent	Statue

Table 9. Approximate location of study scene’s landmarks within 3x3 grid.

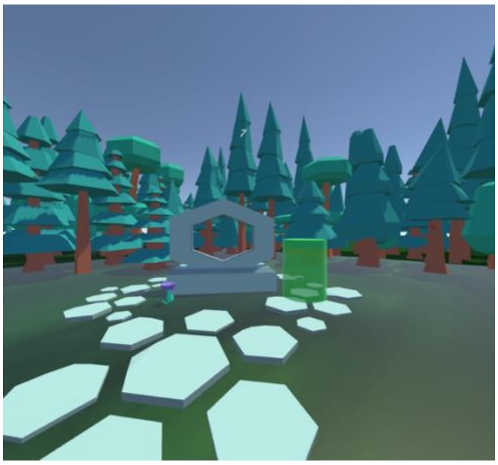

Figure 4. Study scene landmark and destination endpoint from participant perspective.

Figure 5. Study scene from participant perspective with route waypoint enabled.

Figure 4 and Figure 5 show the final built environment from the perspective of a participant. The study scene used 3D assets from an open-source asset library (Appendix B). From this library, assets were chosen that shared the same design philosophy and colour palette to give the scene a uniform visual identity that ensured objects were familiar and distinguishable, and allowed participants to feel immersed in the scene even if it was not realistically rendered.

3.4.7 Measurements

To address the study's aims and its hypotheses, the experiment was designed to capture the following quantitative and qualitative measurements (Table 10).

Goal	Hypothesis	Specific measurements
1. Compare participant efficiency for a given locomotion method when completing a route with waypoints enabled/disabled.	H1	*Where efficiency is a combination of:* a. Low duration to complete a route. b. Low distance travelled, including low deviation from optimum path.
2. Compare participant spatial awareness for a given locomotion method when completing a route with waypoints enabled/disabled.	H2	*Where spatial awareness is a combination of:* a. Re-use Goal 1 measurements. b. Good recall of landmarks during post-study questionnaire. c. Route traces showing where participants travelled.
3. Compare feelings of participant motion sickness for a given locomotion method.	H3	a. Low reported feelings of motion sickness reported by participants.

Table 10. Measurements used in the experiment.

3.4.7.1 Pre-study measurements

A pre-study questionnaire was completed by participants (Appendix L) asking about their experience with VR and 3D environments. This was used to understand whether prior experience affected the study's results. For the same reason participants were also asked to volunteer their age (within a range of years) and their gender.

3.4.7.2 During study measurements

When the experimental VR software is used by a participant, specific metrics (Table 11) were captured on device for each pairing of locomotion method and route. This data provided quantitative measures to support investigations of H1 and H2.

Data	Capture frequency
Position of user (x,y,z)	Every 50ms
Head rotation of user (x,y,z)	Every 50ms
Participant facing waypoint	Every 50ms

Distance travelled	Every 50ms
Distance to next waypoint	Every 50ms
Participant started the route	When triggered by participant
Participant reached waypoint	When triggered by participant
Participant teleported	When triggered by participant
Duration to complete route	When triggered by participant

Table 11. Data captured on device during the study.

To address H3, during the study participants were asked verbally by the researcher to rate on a scale from 0 to 20 how much motion sickness they were feeling (Appendix M), an approach known as the Fast Motion Sickness (FMS) scale introduced by Keshavarz and Hecht (2011). FMS was chosen because its use of one question can be easily answered by a participant whilst they are in the VR study, allowing the researcher to ask the question just after each locomotion method is completed. This means feelings of motion sickness can be mapped directly to each locomotion method, rather than at the end where it may be unclear which locomotion method the score is related to. FMS addresses a weakness of other methods such as the Simulator Sickness Questionnaire (Kennedy et al., 1993) which requires the participant to answer many questions, making it impractical to ask each time a participant completes a route as it would significantly slow down the study. Participants were informed and reminded throughout the study that if they experienced feelings of motion sickness that they should not continue.

3.4.7.3 Post-study measurements

After the software experiment was completed, participants were asked to qualitatively assess their experience for each locomotion methods using a Likert scale (Appendix N). Participants rated each locomotion method on ease of use, stated their preferred method for locomotion, and were asked to evaluate if a method allowed them to move to where they wanted to go. To specifically address H2, participants were asked to recall landmarks they passed when using a locomotion method. These qualitative questions are designed to provide the study with holistic data that takes participant preference into account: just because a locomotion method might quantitively be better than another, if participants dislike using it, the method may be impractical for use in future VR applications. A notable weakness of the post-study approach is that it is conducted after users have completed the experimental software, resulting in participants being unable to differentiate between different routes and locomotion methods and potentially leading to recency bias. This was considered an acceptable risk versus taking too much time during the study to ask each question after a locomotion method was completed.

3.4.8 Experimental procedures

All participants experienced the same software, virtual environments, locomotion methods and routes, within the same physical space. Participants entered the study one at a time and were expected to complete the study within 15 to 20 minutes. Each participant completed the study in the following order:

1. Participant read Participant Information Sheet and signed Participant Consent Form.
2. Participant completed Pre-Study Questionnaire.
3. Participant fitted VR headset and adjusted straps for comfort.

4. Participant started experimental software and began the training scene, using each locomotion method and completing each route.
5. When the training scene is completed, the software loads the study scene. The participant used each locomotion method and completed each route as randomly decided by the software. After each locomotion and non-waypoint route pairing is complete, the researcher conducted the Fast Motion Sickness Scale survey verbally.
6. When the study scene was completed, the software ended.
7. Participant removed headset and completed the post-study questionnaire.
8. Researcher verbally debriefed the participant and answered their questions.
9. Researcher retrieved motion data from the device and reset the experimental software.

During the study scene, the order of locomotion methods (and each assigned route) was fully randomised to ensure participants across the study did not build spatial knowledge of the environment in the same order, potentially influencing the performance of a locomotion method.

The study was conducted at the researcher's home (Appendix O: Figure 30). The participant was required to stand whilst wearing the headset and participating in the experiment. The researcher was present throughout the experiment to assist participants in fitting or removing the headset and ensuring manufacturer recommendations were followed (Meta, 2023d), including staying within bounds of the 'Guardian' safe space feature and to be available should the participant require the experiment to stop. Participants were informed they could not ask the researcher to help them with completing the software or answering the questions.

3.5 Summary

Findings from the literature and technology review identified several limitations in prior studies that this study seeks to address. These ranged from only a small number of studies being conducted into comparisons of different teleportation techniques and limited use of modern consumer hardware in VR studies to the use of restricted pointing techniques in measuring spatial awareness and low-fidelity graphical environments.

From these findings, the study's primary aim was identified as measuring and comparing how different teleportation locomotion methods effect wayfinding when using modern consumer VR hardware. This enables its secondary aim of recommending to VR researchers and developers which teleportation locomotion methods are best for efficient VR wayfinding. The software's requirements, scope and implementation tools were then defined and used to outline the parameters the experiment needed to operate within, from what data was needed to test each of the three hypotheses to outlining its operational and ethical procedures for running the experiment with participants. Once the experiment was completed, the collected data was analysed.

4 Results and analysis

Once the experiment was complete the collected data was analysed. Its results and their application to the findings of the literature and technology review and the study's aims are discussed in the following section.

4.1 Experimental appropriateness and limitations

10 participants participated in the study, pooled from the researcher's family and friends over one weekend in April 2023. All participants followed the same experimental procedure outlined in 3.4.8. All but one participant completed the study; the drop out completed 75% of the study before stopping after reporting feelings of motion sickness. Data was analysed in a MySQL database, with additional work completed in Excel. One-way ANOVA was used for statistical significance with sample standard deviation used to calculate mean variance.

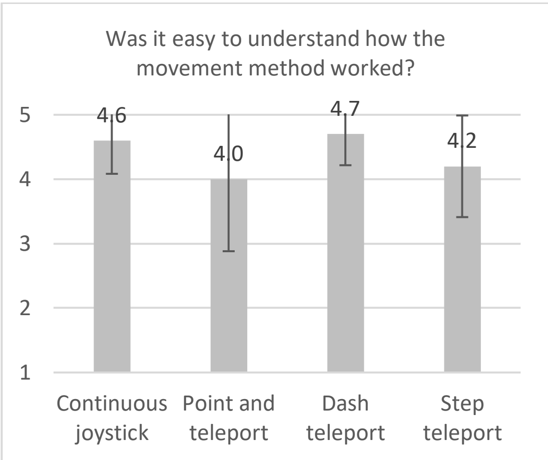

Figure 6. Mean 'ease of understanding' rating.

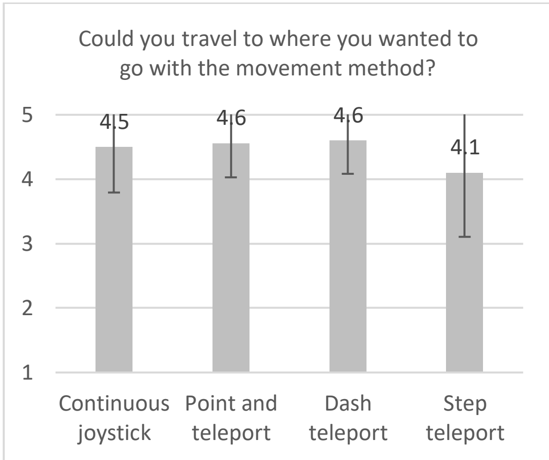

Figure 7. Mean 'ease of travel' rating

From the post-study qualitative survey, all users reported that each locomotion method was easy to use, each scoring M >=4.0[3] (Figure 6). Additionally, all users reported each locomotion method enabled them to travel to where they wanted to, each scoring M >=4.1[4] (Figure 7). Each locomotion method was distributed similarly for order of appearance (Appendix P: Figure 33) meaning no method was advantaged or disadvantaged by appearing earlier or later in the study. These results indicate that neither the design of the experiment nor the locomotion mechanics unduly influenced the results due to difficult to use mechanics.

There were several limitations of the collected data that affected the study:

- One participant dropped out. Their results are excluded from all totals (such as overall

[3] Scored out of 5. A higher score indicates the method was easier to understand.
[4] Scored out of 5. A higher score indicates the method allowed them to travel where they wanted.

study completion time) but are included where applicable when comparing individual locomotion methods.

- A planned measurement logged if a user was heading towards an endpoint, even if an object in the environment obstructed their view. Whilst this appeared to work during testing, in the study itself the data was found to be flawed and was not used.
- Participant recall of objects and landmarks for each route was more inconsistent than expected. Post-study, it was found that participants could not reliably remember which landmarks mapped to each locomotion method and route. This data has not been used.

These limitations are discussed in more detail in 5.2.

4.2 General observations

60% of participants were male and 40% were female. Age ranges were distributed fairly (Table 12). 60% of participants reported no use of 3D video games or VR applications per week; 20% of participants reported usage between 0-5 hours per week and 20% reported more than 10 hours per week, indicating reasonable variance in usage patterns. The broad range in experience and demographics mean the results generalise reasonably well for a study interested in consumers and consumer hardware, although attention is drawn to the pool of participants not reflecting general society due to being limited to the researcher’s friends and family. Very minor performance differences were observed between age, gender and usage in several metrics but are not discussed as they are not the focus of the study.

Age range	18-25	26-35	36-45	46-55	56-65	*N*
Participants	30%	10%	20%	20%	20%	10

Table 12. Distribution of participants by age range.

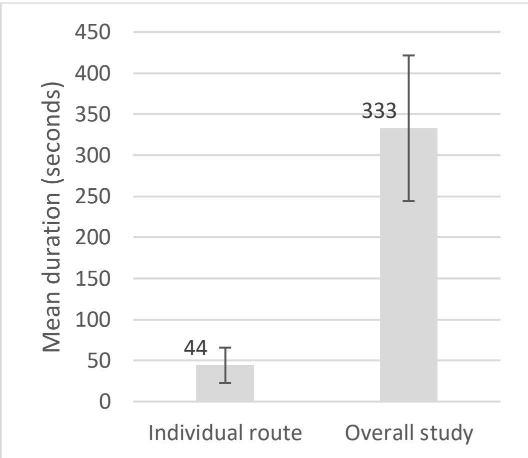

Figure 8. Mean duration to complete the study scene.

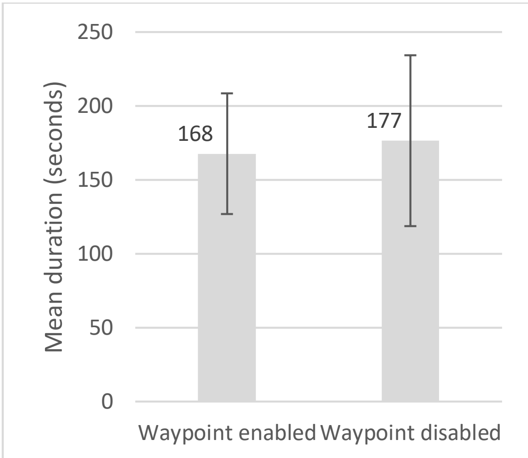

Figure 9. Mean study scene completion duration by waypoint category.

Participants wore the headset for a mean duration of 8 minutes and 20 seconds across the tutorial and study scenes. Mean participant duration for the study scene was 333 seconds (5 minutes and 33 seconds); individual routes were completed in M=44 seconds (Figure 8). 78 routes were completed, 89.7% of which were within the 90 second time limit. Route completion duration increased by 5.4% when waypoints were disabled, from M=168 seconds to M=177 seconds, with variance also increasing (Figure 9). As increases in duration were expected when visual navigational aids were removed (due to participant uncertainty increasing), it is where results contradict this trend that will be of interest during the analysis.

4.3 Hypothesis 1

Hypothesis 1: Use of any teleportation locomotion method results in more efficient completion of routes by participants than using continuous motion via controller joystick when waypoints are disabled.

Two measurements were used to evaluate H1:

1. Duration to complete route (where lower duration = more efficient)
2. Deviations from the optimum path, measured using a participant's total travelled distance (where lower distance travelled = more efficient)

4.3.1 Results

4.3.1.1 Measurement: duration to complete route

One-way ANOVA was conducted to compare the effect of the four locomotion methods on the dependent variable duration. No statistical significance was found ($F(3,35) = [2.708]$, $p = 0.06$), $p > 0.05$ between the four methods, meaning the study failed to reject the null hypothesis for H1, indicating that duration was not statistically affected by locomotion method.

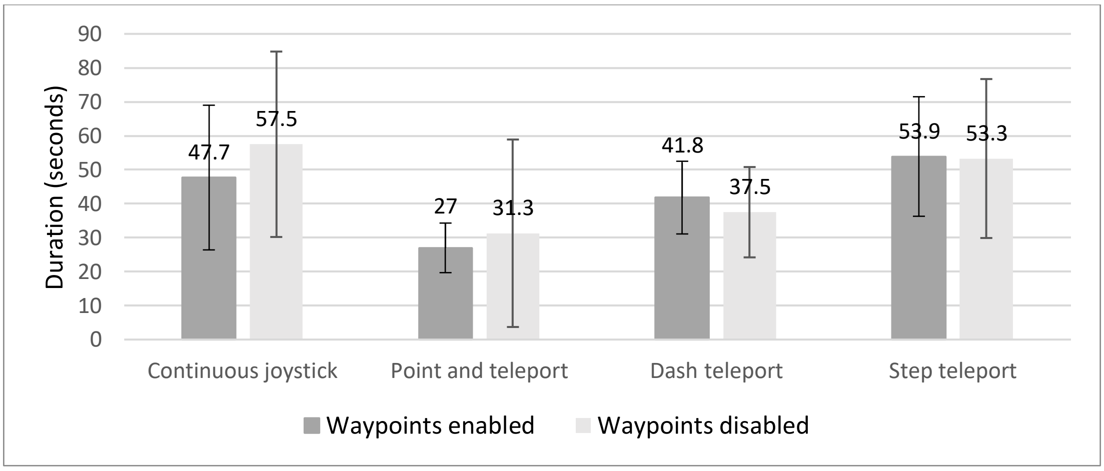

Figure 10. Mean duration for route completion by teleportation method.

Despite failing to reject the null hypothesis, sample observations (Figure 10) show that the mean duration to complete a route increased when waypoints were disabled for continuous joystick (M=57.5) and point and teleport (M=31.3) but decreased for dash teleport (M=37.5) and step teleport (M=53.3), contrary to the expected trend. All methods saw variance increase for duration when waypoints were disabled (Figure 10). Continuous joystick saw the biggest overall percentage increase in duration (18.6%) when waypoints were disabled (Figure 11), whilst dash teleport saw the biggest decrease (-10.8%).

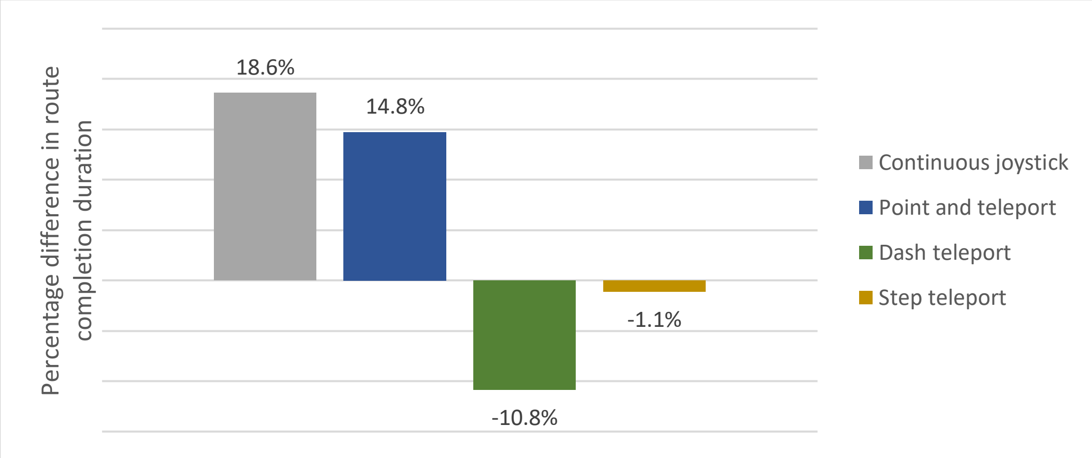

Figure 11. Route completion duration percentage difference with waypoints disabled.

4.3.1.2 Measurement: distance travelled and deviation from optimum path

One-way ANOVA was conducted to compare the effect of the four locomotion methods on the dependent variable distance travelled. No statistical significance was found ($F(3,35) = [0.076]$, $p = 0.972$), $p > 0.05$ between the four methods. The study failed to reject the null hypothesis meaning travel distance was not statistically affected by the locomotion method.

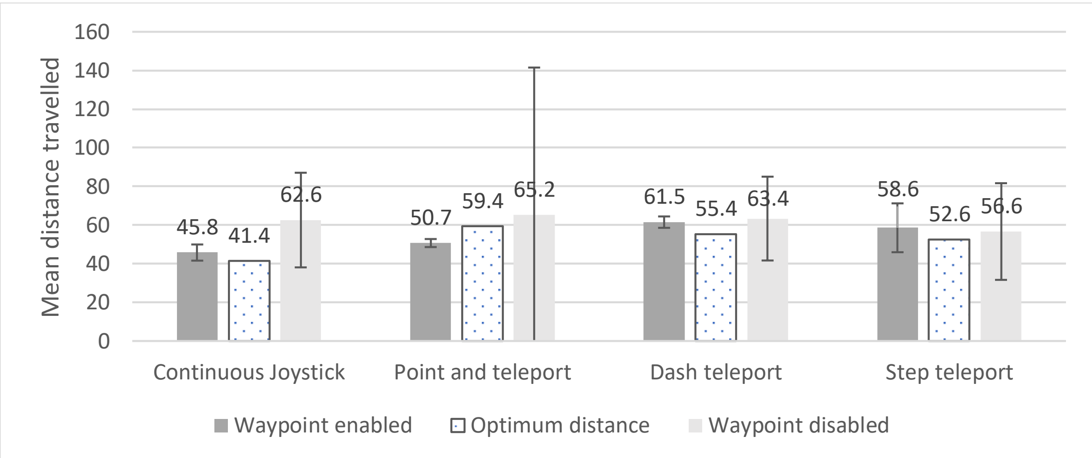

Figure 12. Mean distance travelled by locomotion method.

As with duration, distance variance increased when waypoints were disabled (Figure 12). Notably, point and teleport saw an extremely large range due to one participant travelling 257.8 metres versus a mean of 41.2 metres for the other participants. This is investigated in more detail in the route travel traces analysis in 4.4.1.3.

Despite failing to reject the null hypothesis, the sample's data could be used to calculate the difference between a participant's travelled distance and a route's optimum path distance (when waypoints were enabled) to determine how much a teleportation method caused participants to deviate. Step teleport was the only method to see travel distance decrease slightly from 11% to 7% when waypoints were disabled (Figure 13). All other methods saw participants travel further when waypoints were disabled. Continuous joystick saw one of the largest differences (41%), with participants deviating the most from the optimum path. Of the teleportation methods, point and teleport saw the biggest performance change: participants beat the optimum distance by 16% when waypoints were enabled, but travelled 9% further when waypoints were disabled, the biggest overall swing (25%).

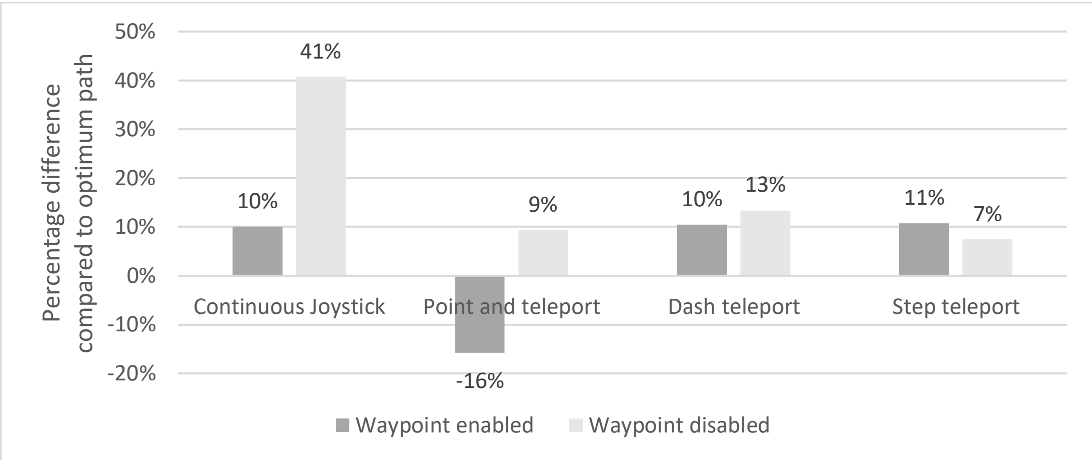

Figure 13. Percentage difference to optimum path distance by locomotion method.

4.3.2 Discussion and implications

All H1 measurements failed to reject the null hypothesis, meaning not all teleportation methods are statistically more efficient at wayfinding when completing routes than continuous joystick. This outcome is possibly due to N=10 resulting in insufficient evidence to reject the null hypothesis. Failing to reject the H1 null hypothesis means that no locomotion method is a poorer or better choice for wayfinding efficiency: all methods allow participants to wayfind with a reasonable degree of efficiency. However, some observations limited to the sample do show that teleportation methods can influence duration and travel distance.

The smaller differences in distance deviation (Figure 13) for all three teleportation methods versus continuous joystick suggest that teleportation is a more efficient locomotion method when wayfinding. However, within the three teleportation methods, there are notable differences. When waypoints were enabled, meaning participants knew where to go, point and teleport was most efficient in duration and distance, as it allowed participants to see where they could take shortcuts through or over obstacles to reach their desired destination. This method appears to have reduced participant spatial awareness however: when waypoints were disabled, point and teleport saw efficiency decrease more for both duration and travel distance than step teleport and dash teleport. Reduced efficiency aligns with observations by Habgood et al. (2018), Liu et al. (2018) and Cherep et al. (2020) that the instantaneous advantages of point and teleport are also its biggest hindrance: bypassing the landscape enables faster travel but means user spatial awareness of the environment remains low. This results in users taking longer to work out where they are in relation to their destination, either by taking longer to look around to orientate themselves or by travelling further as they explore to determine where to go. This finding is matched by the decreases in duration observed when waypoints were disabled for dash teleport and step teleport. These decreases indicate these methods may perform better at helping participants build their spatial awareness and learning the route when waypoints were enabled. This increased awareness resulted in faster route completion when waypoints were switched off. To explore these differences further between the locomotion methods, future work could investigate the duration taken to consider their next move before they teleport. This is discussed further in 5.3.

Whilst limited to the sample, the implications of these findings mean VR researchers and developers should consider choosing teleportation methods according to the design of their software. Where users can be expected to have good spatial knowledge of the virtual environment or can access visual aids, point and teleport is most efficient for wayfinding. However, dash teleport and step teleport allow users to build up better spatial awareness, meaning they can wayfind efficiently without requiring the software to provide visual aids.

4.4 Hypothesis 2

Hypothesis 2: Using continuous motion via controller joystick for locomotion results in improved spatial awareness versus any teleportation method.

Three measurements were used to evaluate H2:

1. Re-use of H1 measurements: distance travelled and deviation from the optimum path.
2. Participant recall of landmarks during post-study questionnaire.
3. Route traces showing how participants travelled in the study environment.

4.4.1 Results

4.4.1.1 Measurement: use of H1 results

H1’s measurements can also be used to indicate if participants were spatially aware, and are summarised again below:

- Step teleport was the only method to see travel distance decrease slightly from 11% to 7% in comparison to the optimum path when waypoints were disabled (Figure 13).
- Continuous joystick saw the largest travel distance (41% further than the optimum path) when waypoints were disabled (Figure 13). Participants travelled further using continuous joystick than all teleportation methods.
- Of the teleportation methods, with waypoints enabled point and teleport was most efficient; when waypoints were disabled dash teleport and step teleport were more efficient than point and teleport.

4.4.1.2 Measurement: landmark recall

The collected post-study data for this measurement was excluded from the results (see 5.2 for more details) due to inconsistencies with how participants answered the recall question: *List all notable landmarks or objects you remember seeing when using a particular movement method.* Instead another post-study question asking participants to describe their wayfinding strategy when waypoints were disabled highlighted that 40% of participants deliberately utilised their 'memory' (Appendix P: Table 15), indicating that recall of the environment does play some factor in wayfinding even if participants were unable to precisely list landmarks.

4.4.1.3 Measurement: route travel traces

Traces were created using in-environment coordinates to show how participants travelled when waypoints were disabled (Figure 14, Figure 15, Figure 16, Figure 17).

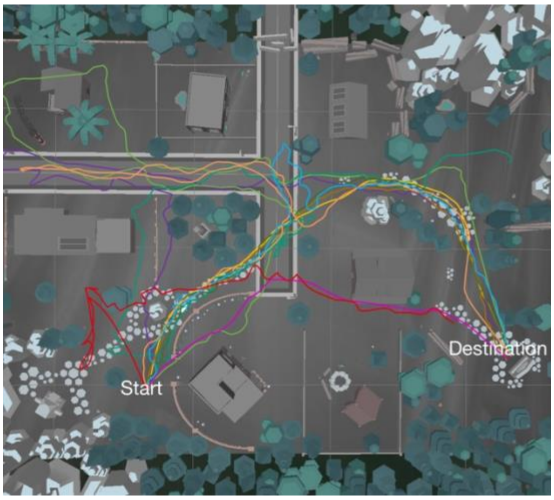

Figure 14. Continuous joystick route trace.

Figure 15. Point and teleport route trace.

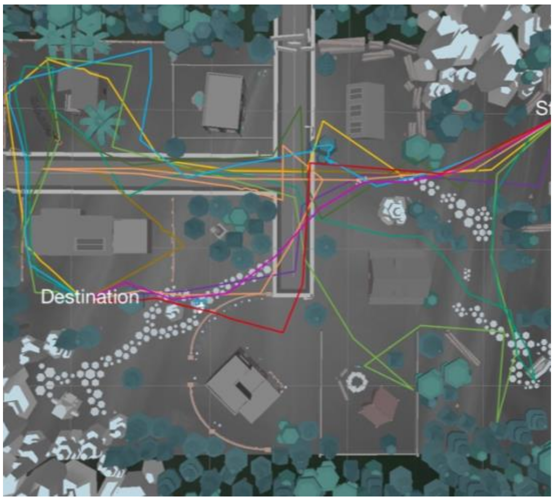

Figure 16. Dash teleport route trace.

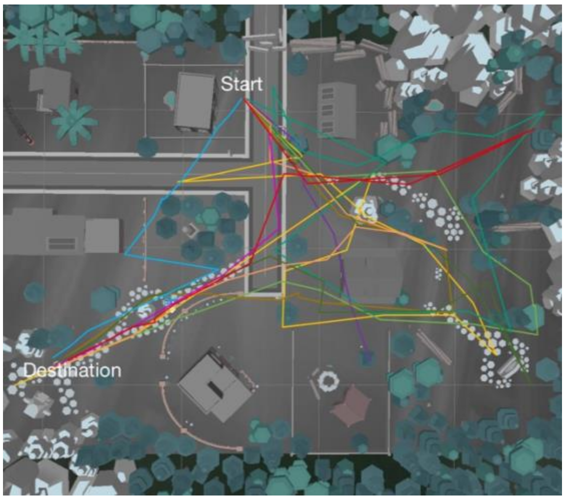

Figure 17. Step teleport route trace.

Traces are useful as they indicate how many participants followed the optimum path, used a shortcut or travelled in an entirely unexpected direction. Each trace was categorised (Table 13) to quantitively assess how each locomotion method aided or hindered spatial awareness.

Category	Continuous joystick	Point and teleport	Dash teleport	Step teleport
A. Followed optimum path	20%	11%	40%	20%
B. Took shortcut	20%	44%	40%	20%
C. Got lost early but reached destination	30%	33%	20%	40%
D. Got lost midway but reached destination	20%	0%	0%	0%
E. Got lost and never reached destination	10%	11%	0%	20%
N	**10**	**9**	**10**	**10**

Table 13. Categorisation of participant disabled waypoint journeys using traces.

Categories A and B indicate good spatial awareness, with participants either following or improving upon the optimum path. Point and teleport saw the highest number of shortcuts taken by participants (44%), matching H1's shortest travel distance findings (Figure 12). 80% of participants navigated without wayfinding errors when using dash teleport. This matches H1's lowest duration findings (Figure 10), where dash teleport saw the largest duration decrease when waypoints were disabled. Categories C, D and E indicate poor spatial awareness, with participants becoming lost at some point and in some cases never reaching the destination. All locomotion methods saw some participants portray wayfinding errors. Dash teleport saw the lowest number of errors (20% overall), with all participants eventually reaching their destination. Continuous joystick and step teleport shared the highest number of errors (60%), with step teleport seeing the most participants fail to reach the destination (20%).

Figure 18. Point and teleport comparison. Red is optimum path.

Figure 19. Continuous joystick comparison. Red is optimum path.

Several participant traces presenting extreme differences in travelled distance were compared in isolation, along with watching their recorded video, to understand why these participants were so different from other participants who travelled less (Figure 18 and Figure 19). From video observation, participants who travelled less and took shortcuts appear to move their heads in a much wider range of movement than participants who became lost, scanning as much of the environment as possible and looking beyond the headset's field of view (FOV). In both figures this can be seen where the purple line meets the road: both participants look around fully, rotating beyond their FOV before spotting the waypoint next to the tent (Figure 18) or the statue (Figure 19). In comparison, many of the lost participants passed their destination endpoint but did not see it, even when the endpoint is in the corner of their periphery or only slightly out of their FOV. These participants rarely turned their heads and generally moved in the direction they were facing unless there was a clear obstacle in front of them that forced them to change direction.

4.4.2 Discussion and implications

Across the two measurements with usable data, there is no clear finding that all teleportation methods improve spatial awareness versus continuous joystick. The outcome matches findings by Zhao et al. (2020) who observed no differences when comparing teleportation methods versus continuous joystick and does not support Cherep et al. (2020) who observed teleportation was worse for spatial awareness than continuous joystick. Despite failing to reject the null hypothesis, some observations limited only to the sample do show practical findings for VR applications.

Whilst all methods allowed most participants to reach their destination, the categorisation of route traces showed participants experienced wayfinding errors across all locomotion methods. VR applications should expect users to make errors and introduce methods to help overcome them. Of the three teleportation methods, dash teleport matched its good H1 performance, with 80% of participants successfully reaching their destination. Unlike its similarly good performance in H1, step teleport saw the highest number of errors, with 60% of participants becoming lost at some point, a result higher than point and teleport (44%) which saw the worst performance in H1. Step teleport's high error rate is contrary to observations by Rahimi et al. (2020) that discrete steps improved spatial awareness, especially as step teleport allows participants to observe the environment and develop spatial awareness as they move.

Of the participants who became lost despite passing the destination endpoint several times, all answered the pre-study questionnaire that they used 3D video games or VR software zero hours per week. Whilst N=10 makes this observation difficult to generalise, it does suggest that inexperienced VR users may need more support from the software to guide them when they are almost at their destination but for some reason can't locate it in their FOV. Future work could investigate differences between how individual humans visually scan VR environments. This is discussed further in 5.3.

Failing to reject the H2 null hypothesis means it is unlikely that any of the four locomotion methods are poor choices: all methods allow users to build up some amount of spatial awareness. However, there are some differences, with a key implication for VR developers being that some teleportation methods such as dash teleport appear to support building spatial awareness more easily than other methods. In addition, users need support from VR applications: developers should expect users to make wayfinding errors, and to be aware that some users do not scan the virtual environment or look beyond the headset's FOV. Such support may be via visual aids that point users towards their goals or alert them that an object is nearby but out of sight, or it could be via the environment's design, such as by using textures, colours or shapes to allow important objects to stand out and be noticed by users more easily, helping them locate themselves spatially in the environment.

4.5 Hypothesis 3

Hypothesis 3: Use of continuous motion via controller joystick results in increased feelings of motion sickness versus any teleportation method.

Two measurements were used to evaluate H3:

1. Self-reported feelings of motion sickness by participants.
2. Self-reported feelings of comfort using each locomotion method.

4.5.1 Results

4.5.1.1 Measurement: participant motion sickness

One-way ANOVA was conducted to compare the effect of the four locomotion methods on the dependent variable of motion sickness as scored by FMS. With the single drop out removed, no statistical significance was found between the groups ($F(3,32) = [0.524]$, $p = 0.669$), $p > 0.05$. The study failed to reject the null hypothesis meaning feelings of motion sickness are not statistically affected by the locomotion method.

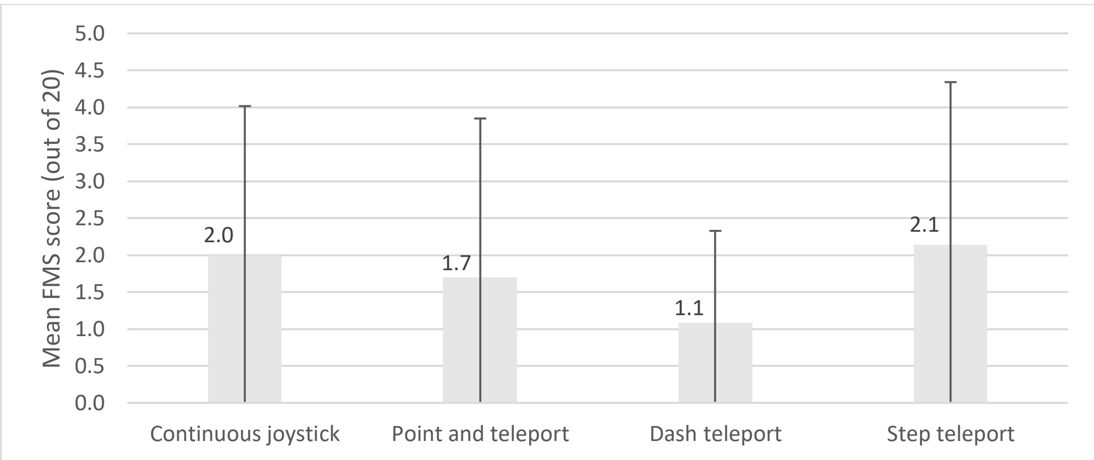

Figure 20. Mean FMS score for each locomotion method.

Despite failing to reject the null hypothesis, within the sample and excluding the single participant who dropped out, the mean reported FMS score was very low across all locomotion methods (Figure 20). Step teleport saw the worst score of the four locomotion methods

(M=2.1) closely followed by continuous joystick (M=2.0), but it is important to note that the rating is out of 20 and even when considering participant variance, no score was higher than 4.5. Dash teleport achieved the lowest score (M=1.1) and the lowest variance (SD=1.1).

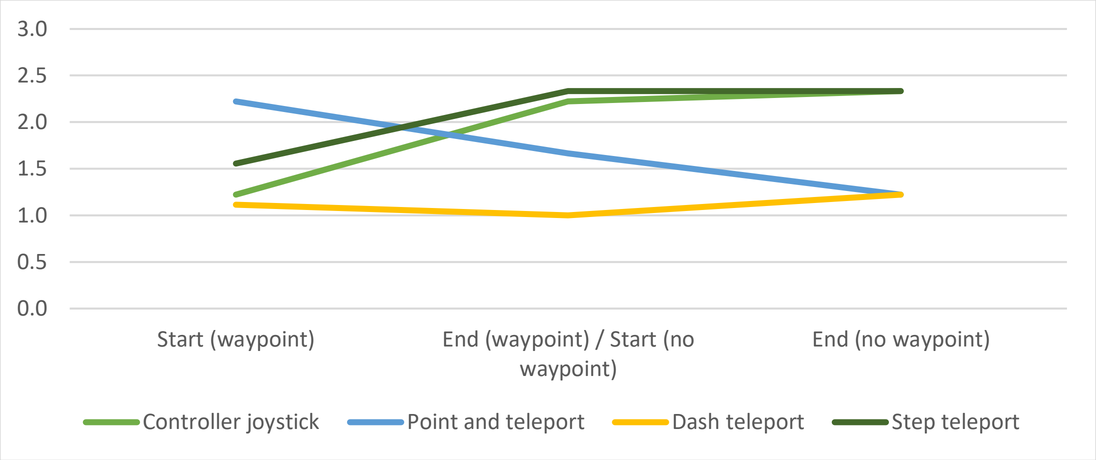

Figure 21. Mean FMS scale in sequence for each locomotion method.

FMS' ability to ask the same question frequently throughout the study makes it possible to observe how feelings of motion sickness change over time when using a locomotion method (Figure 21). Again, the scale is out of 20, making mean differences marginal (1.0 < n >2.5). Several differences are observable however: methods that allow participants to observe their surroundings during movement appear to cause more motion sickness as participants move: continuous joystick increased from 1.2 to 2.3 and step teleport increased from 1.6 to 2.3. However, this is not consistent: dash teleport, which also lets participants see the environment as they move, scored the joint lowest rating (M=1.2). Point and teleport saw motion sickness decrease when using it, with its mean score falling from 2.2 to 1.2.

4.5.1.2 Measurement: self-reporting participant comfort

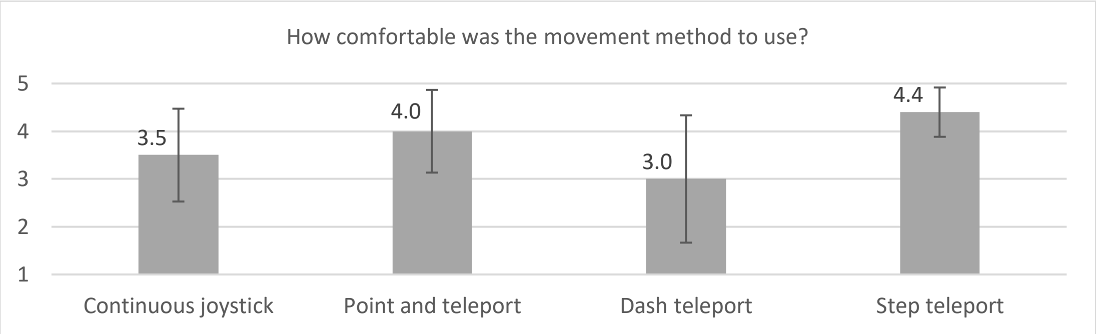

Figure 22. Mean 'comfort' rating.

In addition to FMS, participants were asked how comfortable they felt using each method

(Figure 22) [5,6]. Dash teleport, despite achieving the lowest FMS mean score, received the worst rating by participants (M=3.0) but also saw the highest variance of the four methods. Step teleport was scored by participants as most comfortable (M=4.4) with low variance despite achieving a higher FMS score.

4.5.2 Discussion and implications

H3 measurements failed to reject the null hypothesis, meaning that not all teleportation methods are statistically likely to lower feelings of motion sickness than continuous joystick. This outcome is possibly due to N = 10 resulting in insufficient evidence to reject the null hypothesis. However, some observations limited only to the sample show that locomotion methods can be found to influence feelings of motion sickness.

It is important to note the overall low FMS scores for all locomotion methods. With 60% of participants reporting zero hours of weekly VR usage, the low variance in reported feelings of motion sickness is perhaps a sign of maturity with consumer VR hardware in the last decade –many identified causes of motion sickness (Bowman and McMahan, 2007) appear to have been removed or reduced by more modern hardware. This suggests there may be additional headroom for VR software to push boundaries further when exploring locomotion methods and what users can manage before feeling sick. However, it is worth noting that participants only wore the headset for an average of 8 minutes and 20 seconds across the tutorial and study scenes, meaning it is possible participants did not spend enough time in VR to begin feeling sick.

Where there are differences, of the three teleportation methods, dash teleport achieved the lowest FMS score during the study. This result is contrary to Coomer et al.'s (2018) findings that using a similar technique caused higher feelings of motion sickness. It also refutes expectations that dash teleport's mechanic of displaying the environment as the user is pulled forwards would cause motion sickness due to conflicts between visual and vestibular systems (Bhandari et al., 2018; Liu et al., 2018; Weißker et al., 2018). This conflict was observed in the higher FMS scores for step teleport and continuous joystick, both of which also show the environment fully as the participant moves. This suggests that whilst the VR industry may now better understand how to mitigate primary causes of motion sickness, for locomotion there may remain additional factors that still cause discomfort to participants, as seen by dash teleport's low comfort rating despite it not causing motion sickness.

These contradictions within this study and with other studies' findings means VR researchers and developers must remain vigilant when designing their VR software and choosing their locomotion methods to ensure they do not inadvertently cause user discomfort or feelings of sickness, even if with modern consumer hardware it appears more difficult to trigger than with previous hardware.

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[5] A notable limitation of this question is the vagueness of the term 'comfortable'. This is discussed further in 5.2.

[6] Scored out of 5. A higher score indicates the method was more comfortable to use.

4.6 Other observations

4.6.1 Participant locomotion method preference and comments

In the post-study questionnaire, participants were asked to rank each locomotion method in order of their preference for using that method to move (Figure 23). Notably, participant ratings contradicted findings for efficiency, spatial awareness and motion sickness: continuous joystick ranked highest for participant preference (M=1.7) despite being the least efficient at wayfinding, causing higher feelings of motion sickness along with two participants commenting that it was 'too slow'. Dash teleport achieved the lowest preference ranking (M=2.9) correlating with higher participant discomfort in 4.5.1.2, despite it not causing motion sickness and being the most efficient locomotion method for wayfinding.

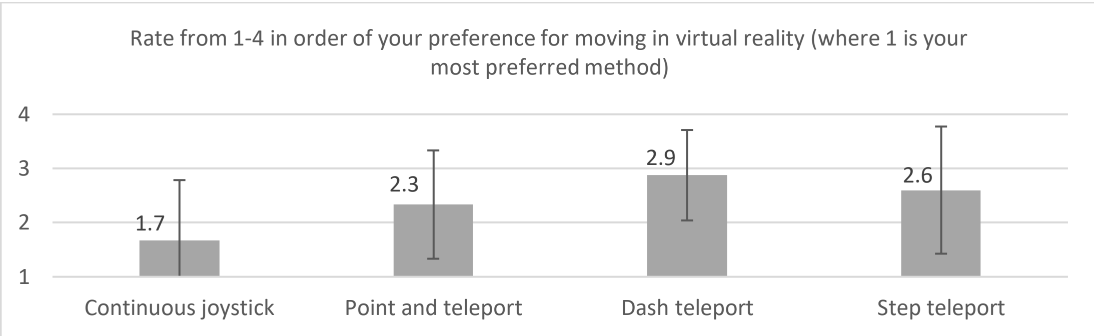

Figure 23. Mean participant preference rating for each locomotion method.[7]

Despite the clear mean ratings, it is worth noting that participant preference ranking is subjective. This is seen in the rating variance – it is high and overlaps in places across the locomotion methods. It is also observed in participant comments: point and teleport ranked highest of the three teleportation methods (M=2.3) but it is not a unanimous winner: one participant commented it was their 'favourite' method due to the freedom of movement it granted, but another ranked it lower because they felt it was 'disorientating' to use. These results show that different participants appear to value different features of locomotion methods. Additionally, few participants appeared to prioritise the utility of a VR locomotion method in the same areas that this study was interested in – those of wayfinding efficiency, good spatial awareness and low feelings of motion sickness.

4.7 Summary

All three hypotheses failed to reject their null hypothesis, with no teleportation method significantly outperforming continuous joystick for efficient wayfinding, increased spatial awareness or reduced feelings of sickness. However, in-sample observations were possible with findings that remain useful even if they cannot be applied to the wider population.

With waypoints enabled and participants understanding where they needed to move towards, point and teleport was most efficient for wayfinding in duration and distance, befitting its

[7] Ranked out of 5. A lower score indicates the method was more preferred (e.g. 1 = most preferred).

instantaneous mechanics. However, point and teleport saw performance worsen when waypoints were disabled, suggesting its mechanics prevented participants from building spatial awareness (when waypoints were enabled in their prior run through), matching findings observed in other studies. Overcoming this limitation of point and teleport might be achieved by using dash teleport or step teleport instead: decreases in duration for these two methods suggest they may improve participant spatial awareness, resulting in better performance than point and teleport when waypoints were disabled.

A notable difference arose between step teleport and dash teleport however, despite both performing well against point and teleport: dash teleport saw the lowest number of navigational errors whilst step teleport saw the highest number of navigational errors. This difference is notable as both methods allow participants to observe the environment as they move. From video observation, across all methods, navigational errors appear to increase for participants who rarely rotated their head beyond the headset's FOV, despite passing the destination several times.

Whilst one participant dropped out due to motion sickness, all other participants reported very low motion sickness scores all four locomotion methods, suggesting some of the common causes of VR sickness for most users may have been minimised through maturing hardware and better understanding in how to build VR software. Contradictions remain however, notably with dash teleport: despite causing the lowest feeling of motions sickness it was rated as least comfortable to use by participants and was ranked lowest on participant preference.

Overall, there was no single best-performing teleportation method of the three used in the experiment. Whilst dash teleport performed best overall for efficiency, spatial awareness and motion sickness, compared to the other teleportation methods, it also performed worst for participant comfort and preference. Whilst the low scores are from subjective qualitative measurements, they remain important: it doesn't matter how well a locomotion method performs at a given task if no user wants to use it. The implications of these findings are threefold. With no single best-performing teleportation method and a contradictory set of preferences, it seems sensible that VR developers should provide users with multiple locomotion methods and allow users to choose the method most suitable for them and the task they are trying to achieve. If VR developers must constrain a user's choice of locomotion method, they should provide methods most appropriate to the priorities of the software. Where users already have good knowledge of the environment or can access appropriate visual aids, point and teleport is the most efficient at travelling and causes one of the lowest feelings of motion sickness. In contrast, alternatives such as dash teleport and step teleport allow users to build up spatial awareness of the environment and allow them to wayfind without relying upon visual aids. Finally, VR developers need to understand how humans scan the VR environment in front of them to determine where to go, particularly within the FOV constraints of VR hardware. They should consider changing the environment to make certain objects stand out or support guiding users who are near to their destination but appear unable to find or reach it.

5 Conclusions

In Chapter 2, a literature and technology review identified gaps and opportunities in prior studies' teleportation and spatial awareness findings. Chapter 3 outlined a set of requirements used to develop VR software and designed an experiment to use this software and address this study's aims:

1. Measure and compare the effect of different teleportation locomotion methods on wayfinding using modern consumer VR hardware.
2. Recommend teleportation locomotion methods for efficient VR wayfinding.

Once the experiment was conducted its results and findings were discussed in Chapter 4. This chapter (Chapter 5) reflects upon how well the experiment achieved these aims, its contribution to the fields of HCI and VR and the future work that could be conducted to extend its findings.

5.1 Contribution

This study achieved its measures of success: it designed and built software and an experiment that compared four locomotion methods and evaluated how each performed at efficient wayfinding within a VR environment running on modern consumer VR hardware, building upon prior studies that explored the same or similar locomotion methods conducted on older unrepresentative VR hardware. The study explored and extended prior studies' methodologies and findings and provided wayfinding, spatial awareness and motion sickness recommendations to VR researchers and developers to support the creation of better VR software.

Whilst the study failed to reject all null hypotheses there were still several important sample specific findings that contribute to the study's goal of providing recommendations for researchers and developers:

1. With no single best-performing locomotion method across the scope of wayfinding, spatial awareness, motion sickness and user preference, VR developers should consider providing users with several locomotion options to choose from, with an awareness that some locomotion methods appear to perform more efficiently at wayfinding tasks depending on a user's prior spatial knowledge of an environment and the number of visual aids provided by the software's UI. Where visual aids are used, developers should consider recognising when users deviate from optimum paths or consider alerting users when they are near to but have not yet arrived at their destination.
2. Individual users scan VR environments and observe objects in that environment differently from each other. Some users utilise the full rotational capabilities of a VR headset whilst others appear to limit their vision to only that of the headset's FOV with limited head movements. These differences appear to affect spatial awareness and the ability to wayfind efficiently. Whilst the possible reasons for these differences are not explored in this report, VR developers should be aware that differences

between users exist and should consider supporting users via their software's interface, such as by pointing users towards an object of interest that is nearby but out of sight, or using textures, colours or shapes to allow important objects to stand out and be noticed by users more easily. These may help improve user spatial awareness and improve their VR experience.

3. Feelings of motion sickness on modern consumer VR hardware appears to be low and suggests there may be headroom for VR developers to push boundaries further in their use and configuration of teleportation techniques. However, this does not negate the need to develop software carefully to ensure motion sickness is not triggered carelessly causing user discomfort.

5.2 Limitations

Whilst the study achieved its general success measures of building and deploying software onto VR hardware, alongside designing and running an experiment with participants, on reflection there were limitations of the study across several categories that prevented it from maximising its potential.

Several limiting factors were caused by the VR software, resulting in the experiment being unable to measure several specific participant behaviours:

- The metric determining if a user was heading towards a destination was inconsistent and was not picked up during testing. This was likely due to the metric's calculation being mapped to the headset and not the participant's virtual body. This meant it was difficult from the data to determine how much a participant was heading in the right direction because the metric changed rapidly between true and false when a participant looked around, even if their virtual body was moving in the right direction.
- Software did not capture the duration participants paused for before teleporting due to no timestamp being captured when participants performed actions. This prevented the study from quantitatively comparing the performance of different participants who found the destination quickly and who became lost.
- Not all routes were the same distance. Making each route the same distance, meaning locomotion methods can be compared across routes at identical points in a participant's journey rather than only comparing overall route results by waypoint enabled / disabled.

These limitations are easily resolved by additional configuration of the routes, improved testing and the addition of more granular data. However, other limitations were caused by the design of the experiment or its execution:

- The study's failure to reject all three null hypotheses is most likely due to N=10: the sample size was simply too small. Given more resource, the study should have been conducted for longer so more participants could enter, reducing the sample size as a possible factor of failing to reject the hypotheses.
- The study recruited participants only from the researchers' friends and family. This limits findings to a narrow demographic. Additionally, the study was not open to

participants aged under 18 due to the additional steps required to safeguard participants and their data. As under 18s are a clear target audience for VR hardware manufacturers it is a notable omission and prevents the findings applying to this demographic.
- Motion sickness findings may have been unduly influenced by the study's short running time: whilst the study suggests that motion sickness may be much reduced on modern hardware it remains possible participants did not have enough time to begin feeling sick. Additionally, in the post-study questionnaire, avoiding slightly ambiguous terms such as 'comfortable' would allow participants to be more precise when describing how they felt.
- The experiment was conducted only on the Meta Quest 2 hardware using a game-like virtual environment. As one of the most popular consumer headsets and applications of VR this was sufficient for the scope of this project but may mean the findings and recommendations of this report may not apply to other VR hardware or software.

Elements of the post-study questionnaire meant several H2 measurements could not be fully analysed:

- The landmark recall question failed to anticipate participants becoming confused about which route (and its landmarks) applied to each locomotion method. On reflection, participant responses may have been consistent if the question had been asked at the same time as the FMS question. In addition, it is possible that the question about comfort was not linked clearly enough to feelings of motion sickness and may have been interpreted differently by participants to that of the question's intent.
- Participants were not asked if they considered themselves to have become lost when they deviated from a route's optimum path. This additional qualitative data may have added useful context to a route trace: it is possible some participants were exploring and were not lost but this cannot be determined by analysis of only the route traces.
- Similarly, asking participants to justify their locomotion method preference rank would have provided additional context to the results, particularly where participants preferred methods that contradicted the method's efficiency at wayfinding.

Adding or updating these questions before repeating the experiment for longer with a broader participant pool would be straightforward to conduct. These changes would help the study generalise its findings further with greater ecological validity and would potentially help avoid the study's small sample size detracting from the statistical significance of its results.

5.3 Future work

The study's findings and its limitations highlight several areas that could be addressed by future research.

Starting with improving the current study, repeating the study with a wider demographic range, including participants aged under 18, and conducting it on other manufacturers' hardware would increase ecological validity and help the study further its goal of providing recommendations for VR researchers and developers that generalise for all VR consumers. Additionally, broadening the number of locomotion methods or looking at different configurations (e.g. dash teleport's speed) of the methods used in this study would ensure all possible locomotion methods that a consumer might experience are studied and understood. Comparison of a method's possible different configurations may provide more insight into why a technique such as step teleport performed much worse than other methods for user spatial awareness despite sharing mechanical similarities.

Looking beyond improvements to the current study, the finding that different participants scan the environment differently, with some cases appearing to negatively affect spatial awareness and wayfinding, could be explored by future work, and would also build upon recent work conducted by Cherep et al. (2020). Such future work could compare whether limiting a user to a headset's FOV versus allowing full-head or full-body rotation affects a user's spatial awareness.

Immersion is an essential factor of VR and a key attraction to consumers. Whilst immersion was not the focus of this study, the study aimed to provide an environment that visually appeared open-world (even if it wasn't open-world or rendered realistically due to resource constraints) to ensure participants moved naturally around objects that appeared familiar to them. Future work could look to see how graphical hyperrealism or truly open worlds affects how humans approach wayfinding, and could be used to help design physical spaces (such as buildings) to understand how humans move through them before they are physically built. To extend this even further, the addition of moving objects and avatars into a study would better reflect that humans must attempt to wayfind in a continually changing real-world with other people that requires them to adjust and adapt accordingly.

This study focused only on the visual and limited motor senses for wayfinding and it is possible the curtailment of other human senses limited the performance of participants in the study – alongside visual and elevation landmarks, humans use sound and smell to help orientate themselves and to understand how far they've travelled. Designing a study to explore whether the addition or suppression of certain sensory systems helps or hinders spatial awareness in VR may help VR software with environmental design decisions and whether it should use certain UI navigational aids or software features.

Finally, research is never static, and the available technology has already improved since this study was started. The Meta Quest 2 was the leading consumer VR headset in August 2022, but at the point of finishing this project in July 2023, Meta has released the Quest Pro and announced the Quest 3, both improvements on the Quest 2, whilst the Apple Vision Pro has been announced for 2024 with a very different set of hardware and software priorities to other manufacturer headsets. Just as this study updated the hardware and graphics used in similar studies conducted in the 1990s and 2000s, revisiting the key topics of this study in the future with new headsets is recommended to see how further technology improvements affect wayfinding efficiency and spatial awareness when using teleportation locomotion methods in VR.

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Appendix A: Software requirements

Functional requirements

1. Software must portray a 3D environment that must run on Meta Quest 2 VR hardware.
2. Must utilise hardware headset and handset interaction features:
   a. Move or rotate headset to change gaze direction.
   b. Move handsets and press buttons to interact with environment.
3. Must display current state of physical handsets in the VR environment.
4. Software must provide the following 3D environments:
   a. Training/tutorial scene.
   b. Study scene.
5. Each scene in the study must:
   a. Allow users to move in the environment.
   b. Obey realistic physics (e.g. gravity).
   c. Prevent users from moving through objects.
   d. Prevent objects from moving (e.g. dynamic or scripted movement).
   e. Prevent uses from interacting with objects (e.g. pick up or move).
   f. Be well-lit, allowing users to clearly see the scene and its objects.
   g. Utilise accessible colours for accessibility.
6. Incorporate 3D assets that reflect real-world objects, including:
   a. Landmarks (e.g. statue, houses, rock features).
   b. Obstacles (e.g. trees, fences, buildings).
   c. Paths and roads.
7. Software must proceed in order though the following states:
   a. After loading the application, reset all values and load the training/tutorial scene.
   b. After a user completes the training/tutorial scene, the software must reset all values and load the study scene.
   c. After a user completes the study scene, the application must stop running.
8. Software must support key features of the study:
   a. Must allow researcher to configure specific routes using in-scene. coordinates for user to follow in each scene.
   b. Must allow researcher to assign locomotion methods to each route.
   c. Must allow randomisation of the order of routes in each scene.
   d. Must display user instructions at the start of each scene, route and locomotion method.
   e. Must prevent users from travelling to invalid destinations.
   f. Must display destinations as valid or invalid when the user attempts to travel.
9. Must allow users to move using the following locomotion methods:
   a. Continuous locomotion using joystick on controller
   b. Point and teleport
   c. Step teleport

    d. Dash teleport
10. Must allow users to rotate their head or body to change the direction they are looking within the VR environment.
11. When following a route inside a scene, software must:
    a. Allow user to choose when to begin each route.
    b. Display visually identifiable waypoint(s) so a user can follow a route.
    c. Upon reaching a waypoint, hide the current waypoint and display the next waypoint (or endpoint if it is the last waypoint).
    d. Display visually identifiable route endpoint.
    e. Upon reaching an endpoint, either:
        i. Load the next route.
        ii. End the scene if all routes for the scene are completed.
12. Software must incorporate the following user interface requirements:
    a. Display user instructions at the start of each route.
    b. Do not display any UI hints that help a user find the next waypoint/endpoint.
    c. Do not present any interactive menus or options for the user to configure.
    d. Display a countdown displaying how much time a user has left for each route.
        i. If route time passes maximum allowed time for a route, the route should end, following 11e above.
    e. Must prevent a user from pausing the application whilst following a route.
13. Data must be captured according to requirements in 3.4.7:
    a. Data must be retrievable from hardware device post-study in a .csv file format, one file per user per scene.
    b. Data must not include user personal information.

Non-functional requirements

1. Software should seek to minimise motion sickness.
2. Software should seek to maintain a good frames-per-second rate.
3. Software should ensure users feel immersed in the virtual environment.
4. Software must ensure user stays safe by utilising Meta’s zone ‘Guardian’ feature to prevent collisions with physical objects.
5. Software source code should be configurable and maintainable by researcher.
6. Software source code should be accessible to others.
7. Software should minimise loading times.

Appendix B: Hardware and software versions

Hardware firmware

Item	Version	Link / Reference
Meta Quest 2 headset and controllers	49.0.0.186	https://www.meta.com/gb/quest/products/quest-2/ [Accessed 9 February 2023]
macOS (Apple Silicon)	12.6.2	n/a

Development software

Item	Version	Link / Reference
Unity	2022.1.23f1	https://unity.com/releases/editor/whats-new/2022.1.23 [Accessed 9 February 2023]
Microsoft Visual Studio 2019 for Mac	8.10.25	https://visualstudio.microsoft.com/vs/older-downloads/ [Accessed 9 February 2023]

Unity packages

Item [Publisher]	Version	Link / Reference
XR Interaction Toolkit [Unity Technologies]	2.0.4	https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.0/manual/installation.html [Accessed 9 February 2023]
Oculus XR Plugin [Unity Technologies]	3.2.2	https://docs.unity3d.com/Packages/com.unity.xr.oculus@3.2/manual/index.html [Accessed 9 February 2023]
Android Logcat [Unity Technologies]	1.3.2	https://docs.unity3d.com/Packages/com.unity.mobile.android-logcat@1.3/manual/index.html [Accessed 9 February 2023]
OpenXR Plugin [Unity Technologies]	1.4.2	https://docs.unity3d.com/Packages/com.unity.xr.openxr@1.4/manual/index.html [Accessed 9 February 2023]
XR Plugin Management [Unity Technologies]	4.2.1	https://docs.unity3d.com/Packages/com.unity.xr.management@4.2/manual/index.html [Accessed 9 February 2023]

Assets

Item [Publisher]	Version	Link / Reference
3D assets downloaded from	n/a	https://kenney.nl/assets?q=3d

public domain (CCO 1.0 Universal license) using the following asset sets: City Kit (Urban) City Kit (Roads) Holiday Kit Nature Kit Platformer Kit Survival Kit [Kenney NL]		[Accessed 9 February 2023]
Oculus Integration [Oculus]	46.0	https://assetstore.unity.com/packages/tools/integration/oculus-integration-82022 [Accessed 9 February 2023]
Hand painted grass material [LowlyPoly]	1.1	https://assetstore.unity.com/packages/2d/textures-materials/floors/hand-painted-grass-texture-78552 [Accessed 9 February 2023]
Code for UI HUD background colour inside NBS_BackgroundScale.cs	n/a	https://sharpcoderblog.com/blog/unity-3d-create-main-menu-with-ui-canvas [Accessed 14 December 2022]

Support software

Item	Version	Link / Reference
Unity Hub	3.4.1	https://unity.com/unity-hub [Accessed 9 February 2023]
Meta Quest (iOS app)	201.0	https://apps.apple.com/gb/app/meta-quest/id1366478176 [Accessed 16 February 2023]
Meta Quest Developer Hub for macOS	3.1.1	https://developer.oculus.com/blog/meta-quest-developer-hub-mqdh-31/ [Accessed 16 February 2023]
GitHub Desktop	3.1.4	https://desktop.github.com/release-notes/ [Accessed 9 February 2023]
OpenMTP	3.2.10	https://openmtp.ganeshrvel.com [Accessed 9 February 2023]

Appendix C: Source code

- For source code only, all scripts created by the researcher and third-party assets used can be found in the submitted zip file, titled 'NBS_SourceCodeAssets.zip' uploaded as part of the final submission.
- For the full Unity package, including scripts and scenes created by the researcher, and all files and packages generated by Unity, please download the 948MB .zip file from: https://drive.google.com/file/d/17rn2pc-bJk0EIMLBidoQ7lrQY8eD39Fq/view?usp=share_link titled 'NBS_UnityPackageAndScripts.zip'. Unity v2022.1.23f1 is needed to open it.

Source code file name	Purpose
NBS_BackgroundScale.cs	Manages background image display for HUD UI. All code in this script is from https://sharpcoderblog.com/blog/unity-3d-create-main-menu-with-ui-canvas [Accessed 14 December 2022]
NBS_HUDManager.cs	Displaying UI elements
NBS_InputManager.cs	Handling and validating input detected by Unity
NBS_Locomotion_ContinuousJoystick.cs	Manages 'continuous joystick' locomotion
NBS_Locomotion_DirectTeleport.cs	Manages 'point and teleport' and 'dash teleport' locomotion
NBS_Locomotion_Rotation.cs	Manages user rotation
NBS_Locomotion_StepTeleport.cs	Manages 'step teleport' locomotion
NBS_PlayerManager.cs	Manages public setters/getters for accessing or modifying current user state
NBS_RouteConfiguration.cs	Manages coordinates for route waypoint, user starting position and route locomotion method
NBS_RouteManager.cs	Manages route configuration, handles user reaching waypoints, and manages end of route being reached
NBS_SaveToDisk.cs	Manages disk IO and saving log to disk
NBS_StateEnums.cs	Collection of enums used to manage scene and locomotion states
NBS_Strings.cs	Centralised file containing all displayed text across the application for easy editing
NBS_StudyManager.ca	Core class that coordinates loading scenes, loading routes, managing states and calling other class methods as appropriate (such as saving logs to disk)

Appendix D: Guide to key source code

Controller hardware plugin

Key package: Oculus XR Plugin

The Oculus XR Plugin was utilised to leverage pre-built features built by the manufacturer such as animating button presses on the virtual handsets and that handsets were tracked and appeared correctly in VR. Much of this is handled ‘out of the box’ by the plugin, with minor features added by the researcher to support in-display laser pointing, the parabolic arc of the pointer, and visually portraying if teleportation destinations were valid for the user (red for invalid; green for valid).

Handling user inputs

Key script: NBS_InputManager.cs

NBS_InputManager (Appendix O: Figure 27) handles all controller input detected by Unity’s Input Actions prior to triggering a specific action. This class validates controller input before passing it onto a locomotion specific class. This approach helps to generalise input validation and makes it simple to add new locomotion methods if needed.

Scenes and routes

Key scripts: NBS_StudyManager.cs; NBS_RouteConfiguration.cs; NBS_RouteManager.cs

Scene loading is managed primarily by Unity (which loads scenes in the order set in the Build Settings pane). It loads the tutorial scene first. As a route is loaded, NBS_StudyManager is responsible for pausing the software and waits for the user to signal their intention to start the route when they press a button. During the tutorial scene, NBS_StudyManager checks if all routes in the tutorial are completed. If this is true, NBS_StudyManager loads the study scene. It repeats the same check as the study’s routes are completed and pauses the software when all routes are completed, denoting the end of the experiment.

The loading and display of each route is managed by NBS_RouteManager. NBS_RouteConfiguration was designed to make it simple for the researcher to design routes using Vector3 coordinates local to the scene. The class method GenerateWaypointsForRoute() loads a pre-determined set of coordinates for a given routes and manages the placement of waypoints and the endpoint. As a route is simply a set of coordinates for the user to follow, this approach make it quick for the researcher to add or finetune a waypoint’s placement. Other methods manage locomotion assignment, user starting position and whether waypoints were visible or not, depending on the state of the scene and the user.

Continuous motion via controller joystick

Key script: NBS_Locomotion_ContinuousJoystick.cs

NBS_InputManager receives a Vector2[8] from Unity's Input Actions and passes it to NBS_Locomotion_ContinuousJoystick. This 2D vector is multiplied by an acceleration variable and the time delta since the last frame occurred. The product is applied to the user's current physics body position to ensure physics collisions are detected correctly. Assuming there are no physical collisions the user is moved for the current frame. This is repeated for all joystick inputs, frame by frame. If the joystick is not moved, the InputVector is zeroed out which instantly stops the user from moving, keeping them at their current position.

Point and teleport

Key script: NBS_Locomotion_DirectTeleport.cs

NBS_Locomotion_DirectTeleport (Figure 31) receives a Vector3 destination from NBS_InputManager, momentarily fades the screen to black to create the blink effect found to reduce feelings of motion sickness as discussed by Rahimi et al. (2020) before instantly translating the user to their destination, achieved by changing the user's current Vector3 position to the destination's Vector3 position within the method MovePlayerInstantly(). The translation occurs in one frame and from the user's perspective occurs immediately, no matter how far the destination is from the user's starting position. As point and teleport shares code with dash teleport, the variable enableDash must be set to false for point and teleport to work.

Dash teleport

Key script: NBS_Locomotion_DirectTeleport.cs

Dash teleport shares the same code as point and teleport, but the variable enableDash must be true to follow the conditional logic specific to dash teleport. Dash teleport automatically and continuously moves the user towards their destination, using Unity's Lerp method to move a user frame by frame towards the destination with an EaseIn acceleration curve that accelerates the user quickly for the first half of the distance before slowing down as the user approaches their destination. Dash teleport ignores additional user input whilst the user is moving.

Step teleport

Key script: NBS_Locomotion_StepTeleport.cs

Upon receiving a destination from NBS_InputManager, NBS_Locomotion_StepTeleport calculates the distance from the user's current position to the desired destination and divides it by a set distance to calculate the number of steps and the position of each step the user will

[8] Vector2 (x,y) maps to the direction of movement: (0,1) = joystick push upwards on the joystick with no left/right direction. (0,-1) = back only. (1,0) = right only and (-1,0) = left only. (1,1) = push upwards and left.

hop between (Figure 32). Each step is a Vector3 stored in an array. Before moving, the screen fades to black temporarily and the user is instantly transported to the first step in the array. Movement pauses for one second before repeating this process for each step in the array until the user reaches the final step. *Step teleport* ignores additional user input whilst the user is moving.

<u>Data collection and analysis</u>

Key scripts: NBS_StudyManager.cs; NBS_SaveToDisk.cs

NBS_StudyManager is responsible for collecting data, either passively, in response to user action (such as pressing a button or reaching a waypoint), or actively, by logging a user's current position or calculating their travelled distance. The method AddToWriteQueue() logs all required data into a buffer array before writing the buffer to disk every 50ms via the method DrainQueueByWritingToDisk(). A buffer was used to avoid overwhelming the hardware's IO by writing to disk every frame. NBS_SaveToDisk abstracts the actual file management and IO of the application, meaning NBS_StudyManager only needs to call the method WriteToLogFile() to save the buffer to disk as a .csv file. Each record logs the current scene, route, waypoint marker and locomotion method to simplify aggregation of data during analysis. An anonymous participant ID is used to ensure analysis of individual behaviour can be conducted alongside aggregated analysis.

Once a participant completed the experimental software, the data was retrieved from the device and loaded into a SQL database prior to analysis.

Appendix E: Study software configurations

General configuration

Class	Configurable parameters
NBS_Locomotion_ ContinuousJoystick	• moveSpeed = 1.0 [Unity units]
NBS_Locomotion_ StepTeleport	• stepDistance = 1.5 [Unity units] • stepDelayInSeconds = 1 [seconds]
NBS_PlayerManager	• cameraScreenFade = 2 [seconds]
NBS_StudyManager	• maxRouteTimeAllowed = 90 [seconds] • batchLogEveryXMilliseconds = 50 [milliseconds] • writeLogEverySecondInMilliseconds = 1000 [milliseconds] • moveToNextSceneDelaySeconds = 5 [seconds] • moveToNextRouteDelaySeconds = 1.5 [seconds] • endSceneDelaySeconds = 3 [seconds]

Input configuration

Action	Configuration
Start route	A button on right controller
Point teleport reticle*	Point left controller
Initiate teleport*	Pull bottom / main trigger on left controller
Move user with joystick^	Move joystick on right controller
Rotate view with joystick	Move joystick on left controller

* Action enabled only when a teleportation locomotion method is in use.
^ Action enabled only when a joystick locomotion method is in use.

Appendix F: Internal testing and changes

Internal testing and user feedback resulted in the following changes:

- Changed light sources and use of shadows to ensure objects were sufficiently lit whilst also providing enough contrast to provide a feeling of depth to the study scene so that it felt naturalistic.
- Changed the movement and rotation acceleration of the user to ensure they could move more quickly around the environment after users felt frustrated it was too slow.
- Changed the size of physics bodies to ensure users did not pass through objects without snagging on objects that in-camera they didn't appear to be near.
- Introduced a clearer colour palette to ensure participants understood which objects they could interact with or were impassable, including changing waypoints from blue to pink to ensure they stood out.
- Addition of 'filler' background trees were placed beyond the study scene's traversable zone to provide a sense of depth and make the world feel larger and more representative of modern 3D game environments.
- Specific issues fixed were ensuring data log accuracy, preventing users from escaping the traversable zone of the environment scene and that in-game physics collisions did not result in users being suddenly catapulted across the scene.

Appendix G: Factors of experimental invalidity

Table 14 identifies possible factors of experimental invalidity. These factors were controlled as much as possible to reduce their impact on the study's results.

Factor	Issue	Minimised by
Interaction between participants	Participants who have already completed the experiment could inform other potential participants of the experiment's design, procedures and aims. This could result in potential participants behaving less naturally in the study or behaving in specific ways to 'beat' or 'game' the experiment, altering the study's findings.	Asking participants not to speak about the study until 12 hours had elapsed since they participated.
Participant nausea	Participant nausea could affect the study's findings preventing a user from acting naturally from completing the experiment.	To reduce feelings of nausea, manufacturer best practice was followed, along with significant testing by the researcher and pre-study testers to identify potential causes software.
Withdrawal of participants from the study	The researcher deemed the most likely causes of withdrawal are feelings of nauseous or participants becoming fatigued due to the weight of the VR headset	Attempts to mitigate nausea are described above. To reduce feelings of fatigue, the length of the study was kept as short as possible (15 - 20 minutes). Participants were informed they could withdraw at any point and were reminded of this if they self-reported a rating of 5 or greater on the FMS scale.
Range of participants and participant selection bias	Participants were recruited from researchers' friends and family. The study's non-public participant pool risks participants skewing towards a particular demographic.	It will be mentioned in the study's limitations to ensure readers are aware.
Hardware limitations	Limitations of the Meta Quest 2 include slow frame rates or frame tearing should assets be of too high-fidelity or if real-time light raytracing is used. This could cause feelings of motion sickness for participants, influencing results.	As the focus of the study is not photorealism, baked lighting and lower quality 3D assets were used to ensure the Quest's frame rate remained at 72 FPS, as recommended by the manufacturer to reduce motion sickness (Meta, 2023c).

Influencing external factors	Different external factors, such as different headsets, battery levels or controller button layouts could influence results, as one combination of factors could advantage one participant other another	To minimise these factors the same Meta Quest 2 hardware will be used by each participant. It will be operated cordlessly charged fully each time to prevent any throttling of CPU / GPU by the device’s battery management system. In addition, button mapping on each controller will be the same for each participant.

Table 14. List of potential factors affecting experimental validity.

Appendix H: 12-Point ethics checklist

Department of Computer Science
12-Point Ethics Checklist for UG and MSc Projects

Student: Nicholas Blake-Steele

Academic Year: MSc Computer Science **(**2020-2023)

Project Title: Comparison of teleportation locomotion methods for efficient wayfinding in virtual reality environments

Supervisor: Dr Zack Lyons

This form must be attached to the dissertation as an appendix.

Does your project involve people for the collection of data other than you and your supervisor(s)? YES

If the answer to the previous question is YES, you need to answer the following questions, otherwise you can ignore them.

This document describes the 12 issues that need to be considered carefully before students or staff involve other people ('participants' or 'volunteers') for the collection of information as part of their project or research. Replace the text beneath each question with a statement of how you address the issue in your project.

1. *Will you prepare a Participant Information Sheet for volunteers?* YES

Participants will be informed about the nature and purpose of the study. They will be informed that the study requires them to wear a virtual reality (VR) headset and that they will be asked to move about and navigate within the VR environment, but not why they are doing so. They will be informed about any known health risks that VR can induce in participants (such as nausea or disorientation) and any physical risks that might be present in the space, along with the ways they have been mitigated or minimised. They will also be informed they can withdraw from the study at any time, including withdrawing their data at any time. They will be told about how their data will be stored and how to contact the investigator running the study.

2. *Will the participants be informed that they could withdraw at any time?* YES

Details of this will included in the Participant Information Sheet. This will detail that during the study participants can withdraw at any time, and they will be provided information of how to contact the researcher after the study to withdraw their data.

3. *Will there be any intentional deception of the participants?* NO

No content in the VR environment in the study is considered misleading, distasteful or offensive, and no part of the study should go beyond what a participant expects from wearing a VR headset and interacting with a VR environment.

4. *Will participants be de-briefed?* YES

The debrief will provide information about how their participation contributed towards gathering data and what this study's goals were. Depending on how the study is conducted on campus, a more detailed debrief may be shared after the full study has been completed to ensure participants cannot inform or influence other participants on campus.

5. *Will participants voluntarily give informed consent?* YES

It will be made clear that participants must voluntarily provide consent. It is anticipated that this will be an online consent form for persistent storage of the consent. The form will ask participants to confirm they are over 18 and that they understand the risks of using VR headsets. It is likely that no personal information is required to complete the study; if this is the case consent will be captured anonymously.

6. *Will the participants be exposed to any risks greater than those encountered in their normal work life (e.g., through the use of non-standard equipment)?* YES

The Meta Quest 2 VR headset is commercially available to consumers, so its use in a study is not considered non-standard equipment.

However, VR headsets may still be unfamiliar equipment to some people, especially the suppression of certain senses, and therefore the use of VR equipment increases the risk of a participant tripping, falling, feeling disorientated or becoming nauseous beyond that encountered in their normal work lives. Such risks will be clearly flagged to participants on the Participant Information Sheet and also on the consent form.

The study will adhere to manufacturer guidance for equipment set up and usage. Physical risks will be mitigated as much as possible by:

- conducting the study in a large physical space, ideally on campus.
- creating a physical safe space and ensuring it is kept free of obstacles and hazards when participants are wearing the VR headset.
- using software tools provided by the Quest 2 headset to track movement in the physical safe space and present in-display boundaries to the participant to prevent them leaving the physical safe space.

- ensuring the investigator is present in the study space when participants are wearing the VR headset to monitor if a participant is likely to trip or fall.
- speaking to the ReVEAL Centre about their experiences conducting VR studies with participants.

Participant will be informed that they can withdraw from the study at any point should they feel disorientated or nauseous.

7. *Will you be offering any incentive to the participants?* NO

8. *Will you be in a position of authority or influence over any of your participants?* NO

9. *Will any of your participants be under the age of 16?* NO

10. *Will any of your participants have an impairment that will limit their understanding or communication?* NO

11. *Will the participants be informed of your contact details?* YES

Details of how to contact the investigator will be made available to participants on the Participant Information Sheet, the consent form and in the debrief material.

12. *Will you have a data management plan for all recorded data?* YES

It is not anticipated that any personal data will be collected, but if any personal data must be collected to conduct the study, a plan will be made to anonymise this data as soon as the study is complete. A retention plan will be followed to ensure data is deleted and destroyed as soon as it is no longer needed. Data will be stored on university servers according to the Department of Computer Science's requirements for personal data storage.

Appendix I: Ethics sub-committee review

FORM A: ETHICS REVIEW CHECKLIST FOR RESEARCH WITH HUMAN PARTICIPANTS

This checklist should be completed for every research project involving human participants in order to identify whether a full application for ethics approval needs to be submitted to one of the University Ethics Sub-Committees. The principal investigator or, where the principal investigator is a student, the supervisor, is responsible for exercising appropriate professional judgement in this review.

Section 1: Project details			
Project title:	Comparison of teleportation locomotion methods for efficient wayfinding in virtual reality environments		
Brief synopsis of study: (no more than 250 words)	Virtual reality (VR) study performed using Meta Quest 2 VR headset and controllers. Participants will wayfind and travel along pre-determined routes in VR, randomly shuffled. Each route requires users to travel using a different locomotion method implemented by the study. Each locomotion method can be performed ‘in-place’, either standing or sitting, and does not require participants to physically move in the real-world. On-screen navigation aids will be provided the first time a route is experienced. When participants experience a route for a second time navigation aids will be removed and participants must use their memory recall to wayfind successfully. Data will be captured anonymously during the study within the VR study application. Data includes (but is not limited to) the actions and position of the participant within the VR environment. Data will be analysed post-study to assess the wayfinding effectiveness of each locomotion method. No identifiable personal data will be captured, stored or analysed at any point during the study. Whilst VR hardware is widely available to consumers, as participants may have little experience using it they will not be left unattended during the study. The study space will be cleared of obstacles and the study will follow manufacturer’s guidance for implementing virtual boundaries that warn participants if they physically move out of the safe space. Participants will be informed prior to the study that they may experience feelings of motion sickness and that they can withdraw at any point during the study.		
Planned start date:	September 2022	Planned end date:	August 2023
Funder:	n/a		
Do you have prior approval?	No		
If so, please state where from	n/a		

Section 2: Applicant details			
Applicant name and username:	Nicholas Blake-Steele ndbs20		
Department:	Department of Computer Science		
Email:	ndbs20@bath.ac.uk		
Undergraduate ☐	Masters ☒	Research Postgraduate ☐	Staff ☐

(NB: If you have prior ethical approval from the NHS, SCREC or a UK academic institution, please sign this checklist and attach evidence of that approval. There is no need to complete any more questions.)

September 2020

FORM A: ETHICS REVIEW CHECKLIST FOR RESEARCH WITH HUMAN PARTICIPANTS – FACULTY OF HUMANITIES AND SOCIAL SCIENCES

3(A) Research that may need full review by a University of Bath Ethics Sub-Committee	**YES**	**NO**
Do you and/or your supervisor intend to submit your results for publication to the wider research community (other than in your dissertation) where evidence of ethical approval is required?	☐	☒
Does the project involve the collection of material that could be considered of a personal, biographical, medical, psychological, social or physiological nature?	☐	☒
Does the research involve vulnerable groups: e.g. children; those with cognitive impairment; or those in unequal relationships (e.g. your own students)?	☐	☒
Will the study require the cooperation of a gatekeeper for initial access to the groups or individuals to be recruited (e.g. headmaster at a School; group leader of a self-help group)?	☐	☒
Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g. covert observation of people in non-public places?)	☐	☒
Will the study involve discussion of sensitive topics (e.g. sexual activity; drug use; criminal activity)?	☐	☒
Is pain or more than mild discomfort likely to result from the study?	☐	☒
Could the study induce psychological stress or anxiety or cause harm or negative consequences beyond the risks encountered in normal life?	☐	☒
Will the study involve prolonged or repetitive testing?	☐	☒
Will the research involve organisational administrative or secure data that requires permission from the appropriate organisation/authorities before use (data that is not in the public domain)?	☐	☒
Does the research involve participants carrying out any of the research activities themselves (i.e. acting as researchers as opposed to just being participants)?	☐	☒
Is there a possibility that the safety of the researcher may be in question (e.g. international research; locally employed research assistants)?	☐	☒
Will personal data be transferred to/from the UK (including to/from the EEA?)	☐	☒
Will the outcome of the research allow respondents to be identified either directly or indirectly (e.g. through aggregating separate data sources gathered from the internet)?	☐	☒
Will research involve the sharing of data or confidential information beyond the initial consent given?	☐	☒
Will financial inducements (other than reasonable expenses and compensation for time) be offered to participants?	☐	☒
Will the proposed findings be controversial or are there any conflicts of interest?	☐	☒
Will the study involve the publication, sharing or potentially insecure electronic storage and/or transfer of data that might allow identification of individuals, either directly or indirectly? (e.g. publication of verbatim quotations from an online forum; sharing of audio/visual recordings; insecure transfer of personal data such as addresses, telephone numbers etc.; collecting identifiable personal data on unprotected** internet sites.) [**Please note that Qualtrics provides adequate data security]	☐	☒

3(B) Security Sensitive Material	**YES**	**NO**
Does your research involve access to or use of material covered by the Terrorism Act? (The Terrorism Act (2006) outlaws the dissemination of records, statements and other documents that can be interpreted as promoting and endorsing terrorist acts. By answering 'yes' you are registering your legitimate use of this material with the Research Ethics Advisory Group. In the event of a police investigation, this registration will help you to demonstrate that your use of this material is legitimate and lawful).	☐	☒

3(C) Prevent Agenda	**YES**	**NO**
Does the research have the potential to radicalise people who are vulnerable to supporting terrorism or becoming terrorists themselves?	☐	☒

Appendix I: Ethics sub-committee review

FORM A: ETHICS REVIEW CHECKLIST FOR RESEARCH WITH HUMAN PARTICIPANTS – FACULTY OF HUMANITIES AND SOCIAL SCIENCES

If the answer to <u>all</u> questions in Sections 3(A) and/or 3(B) and/or 3(C) is 'no', please complete a an EIRA1 submission for review within the Department of Computer Science, and attach this form to your EIRA1 submission.

If the answer to <u>any</u> questions in Sections 3(A) and/or 3(B) and/or 3(C) is 'yes', please complete the full application form for an appropriate University Ethics Sub-Committee and send it to the sub-committee secretary, together with required supporting documentation.

Section 4: Declaration and signatures			
Please note that it is your responsibility to follow, and to ensure that, all researchers involved with your project follow accepted ethical practice and appropriate professional ethical guidelines in the conduct of your study. You must take all reasonable steps to protect the dignity, rights, safety and well-being of participants. This includes providing participants with appropriate information sheets, ensuring informed consent and ensuring confidentiality in the storage and use of data.			
Applicant signature		**Date**	14 January 2023

Supervisor name	Dr Zack Lyons	**Date**	14/01/2023
Supervisor signature			

Appendix J: Participant information sheet

PARTICIPANT INFORMATION SHEET

Comparison of teleportation locomotion methods for efficient wayfinding in virtual reality environments

Student researcher: Nicholas Blake-Steele	Supervisor: Dr Zack Lyons
Contact details: ndbs20@bath.ac.uk	Contact details: zl221@bath.ac.uk

This Information Sheet forms part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. Please read this Information Sheet carefully and ask one of the researchers named above if you are not clear about any details of the project.

1. What is the purpose of the project?

This experiment will compare different ways of moving in virtual reality (VR) when follow pre-determined routes inside a virtual reality 3D environment.

The study requires you to wear a VR headset whilst standing and participate in the experimental software running on the VR headset by following its instructions. You will be also asked questions before, during and after the study, both verbally and on paper.

2. Who can be a participant?

<u>Inclusion criteria</u>

You can take part in this study if:

- You are aged between 18 and 65. *This is based on recommendations by the VR headset's manufacturer and the study's ethics plan.*
- You can stand whilst wearing a VR headset and holding a handset in each hand.

<u>Exclusion criteria</u>

You should not take part in this study if:

- You do not meet all parts of the inclusion criteria.

- You are currently under the influence of alcohol or recreational drugs.
  You are currently taking any prescribed or unprescribed drugs for a medical condition.
- You are pregnant.
- You have suffered from epilepsy, have recurrent fainting spells or fall frequently.
- You have suffered from neurological or psychiatric conditions.
- You have undergone a neurosurgical procedure (including eye surgery).
- You have the following fitted to your body:
    - Heart pacemaker
    - Cochlear implant
    - Medication pump
    - Surgical clamps

List of exclusions taken from the University of Bath's VR screening criteria.

3. Do I have to take part?

You are a volunteer, and it is up to you to decide if you want to participate in this research.

Before you decide, you should read this Information Sheet. You should ask the researcher if you have any questions so you understand what you will be asked to do. If you still agree to take part the researcher will ask you to sign a Participant Consent Form.

If at any time you decide you no longer wish to take part in this project, even after signing the Participant Consent Form, you are free to withdraw without giving a reason.

During the experiment:

- If you wish to stop participating during the experiment please inform the researcher verbally. You can withdraw from the project at any time without providing a reason for doing so and without any repercussions.

After the experiment is complete:

- If for any reason you wish to withdraw your data, please contact an identified researcher by email. It may not be possible to withdraw any anonymous data as it will not be possible to identify your data, and some results may have been published. Your individual results will not be identifiable in any way in any presentation or publication.

4. What will I be asked to do?

Before the experiment begins:

- You will read this Information Sheet and you can ask the researcher any questions you may have.
- You will be asked to sign the Participant Consent Form before starting and answer a pre-study questionnaire.
- The study will be conducted in the room you are currently in. It is an in-person experiment and will be completed entirely in approximately 15-20 minutes.
- You will be asked to wear a VR headset (Meta Quest 2) and hold wireless hand controllers. You can adjust the fit of the VR headset so it is comfortable for you to wear.
- The researcher will be present in the room at a distance whilst you wear the VR headset and complete the experiment for safety purposes to ensure the study space is free of obstacles, that you do not trip or fall, or to stop the study if you wish to withdraw for any reason. They will ask you a question (see below) at set points during the study whilst you wear the headset.
- No other persons will be involved in the study, either inside or outside of the virtual reality environment.
- You are required to stand whilst wearing the VR headset. You do not need to physically walk around when you are wearing the VR headset. You can physically rotate your body or your head whilst standing in the same spot to turn inside the VR environment.

During the experiment inside the virtual reality environment:

- The first part of the VR software is a short tutorial. This will instruct you through the structure of the study and allow you to practice using each of the four movement methods under investigation whilst following a pre-determined route.
- Once the tutorial is completed, you will begin the main study itself:
    - The study's movement methods are the same as seen the tutorial.
    - The study's environment and routes will be different to the tutorial.
    - Each movement method will ask you to follow a route to a destination twice before moving onto the next movement method.
    - After reading each movement method's instructions you can choose when to start each route by pressing a button when you are ready.
    - Once a route is started you will have a set amount of time (90 seconds) to reach the end of the route before it automatically ends and moves you onto the next route.
    - Once a movement method's routes are complete, you will be asked to rate any feelings of motion sickness on a scale from 0 (no sickness) to 20 (frank sickness). If you are experiencing feelings of motion sickness the researcher will advise (or remind) you that you should not continue participating if you feel discomfort.
    - Once all four movement methods and their routes are completed, the software part of the experiment is complete and you can remove the VR headset.
    - You will then be asked to complete a post-study questionnaire. The study is then complete.

- The researcher will be monitoring and recording the VR headset's display and your actions inside the virtual reality environment from a nearby laptop. This device will only record what you can see on the VR display and does not record your face or body.

Upon completing the experiment inside the virtual reality environment:

- You will be debriefed on the study, and you can ask the researchers any questions you may have.
- All data collected (before, during and after) as part of the study is anonymous and will not be personally identifiable.
- Collected data will be analysed and its findings will be included in the MSc research dissertation and any publications of this research.

5. Are there any reasons why I should not take part in this experiment?

If you meet the criteria stated in Section 2 there are no further reasons you should not take park in the study. It is recommended that you read about the possible benefits of taking part (Section 6) and the possible drawbacks of taking part (Section 7) before deciding whether you should participate.

6. What are the possible benefits of taking part?

There are no benefits for any participants to take part in the project. However by participating in this experiment, you and other participants will help the researcher complete their MSc research dissertation and to further research into virtual reality and the field of human-computer interaction.

7. What are the possible disadvantages and risks of taking part?

There are no disadvantages for any participants to take part in the project.

There are possible risks whilst wearing the VR headset, including but not limited to:

- Experiencing feelings of motion sickness. If you are experiencing feelings of motion sickness you should inform the researcher. You should not continue if you feel discomfort.
- Tripping or falling. *Note: physically walking around whilst wearing the VR headset is not a requirement of this experiment*.

If the researcher or a questionnaire asks a question that you do not want to answer for any reason, you can choose not to answer.

8. Will my participation involve any discomfort or embarrassment?

It is not expected that you will feel any discomfort or embarrassment if you take part in the project. It is possible some participants may experience feelings of motion sickness whilst wearing the VR headset which may cause discomfort. However, if you do feel discomfort or embarrassment at any point during the study and want to stop the study, please state so and the researcher will stop the experiment immediately and you can withdraw from the study.

9. Who will have access to the information that I provide?

Only the student researcher will have access to the data collected during this experiment. No personally identifiable data will be collected any point during this experiment. All anonymous data collected will be treated as confidential.

10. What will happen to the data collected and results of the project?

No personally identifiable information will be collected at any point during this experiment.

Any anonymous data collected during the project will be collected in the following formats:

- Paper questionnaires you complete will be destroyed after being typed into a digital spreadsheet.
- Data collected will be stored and accessed on the researcher's personal computer, any external backup drives and their University of Bath cloud drive.
- Data will not be kept for any longer than 5 years.
- Your name or other identifying information will not be disclosed in any presentation or publication of the research.
- No further use of the data will be permitted for any other project.

After the project has finished, we can provide participants with a summary of the project results if requested by emailing one of the named researchers. This summary will not include any identifiable information and will show the overall findings of the project.

11. Who has reviewed the project?

This project has been reviewed by the formal ethics process within the Department of Computer Science at the University of Bath.

12. How can I withdraw from the project?

During the experiment:

- If you wish to stop participating during the experiment please inform the researcher present verbally. You can withdraw from the project at any time without providing a reason for doing so and without any repercussions.

After the experiment is complete:

- If for any reason you wish to withdraw your data, please contact an identified researcher by email. It may not be possible to withdraw any anonymous data as it will not be possible to identify your data, and some results may have been published. Your individual results will not be identifiable in any way in any presentation or publication.

13. University of Bath privacy notice

The University of Bath privacy notice can be found here: https://www.bath.ac.uk/corporate-information/university-of-bath-privacy-notice-for-research-participants/.

14. What happens if there is a problem?

If you have a concern about any aspect of the project you can speak to the researcher before, during or after the study.

If there is a medical problem or emergency during the study, the following procedures will be followed:

- If on-campus, the University of Bath's security team will be called on 01225 383999
- If elsewhere, the UK emergency services will be called on 999

15. If I require further information who should I contact and how?

Please get in touch with the below contacts if you would like more information about this project.

Student researcher: Nicholas Blake-Steele	Name of Supervisor: Dr Zack Lyons
Contact details: ndbs20@bath.ac.uk	Contact details: zl221@bath.ac.uk

Thank you for your interest in participating in this project.

Appendix K: Participant consent form

UNIVERSITY OF BATH

PARTICIPANT CONSENT FORM

Comparison of teleportation locomotion methods
for efficient wayfinding in virtual reality environments

Student researcher: Nicholas Blake-Steele	Supervisor: Dr Zack Lyons
Contact details: ndbs20@bath.ac.uk	Contact details: zl221@bath.ac.uk

Please initial each box if you agree with the statement

1. I have been provided with information explaining what participation in this project involves.
2. I have had an opportunity to ask questions and discuss this project.
3. I have received satisfactory answers to all questions I have asked.
4. I have received enough information about the project to make a decision about my participation.
5. I understand that I am free to withdraw my consent to participate in the project at any time without having to give a reason for withdrawing.
6. I understand that I am free to withdraw any identifiable data within two weeks of my participation (NOTE: the study does not collect any identifiable data).
7. I understand it may not be possible to remove anonymous data from the study after my participation due to it being anonymous.
8. I understand the nature and purpose of the procedures involved in this project. These have been communicated to me on the information sheet accompanying this form.
9. I understand and acknowledge that the investigation is designed to promote scientific knowledge and that the University of Bath will use the data I provide only for the purpose(s) set out in the Information Sheet.
10. I understand the data I provide will be treated as confidential, and that on completion of the project any identifying information will not be disclosed in any presentation or publication of the research.
11. I understand that my consent to use the data I provide is conditional upon the University complying with its duties and obligations under the Data Protection Act (2018).
12. I hereby fully and freely consent to my participation in this project.

Participant ID (completed by Researcher): ________________________ Date: _____________

Researcher signature: _____________________________________ Date: ________________

Researcher name in BLOCK Letters: ____

Participant ID will be added to the form after the experiment is complete. If you have any concerns or complaints related to your participation in this project, please direct them to the researchers named above.

Appendix L: Pre-study questionnaire

To be entered by researcher:

Participant ID	
Date	
Time	

To be answered by participant prior to wearing headset:

Question	**Response**
Age (in years)	Tick one of the following: ☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ 56-65 ☐ Prefer not to say
Gender (or ‘prefer not to say’)	
How many hours do you spend playing 3D video games?	Tick one of the following: ☐ 0 hours per week ☐ Between 0-2 hours per week ☐ Between 2-5 hours per week ☐ Between 5-10 hours per week ☐ More than 10 hours per week
How many hours do you spend using virtual reality whilst wearing a VR headset?	Tick one of the following: ☐ 0 hours per week ☐ Between 0-2 hours per week ☐ Between 2-5 hours per week ☐ Between 5-10 hours per week ☐ More than 10 hours per week

Appendix M: During study questionnaire

To be entered by researcher

Participant ID	

Researcher to ask participant:

How motion sick are you currently feeling, from a scale of 0 to 20, where 0 equals no sickness and 20 = frank sickness		**Method 1** Controller joystick	**Method 2** Point and teleport	**Method 3** Dash teleport	**Method 4** Step teleport
A. Rating at start of route	Waypoint				
B. Rating at end of route	Waypoint				
C. Rating at start of route	No waypoint				
D. Rating at end of route	No waypoint				

Software presented order (1 = first; 4 = last)				

Note: Steps B and C are combined as they form the same part in time (the end of the waypoint route is the start of the no waypoint route)

Appendix N: Post-study questionnaire

To be entered by researcher:

Participant ID	

To be answered by participant after removing headset:

Question	**Method 1** Controller joystick	**Method 2** Point and teleport	**Method 3** Dash teleport	**Method 4** Step teleport
Was it easy to understand how the movement method worked? 1 = Very difficult to understand 2 = Difficult to understand 3 = Neutral (neither difficult or easy) 4 = Easy to understand 5 = Very easy to understand				
Could you travel to where you wanted to go with the movement method? 1 = Very difficult to travel to where I wanted 2 = Difficult to travel to where I wanted 3 = Neutral (neither difficult or easy) 4 = Easy to travel to where I wanted 5 = Very easy to travel to where I wanted				
How comfortable was the movement method to use? 1 = Very uncomfortable (felt very sick or dizzy) 2 = Uncomfortable (felt slightly sick or dizzy) 3 = Neutral (neither comfortable nor uncomfortable) 4 = Comfortable 5 = Very comfortable				
Rate from 1-4 in order of your preference for moving in virtual reality (where 1 is your most preferred method).				

You can mark a box with X to state you would prefer to never use that method again.				

	List all notable landmarks or objects you remember seeing when using a particular movement method. Enter NONE if you can't remember any.
Method 1 Controller joystick	
Method 2 Point and teleport	
Method 3 Dash teleport	
Method 4 Step teleport	

What was your strategy for reaching a destination for routes without pink cylinders?

Do you have any final thoughts or comments on the locomotion methods used in the study, or about the VR study itself?

This concludes the questionnaire and the study. Thank you for participating.

Appendix O: Additional images

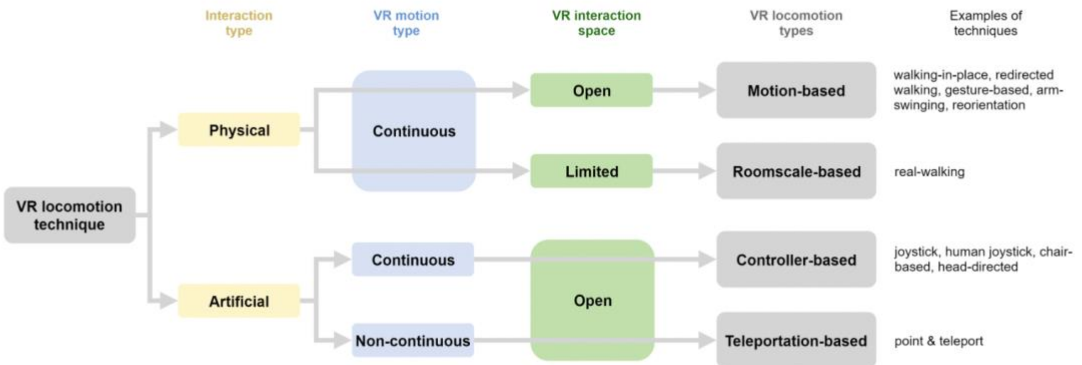

Figure 24. Boletsis' classification of locomotion interaction types (2017, p.12).

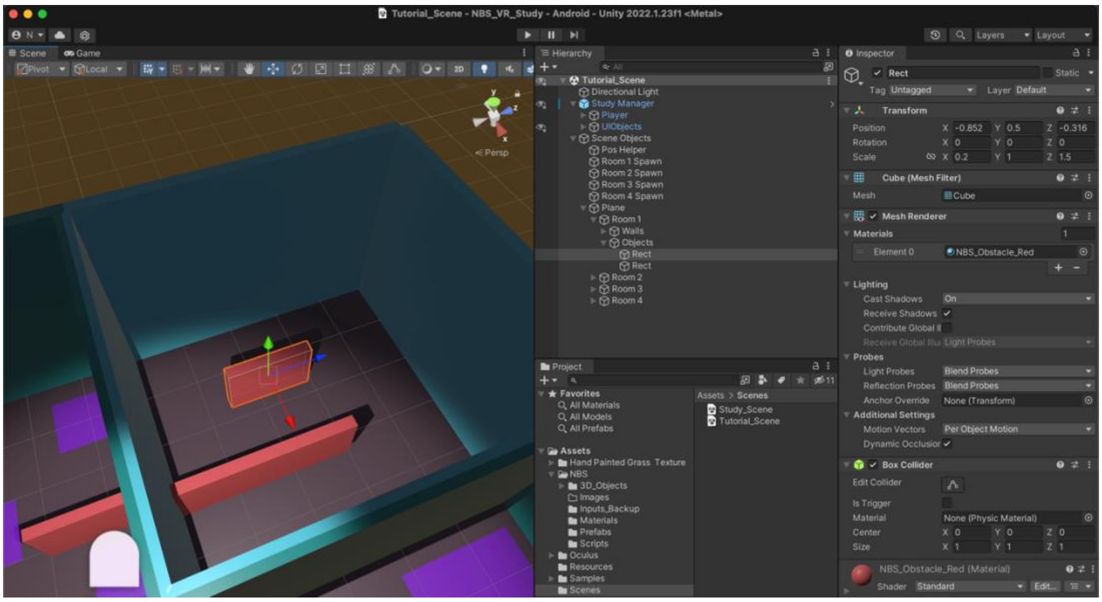

Figure 25. Screenshot of tutorial scene displayed in Unity Editor.

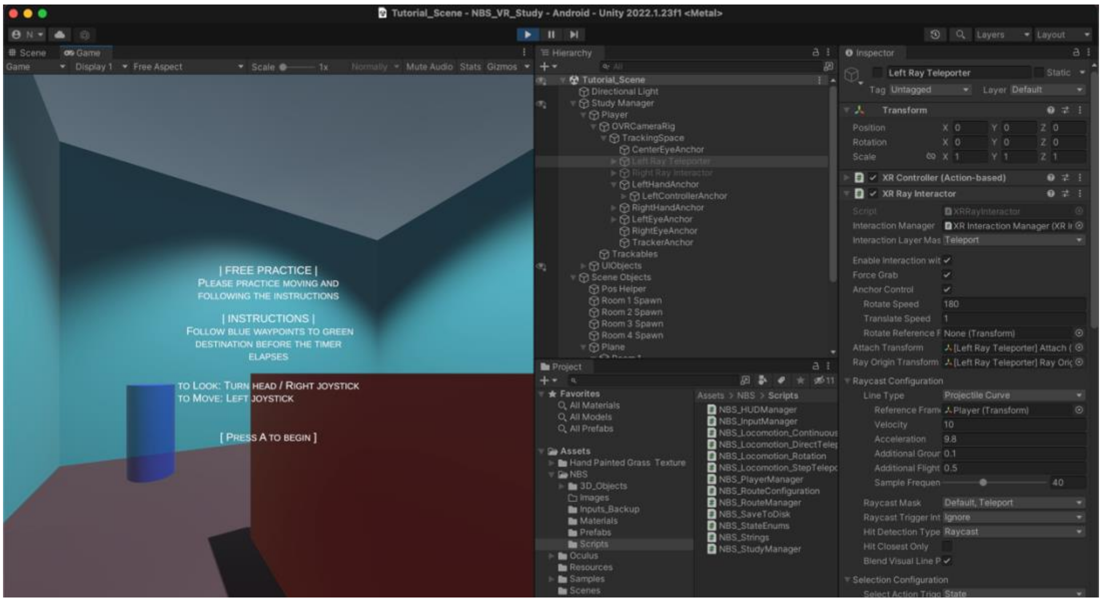

Figure 26. Screenshot of study scene displayed in macOS Unity Game View.

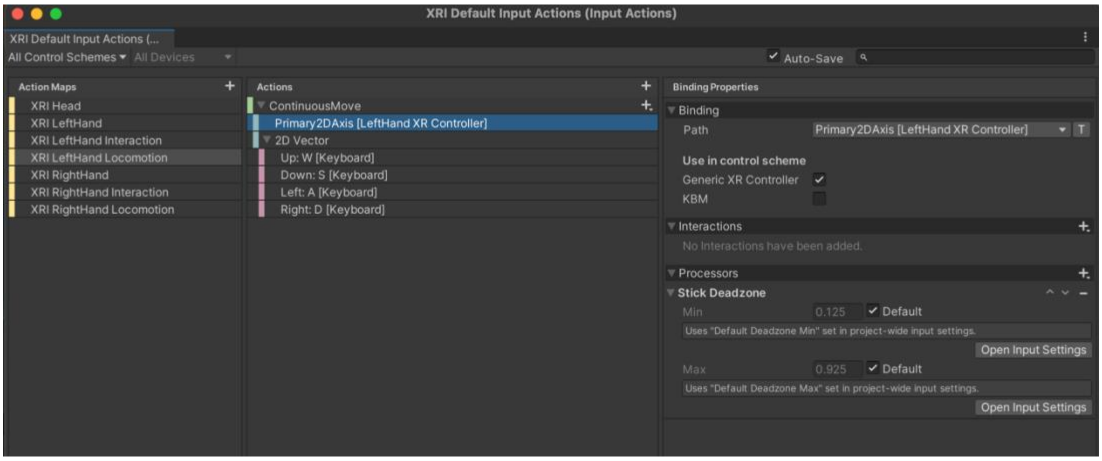

Figure 27. Screenshot of joystick configuration in Unity Input Manager.

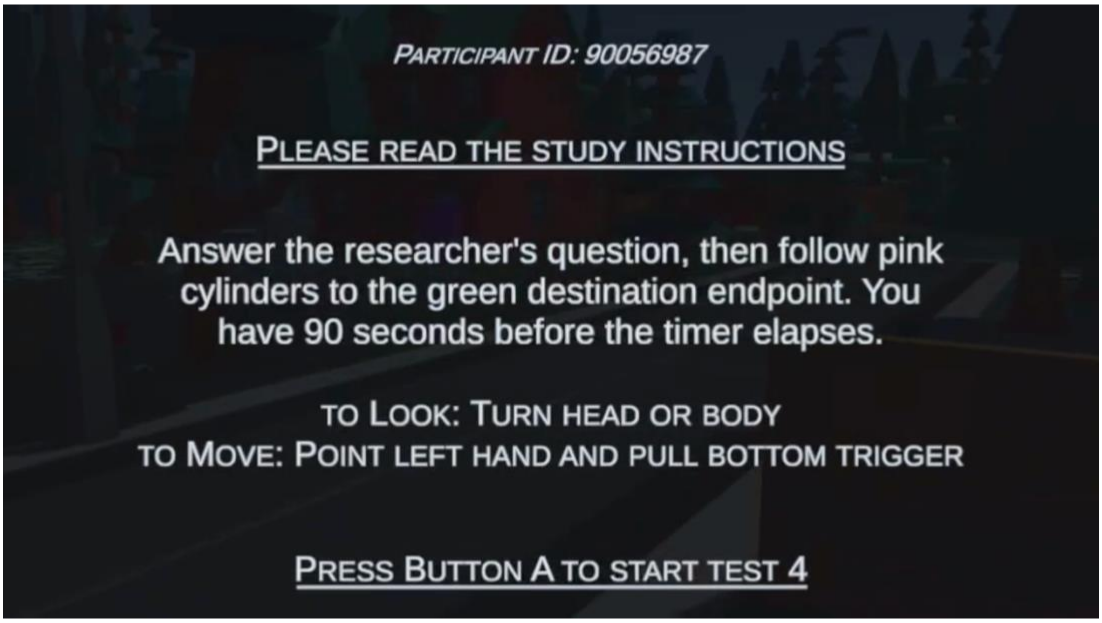

Figure 28. Text displayed at start of the Step Teleport waypoint-enabled route.

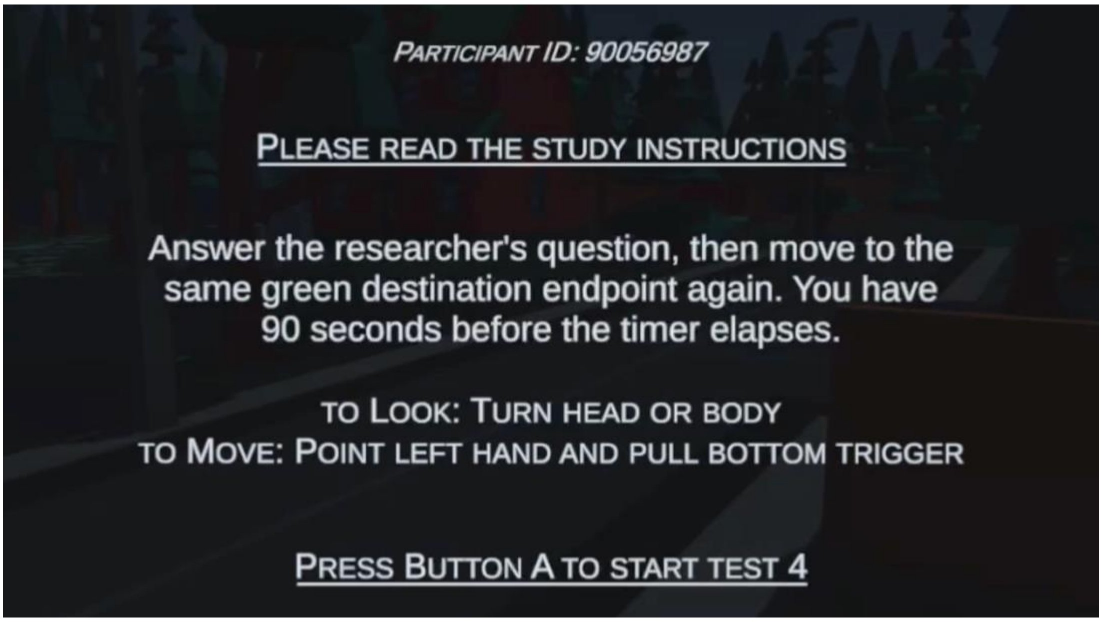

Figure 29. Text displayed at start of the Step Teleport waypoint-disabled route.

Figure 30. Photo of a participant wearing the VR headset in the experiment space.

Figure 31. Parabolic arc with green disc showing teleport destination.

Figure 32. Pink and green discs show current and next step during step teleport.

Appendix P: Additional data

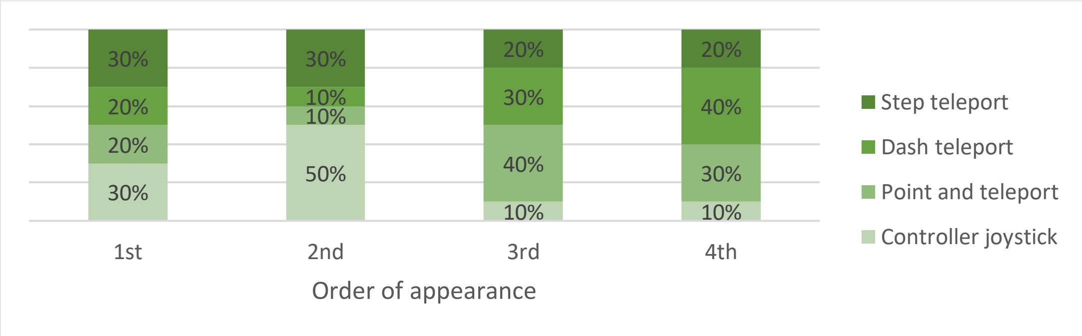

Figure 33. Distribution of appearance order by locomotion method.

Participant strategy	Explore	Memory	Random	No strategy	***N***
Participant %	20%	40%	20%	20%	**10**

Table 15. Approximate categories of how participants approached wayfinding.

Appendix Q: Data management plan

1. Overview

Project title
Comparison of teleportation locomotion methods for efficient wayfinding in virtual reality environments
PI name and department
Note: the most senior University of Bath member of staff involved in the project is the Data Steward for the project.
Student researcher: Nicholas Blake-Steele (ndbs20@bath.ac.uk) Supervisor: Dr Zack Lyons (zl221@bath.ac.uk)
Project description
Virtual reality (VR) study performed using Meta Quest 2 VR headset and controllers. Participants will wayfind and travel along pre-determined routes in VR, randomly shuffled. Each route requires users to travel using a different locomotion method implemented by the study. Each locomotion method can be performed 'in-place', either standing or sitting, and does not require participants to physically move in the real-world. On-screen navigation aids will be provided the first time a route is experienced. When participants experience a route for a second time, navigation aids will be removed and participants must use their memory recall to wayfind successfully. Data will be captured anonymously during the study within the VR study application and using questionnaires (verbal / paper). Data captured by the study application includes (but is not limited to) the actions and position of the participant within the VR environment. Data captured by questionnaires includes whether any locomotion method made the participant experience feelings of motion sickness, along with any opinions on each locomotion method. No identifiable personal data will be captured, stored or analysed at any point during the study. Data will be analysed post-study to assess the wayfinding effectiveness of each locomotion method.

2. Compliance

Information on additional University of Bath policies and UK/EU legislation that may apply to research can be found in our Data Management Plan Compliance Wiki page.

University policy requirements
All projects within the University must comply with the policies provided below. Add any additional relevant policies to the list.
University policy or guidance
University of Bath Research Data Policy
University of Bath Code of Good Practice in Research Integrity
University of Bath Electronic Information Systems Security Policy
University of Bath Intellectual Property Policy
University of Bath Code of Ethics
Legal requirements
n/a

UK Legislation or framework	
n/a	
Contractual requirements	
Check whether your funder has a Data Policy that has specific requirements on data publication or sharing (UKRI funders, other major funders), or whether your research contracts have any confidentiality or non-disclosure clauses with regards to your research data. If you are using third party data check the terms of the licence with regards to data sharing.	
Name of funder	**Data policy URL**
n/a	n/a

3. Gathering data

There is guidance and example wording for this section on the Data Management Plan Guidance Wiki page

Description of the data
No identifiable personal data will be captured, stored or analysed at any point during the study. About the participant: • Their age (in years, banded). There is a choice to enter 'prefer not to say'. • Their stated gender. There is a choice to enter 'prefer not to say'. • Their prior experience using VR / 3D environments (in banded hours per week). Device data: • Position (x,y,z) within VR environment • Head rotation (x,y,z) of user • Distance travelled per route • Distance to next waypoint • Time to complete each route • Time they started the route • Time they reached each waypoint • Time they triggered a locomotion action • Video recording of the VR display (will not capture any facial or body data) Questionnaire data: • If any of the locomotion methods caused feelings of motion sickness. • Participant preference for locomotion methods, including ratings of 'ease of use' and 'ease of understanding' using Likert scale, along with their recall of objects from the VR environment. Participants will be able to add any comments they may have at the end. Format and scale of the data • On-device data is approximate 5,000 rows of data per participant, captured as a .csv

before being loaded into a MySQL database hosted on the researcher's computer for analysis. • Questionnaires are approximate 4 A4 pages per participant, of around 10 questions total. They will be transferred into a digital format in Excel prior to analysis. • Estimated volume is <100 MB of data for the entire study. This can be comfortably stored on the researcher's personal computer and in their University of Bath student cloud drive.
Data collection methods
• By VR headset (during the experiment whilst the participant is using the study's VR headset). • Questionnaires (verbal / paper).
Development of original software
The original software was written using Unity's IDE installed on the researcher's personal computer. The programming language is C#. Several built in libraries and plug-ins published by Unity are utilised to target the specific OS and SDK needed to deploy software onto the Meta Quest 2 hardware. The software does not connect to any networks to function. The software stores all collected data on the hardware device which is retrieved manually from the device by the researcher. The software will only be used for the project. Beyond the initial installation of these libraries and plug-ins there are no ongoing dependencies. Data will be analysed within a MySQL database, hosted on the researcher's personal computer. The query language is MySQL. Beyond the initial installation of this analysis software there are no ongoing dependencies. The data will only be used for this project.

4. Working with data

There is guidance and example wording for this section on the Data Management Plan Guidance Wiki page. There is also guidance on data storage, documentation and sharing with collaborators on our webpages. If you are collecting or processing personal data from **human participants** please ensure that you have read, or are aware of, the guidance regarding the use of encrypted folders for identifiable data.

Short- and medium-term data storage arrangements
All research data will be stored on the University managed storage (X: or H:Drive): ***No***
If No*: provide information on (a) where your data will be stored and (b) file back-up arrangements* As no personally identifiable information is collected, the study's data will be stored in the following locations: • Researcher's personal device inside a MySQL database hosted on the personal device, along with the raw data (as .csv files). • Researcher's University provided storage for raw data (as .csv files). It will be backed up via: • Two external drives owned by the researcher via full disk cloning. • The University of Bath's own back up arrangements for student cloud storage.

Control of access to data and sharing with collaborators
Only the researcher will have access to the raw data.
Documentation that will accompany the data
A readme file will be stored with the .csv data, along with the researcher's own project archive, to ensure the stored data is understandable for any future access.

5. Archiving data

There is guidance and example wording for this section on the Data Management Plan Guidance Wiki page. There is also guidance on archiving data on our webpages.

Selection of data to be retained and deleted at the end of the project
• No identifiable personal data will be captured, stored or analysed at any point during the study. As an MSc project, during the grading period, the raw and aggregated data can be made available to the markers via the University of Bath's Engage Portfolio system. Once the grading period is complete, the raw data will be destroyed. The only remaining data will be any aggregated results data or findings published by the report.
Data preservation strategy and retention period
At the end of the project the raw data will be destroyed and will not be submitted to a research data archive.
Maintenance of original software
• The software source code will be stored in the researcher's personal GitHub repository. As the software is only being used for this project, no ongoing maintenance is required. • Rights to the source code will be owned by the researcher.

6. Sharing data

There is guidance and example wording for this section on the Data Management Plan Guidance Wiki page. There is also guidance on sharing data on our webpages.

Justification for any restrictions on data sharing
As a MSc project, there is no need to share the raw data beyond the project's graders if required.
Arrangements for data sharing
If needed, by specific link via the University of Bath's Engage Portfolio system or via the University of Bath's student cloud storage.

7. Implementation

Review of the Data Management Plan
Initial review: 28 February 2023 Post-experiment review: 30 June 2023 End project review: 30 November 2023