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Rapid, Continuous Movement Between Nodes as an Accessible Virtual Reality Locomotion Technique

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ABSTRACT

The confounding effect of player locomotion on the vestibulo-ocular reflex is one of the principal causes of motion sickness in immersive virtual reality. Continuous motion is particularly problematic for stationary user configurations, and teleportation has become the prevailing approach for providing accessible locomotion. Unfortunately, teleportation can also increase disorientation and reduce a player's sense of presence within a VR environment. This paper presents an alternative locomotion technique designed to preserve accessibility while maintaining feelings of presence. This is a node-based navigation system which allows the player to move between predefined node positions using a rapid, continuous, linear motion. An evaluation was undertaken to compare this locomotion technique with commonly used, teleportation-based and continuous walking approaches. Thirty-six participants took part in a study which examined motion sickness and presence for each technique, while navigating around a virtual house using PlayStation VR. Contrary to intuition, we show that rapid movement speeds reduce players' feelings of motion sickness as compared to continuous movement at normal walking speeds.

Keywords: PlayStation VR; virtual reality; locomotion; motion-sickness; cultural heritage; Edward Jenner; REVEAL.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities;

1 INTRODUCTION

Virtual reality has been the subject of academic study for several decades [1, 2], yet the field is still wrestling with the issue of "cybersickness" and its relationship to locomotion in virtual environments [3]. It is particularly difficult to resolve given the wide range of individual differences observed in both susceptibility and symptoms [4]. Hardware manufacturers are taking the health and safety implications seriously, and have accordingly introduced a 13+ age recommendation for Oculus headsets and 12+ for PlayStation VR. A simple solution to this problem has been to provide locomotion through teleportation, and thus avoid any perceived motion for the user. This significantly reduces the potential for motion sickness and many variations on this approach exist. Nonetheless, they introduce a new problem caused by the disorientating effect of changing position without continuity of motion. While this may avoid motion sickness for many users, it interferes with a user's sense of space [5] and arguably reduces the presence and immersion that VR is celebrated for.

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In this paper, we examine an approach to locomotion which maintains users' continuity of motion by making rapid, continuous movements between nodal waypoints. The motion is made at a fast, linear velocity with instant acceleration and deceleration. Continuous movements made with 'real-world' speeds and accelerations are usually associated with high levels of motion sickness [6]. However, the locomotion approach examined by this research is designed around the observation that continuous movement is comfortable in very short bursts. As continuity of motion is maintained, it is proposed that this technique would be a better alternative to teleportation, providing a locomotion approach with a low susceptibility for motion sickness, while maintaining a user's sense of presence and immersion.

This node-based locomotion technique was subject to empirical evaluation alongside two other approaches, one based on teleportation and one based on continuous free movement. It was hypothesised that the node-based approach would result in lower levels of motion sickness than the free movement approach, and a greater sense of presence than the teleportation approach. Thirty-six users were given multiple navigation tasks to complete using the three locomotion approaches. Questionnaire data was collected alongside process data from the software to examine the comparative effect of this alternative technique on motion sickness, presence and immersion.

2 RELATED WORK

The launch of the Oculus Rift, HTC Vive, Gear VR and PlayStation VR (PSVR) headsets in relatively quick succession has reinvigorated the academic and commercial interest in immersive virtual reality experiences. Twenty-five years has provided many sought-after improvements in visual display systems, but as McCauley and Sharkey predicted in 1992, "The claim that improved visual systems will solve the [cybersickness] problem is simply false. A theoretically perfect visual display system would still provide information about self-motion that conflicts with the lack of vestibular stimulation" [7]. Consequently, it is likely that this will remain a significant problem until configurations can deliver the corresponding physical movements to stimulate the vestibular system in line with the user's visual experience.

Treadmills [8], bicycles [9], wheelchairs [10] and omni-directional platforms [11] have all been shown to help with vestibular stimulation, but consumer solutions have yet to gain traction. More recently, 'roomscale' experiences have been able to relieve vestibular conflict by allowing users the physical space to roam freely in VR, but finite boundaries ultimately just mean the problem is moved further away rather than solved [12]. Free roaming systems also require too much space for average home use, so 'fixed-position' configurations used in a stationary standing or seated position are likely to remain relevant for some time.

Early research into VR locomotion acknowledged that different applications will have extremely different requirements for travel [5]. In the absence of any universal solution, designers must match their designs to the contextual requirements. As such it is relevant to begin by acknowledging the context of our research.

2.1 Context and Contribution

This research was conducted within the context of the REVEAL project which is developing frameworks to facilitate the rapid development of VR-based Educational Environmental Narrative games (EENs) for PlayStation 4. First-person perspective player locomotion is essential to environmental narrative games (e.g. *Dear Esther* and *Gone Home*) which are sometimes even referred to as “walking simulators”. REVEAL aims to develop an inclusive VR locomotion system which is accessible to novice users in museums and school contexts, as well as typical PlayStation users in the home. Therefore, the final locomotion technique must be both simple to use and free from the most extreme effects of motion sickness for all users. Furthermore, to be educationally effective, it must successfully harness the motivational benefits of an immersive learning environment for its educational goals [13].

The application of this research is in no way specific to PlayStation platforms, and would be relevant to any current or future ‘fixed-position’ immersive virtual reality configurations. Our review of the literature was unable to identify any previous studies which had evaluated a node-based approach with rapid movement, such as the one we describe. Furthermore, the inclusion of rapid (but not infinite) movement to reduce motion sickness is counterintuitive and worthy of greater focus within the literature.

2.2 Motion Sickness

Motion sickness incorporates a range of adverse symptoms experienced as a result of real or apparent motion [3]. The term cybersickness is used specifically to describe the effects resulting from apparent motion in VR, and is often associated with symptoms which include headaches, dizziness and nausea. There are a number of theories as to why motion sickness occurs, but Sensory Conflict Theory [14] is the most widely accepted. The vestibular system inside the inner ear, provides the brain with information about the movement and orientation of the head in space. Sensory Conflict Theory suggests that when information from the vestibular system conflicts with the visual perception (such as when a user is standing still but the virtual world is moving) then this creates ‘vection’ which has the potential to induce motion sickness.

Individual susceptibility to cybersickness is known to depend on a range of factors, including age and gender. Children under 12 are traditionally considered most susceptible to motion sickness [14], although this research pre-dates mainstream exposure to videogames. Adults over 50 have been shown to be more susceptible to cybersickness [15] and women are more susceptible than men [16]. Previous exposure also affects symptoms as habituation has been shown to occur over time [17], as does prior exposure to videogames more generally [4].

2.3 Presence

Feelings of presence and immersion lie at the heart of the educational interest in virtual reality [13]. Presence has been defined as, “the subjective experience of being in one place, or environment even when situated in another” [18]. The same authors suggest that experiencing presence is dependent on both involvement (the user’s attentional focus as determined by their level of stimulation and interest) and immersion (the degree to which the user’s senses perceive another environment). This concurs with other perspectives, which see immersion as a direct outcome of the characteristics of the technology which lead to a sense of presence [19]. Because of this, presence is usually examined in terms of enabling characteristics of a technology, rather than differences in individual susceptibility.

Many technological characteristics have been proposed as critical to the creation of immersion, but a recent meta-review [20] suggests that positional tracking, stereoscopic vision, and field of view are the most critical. The traditional focus on image quality and auditory stimuli was not supported by the review. Interestingly a wider field of view is therefore associated with increased immersion, but also increased motion sickness [21].

2.4 Teleportation

Moving a user instantaneously from one position to another is not a recent innovation in virtual locomotion, but early studies found it to be “correlated with user disorientation” [5]. The results of these locomotion studies suggested that teleportation reduces the subject’s spatial awareness, and researchers subsequently went out of their way to avoid it [22, 23]. However, these early studies didn’t examine the effect of different locomotion techniques on motion sickness, and even studies specifically focusing on the accessibility of VR for novice users seemingly overlooked the potential benefits of this simple approach [24].

Teleportation regained traction as a locomotion technique as part of the new wave of headsets [25]; a revival which was fueled by the provision of an arc-based point-and-teleport system in Steam’s (free) VR plugin for Unity and Unreal. First-person games will typically offer teleportation as a default locomotion technique for novice VR users and continuous free motion for the more experienced. More recent studies have now started to focus on the potential of teleportation to reduce motion sickness [26, 27], but the problem of disorientation has not gone away.

A range of teleportation approaches are observable in contemporary research and applications, including arc [28], pointing [26] and node-based interfaces [29], and may sometimes also include an avatar to indicate the player’s final destination [30]. Blink locomotion, in which the user teleports small distances in fixed directions, can also be seen as a subset of the teleportation approach [31]. Teleportation is sometimes instantaneous, but it often includes short fades to soften the transition. In line with “Through the Lens” approaches described in the literature [32], some applications even allow the user to manipulate a physical representation of the destination viewpoint. This is attached to a positional controller, and the user teleports inside it by bringing it to their own viewpoint [33].

Figure 1: One of the finished REVEAL case study applications.

3 The Locomotion Study

The research goals of this study were to implement and evaluate an accessible first-person locomotion technique aimed at novice users, for use in REVEAL. In particular, we were interested in finding an approach with the benefits to motion sickness provided by teleportation, but without the corresponding negative impact on feelings of presence.

A comprehensive review was undertaken of the locomotion techniques employed by existing VR gaming applications [34]. This revealed a single example in which developers had employed rapid continuous movement between closely located nodes instead of teleportation [35]. These movements were particularly fast, lasting only around 100-150ms, but subjectively seemed both to provide continuity of motion and limited motion sickness. This was counter-intuitive, as fast movement speeds have been shown to hasten the onset of motion sickness [36], and the Oculus developer website recommends, “implementing movement speeds near typical human locomotion speeds”, whenever possible [37].

In the same review, rapid rotational speeds were commonly used for turning in the first person. These typically provided continuous turning in segments of 30 degrees over similarly short timespans. Again, within the academic literature, rotational movement is characteristically associated with increased vection and nausea [38], albeit with significantly longer exposure. Nonetheless, our subjective experience from conducting the background review was that free continuous rotation at real-world speeds seemed to be strongly associated with feelings of nausea.

Based on the outcome of our review, we decided to design and implement our own locomotion technique using rapid continuous movement between nodes. The following evaluative study compares our implementation of this technique to established approaches based on teleportation and continuous free movement.

3.1 Prototype System

The three different locomotion techniques were tested within the context of the development of one of REVEAL’s case study applications. This included a VR environment based on a reconstruction of the 18th century family home of Dr. Edward Jenner (the physician credited with the discovery of vaccination). In the prototype, users had the ability to move freely between the first two floors of Jenner’s Georgian mansion, but were unable to leave the building. At this early stage in the wider project’s development, the rooms were mostly empty (a couple of the rooms included tables to provide ‘landmarks’) and were only textured with plain textures. Different colours were used for different rooms, to assist user navigation, and a grid texture was applied on all surfaces to provide movement cues.

The prototype was developed using the PhyreEngine, cross-platform C++ game engine created by Sony Interactive Entertainment’s Research and Development team. It is free and open source to registered PlayStation developers and includes native support for PSVR on the PlayStation 4 console.

The PlayStation VR headset (see figure 2) is comparable to the Oculus, and is similarly designed for use in a sitting or standing position without walking. The headset supports both rotational and positional tracking in 3D space, and all users have access to at least one Dual Shock 4 PlayStation controller (see figure 3). These track position and orientation in 3D space, but are designed for use with two hands. Optional PlayStation Move controllers are also available which can track position and orientation separately for each hand.

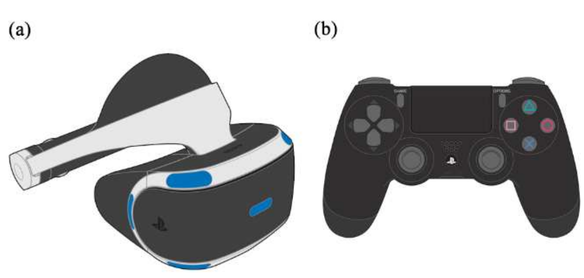

Figure 2: (a) PSVR headset (b) Dual Shock 4 Controller

3.2 Locomotion Mechanics

An identical VR environment and hardware configuration was used for testing each locomotion technique, but several other features were kept consistent between techniques as well. The same segmented, rapid rotation mechanic was used in all three techniques as this was already the most common approach used for ‘accessible’ control schemes in our background review. The potential for inducing motion sickness from free continuous rotation at real-world speeds is quickly obvious to even experienced VR users. This would have the potential to overpower any effects of rapid continuous linear motion that was central to the novelty of a rapid movement approach. It also had the advantage of simplifying the number of different control schemes that participants would have to learn in the study.

Our rotation method turned the player in 30-degree segments using a very fast linear movement, taking 100ms to rotate from one angle to the next with no acceleration or deacceleration. Rotation was always attached to the right analogue stick (rotate left, rotate right) in all three techniques. In each technique movement is activated using any button on the controller, because novice users may not know where the button positions are on a PlayStation controller and cannot see them with the headset on.

3.2.1 Rapid, Continuous Node-Based Locomotion

A *node-based* locomotion technique was iteratively designed and developed, based on the approach used in (parts of) the *Batman: Arkham VR* game studied in the review [34]. A network of navigation nodes was positioned within the virtual environment, and made visible to the user through floating ‘footprint’ icons. All accessible nodes are visible within the environment in a semi-transparent form, but a node becomes opaque and increases in size when the player looks at it (see figure 3). Pressing any button on the controller at this stage will instigate the user’s rapid continuous movement to the selected node.

Node placement was partially dictated by the structure of the house, but typically this put most of them at a real-world equivalent of between 1 and 1.5 metres apart. Movement between nodes was made at an equivalent speed of 5m/s resulting in movements lasting between 150-300ms. This is around double that observed in Batman, but our iterative testing indicated this was appropriate.

3.2.2 Continuous, Free Locomotion

A *free* locomotion technique was implemented to provide continuous motion at normal walking speeds in line with traditional expectations of a first-person movement mechanic outside of VR. This allowed the player to use the left analogue stick to move forward and backwards, as well as side-step left and right. Collision detection and response was implemented including wall-sliding. Movement speed was linear with no acceleration or inertia and was designed to imitate a walking speed of 1.5 m/s.

This locomotion technique was included in the study to provide a baseline for evaluating presence. As a locomotion technique which provides continuous movement within the environment, it should provide maximum opportunity for the player to orientate themselves within the environment, and not interfere with user’s feelings of presence.

3.2.3 Arc-Based Teleport Locomotion

A *teleport* locomotion technique was implemented to provide locomotion without any apparent player movement. An arc-based technique was chosen because of its ubiquity on Oculus and Vive platforms, but with the addition of an avatar model to indicate the final teleportation position (see figure 3). Any button could be held to make the arc appear; head movement was used to position the arc and then releasing the button again would activate the

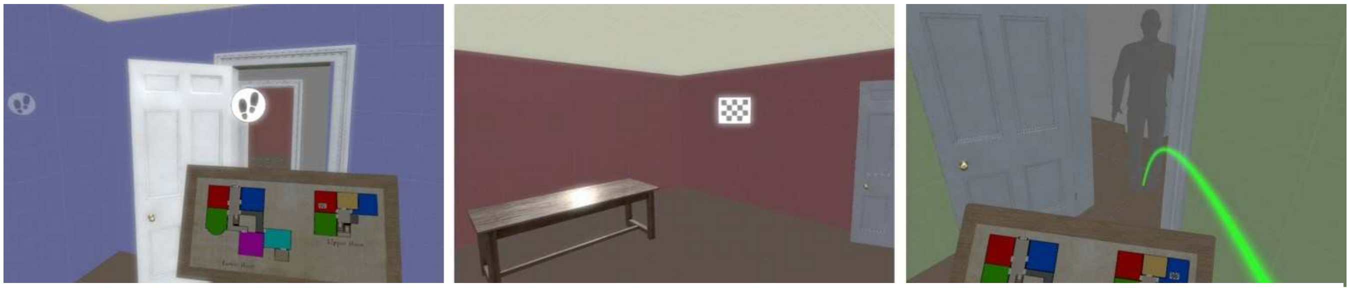

Figure 3: The three locomotion techniques (left) node, (middle) free and (right) teleport

teleportation. The arc included colour coding (red/green) to indicate collisions and a basic avatar representation of the player appeared at the end of the arc, but the ability to rotate the ghost avatar was not included (see figure 3).

This locomotion technique was included in the study to provide a baseline for evaluating motion sickness. As a locomotion technique which provides no apparent movement within the environment, it should minimise any potential vection and nausea.

3.2.4 The Map

All versions of the game included a colour-coded map of Edward Jenner's house, which was attached to the player's (position tracked) controller and could be raised and lowered at will. The map was used to indicate targets with a chequered flag symbol. Initially it also indicated the player's current position, but this was removed after observing that it encouraged users to use the map as an alternative two-dimensional locomotion technique. To aid navigation, the room colours on the map corresponded to the wall colours in the virtual environment and rooms above each other on different floors shared the same colour (see figure 3).

3.3 Experimental Design

Based on the review and justification provided, it was hypothesised that the node-based locomotion approach would result in:

1. Lower levels of motion sickness than free locomotion.
2. Higher levels of presence than teleportation.

The study employed a within-subjects design with the independent variable of 'locomotion' having three levels (node, free and teleport).

3.3.1 Counterbalancing

As each participant in the study would be exposed to all three techniques, order effects were highly likely. Consequently, the software was designed to automatically ensure order balance across participants. Every participant used each of the locomotion techniques in one of six possible order combinations determined by their participant number. This number was randomly assigned and entered into the software at the start of the study. With 36 participants in total, this ensured that all order combinations appeared equally frequently.

3.3.2 Participants

Typical PlayStation users are under 30 and male [39] with a high level of prior experience with videogames. However, the REVEAL project aims to expand the reach of our virtual reality experiences to include older audiences and female gamers. These groups are likely to have less prior experience of both virtual reality and videogames. Research has shown that habituation and prior videogame use can affect motion sickness [17, 40], so we wanted to ensure our locomotion technique will be suitable for both audiences. Participants for the study were recruited from two different populations which characterised these different potential audiences for REVEAL. 18 participants (11 male, 7 female) aged between 20 and 58 (M=37.0, SD=11.2) were recruited from members of administration staff at the university. This first 'novice' video gamers group's mean levels of experience on a self-reported scale of 1-5 were 1.39 for virtual reality and 2.72 for video-games. 18 more participants (17 male, 1 female) aged between 20 and 33 (M=22.7, SD=3.3) were recruited from students studying on the university's video-games degree courses. This second 'expert' video gamers group's mean levels of self-reported experience were 2.78 for virtual reality and 4.83 for video-games on the same scales. Note that while the second group considered themselves experts at videogames, their experience of virtual reality was much lower, in line with what you would expect from the wider population.

3.3.3 Procedure

Most participants undertook the study in a teaching lab set up with PlayStation VR devkits and PSVR headsets. The student group immediately followed the staff group, but were not present in the lab at the same time. Only 15 PSVR headsets were available in the lab on the day, so additional participants were recruited from visitors to an internal showcase event the next day. These participants were subject to the same consent and briefing process, but used the prototype in smaller groups of 1-3 participants.

Participants were given a short briefing on the operation of the study before reading and signing consent forms and filling out a demographic questionnaire. Oral instructions were given on how to put on the headsets, but the prototype then gave participants written instructions on what to do at each stage of the study through the application's user interface.

For each locomotion technique, the participant had to complete six movement tasks which took an average of just over a minute each to complete. Initial tests indicated that three tasks were enough for most users to learn each control technique, and then another three were included to provide a working average. Each task required users to move from their current location to a target room in the house indicated by the chequered flag on the map (and a virtual icon in the room itself). Once they reached the target they were informed that the task was complete, and the icon moved to the next target. Each task involved moving from an upstairs room to a downstairs room or vice versa. The user also had the option to abort a task completely if it was making them feel too nauseous.

Once six tasks had been completed (or aborted) participants were instructed by the game to remove their headset and complete a questionnaire about the locomotion technique they had just been using. Once the questionnaire was complete they repeated the same procedure for the next two locomotion techniques. After completing the third questionnaire about the final locomotion technique, a fourth questionnaire was provided to rank the three techniques in order on different characteristics.

The whole experiment took around 50 minutes to complete with users alternately spending around 10 minutes wearing the PSVR headset (including time to put on the headset, read the instructions and undertake 6 tasks) and then 5 minutes completing the questionnaire for that technique. Users were not encouraged to take additional breaks, and very few wanted to as the use of the headset was already broken up by regular questionnaires. Nonetheless, those that did to were not discouraged or prevented from doing so.

3.3.4 Instruments

Simulator Sickness Questionnaire
The Kennedy Simulator Sickness Questionnaire is a well-established research instrument for measuring the symptoms associated with cybersickness [41]. It was developed with military users of US Navy flight simulators and assesses 16 common symptoms clustered within three categories: oculomotor, disorientation and nausea. Each of the 16 symptoms is ranked on a 4-point scale as "none", "slight", "moderate" or "severe". Each result is encoded as a value from 0-3, resulting in an overall sickness value as well as sub scores for each cluster.

More recent attempts to replicate the original findings has found that a two-group clustering (oculomotor and nausea) is more parsimonious for civilian groups [42]. As our participants are civilians and REVEAL has a particular focus on novice users, the two-group clustering method was applied in this study.

Presence Questionnaire
Witmer and Singer's Presence Questionnaire is a frequently used research instrument for assessing user's experience of presence [18]. It uses 32 questions about the user's experience clustered around four categories of factors: control, sensory, distraction and realism. Each question is answered on a scale from "not at all" to "very" and coded from 1-7 accordingly, resulting in an overall score as well as sub scores for each cluster.

Many of the questions in the Presence Questionnaire were not relevant to the REVEAL prototype at its early stage of development as it didn't include auditory or physical interactions (for example). To reduce questionnaire-fatigue, questions not directly relevant to our prototype were removed, leaving only 8 questions based around control, sensory and distraction factors.

Usability Questionnaire
The usability of the locomotion techniques was assessed using eight different categories of usability based on an approach used for a comparable recent locomotion study [26]. The measures include the user's difficulty in both understanding and operating the technique, whether they felt in control, the effort required to use the technique, how tired it made them feel, how much they enjoyed it, and how overwhelmed and frustrated it made them feel. Each factor was answered on a scale of "not at all" to "very" and coded from 1-5 accordingly.

Ranking Data
The final questionnaire of the study asked the players to rank the three different locomotion techniques according to 'ease of use', 'comfort', 'presence and immersion' and 'motion sickness'. This was included to force participants to make a direct comparison between the three techniques at the end of the study.

In-Game Measures
The prototype software automatically recorded data about all of the user's interactions with the game, including timing, distances travelled and information about whether a player had aborted any trials. These provide objective measures of user performance which can be used to support other observations.

4 RESULTS

4.1.1 Simulator Sickness

One-way repeated measures ANOVAs were performed to compare Simulator Sickness Questionnaire (SSQ) test scores for the three techniques (Node, Free and Teleport). The means and standard deviations are presented in table 2. There was a significant effect of technique on 'nausea' symptoms ($F(2,34)=14.39$, $p<0.0005$, $\eta^2=0.46$) with post-hoc pairwise comparisons[1] revealing differences between Node and Free techniques ($p<0.0005$) and Free and Teleport techniques ($p<0.0005$). There was a significant effect of technique on 'occulo-motor' symptoms ($F(2,34)=6.45$, $p=0.004$, $\eta^2=0.28$) with post-hoc pairwise comparisons[1] revealing differences between Node and Free techniques ($p=0.006$) and Free and Teleport techniques ($p=0.007$). Interaction effects with both groups (expert, novice) and gender (male, female) were subsequently found to be non-significant for either sickness test scores.

Table 1. Simulator Sickness Scores

	Node		Free		Teleport	
	M	SD	M	SD	M	SD
Nausea	0.28	0.36	0.61	0.48	0.26	0.30
Occulo-Motor	0.37	0.42	0.63	0.55	0.40	0.48

4.1.2 Presence

In the modified version of Witmer and Singer's questionnaire [18] participants rated a range of control, sensory and distraction factors on a scale of 1-5. One-way repeated measures ANOVAs were performed to compare presence test scores for the three techniques (Node, Free and Teleport). The means and standard deviations are presented in table 3. There was no significant effect of technique on 'control factors' ($F(2,34)=0.59$, $p=0.56$, $\eta^2=0.03$), 'sensory factors' ($F(2,34)=1.47$, $p=0.25$, $\eta^2=0.08$) or 'distraction factors' ($F(2,34)=1.73$, $p=0.19$, $\eta^2=0.09$).

Table 2. Presence Scores

	Node		Free		Teleport	
	M	SD	M	SD	M	SD
Control Factors	3.56	0.89	3.56	1.00	3.40	0.79
Sensory Factors	3.03	1.16	3.42	1.18	3.06	0.92
Distraction Factors	2.86	0.53	2.62	0.78	2.82	0.77

4.1.3 Usability

One-way repeated measures ANOVAs were performed to compare usability test scores (1-5) for the three techniques (Node, Free and Teleport). The means and standard deviations are presented in table 4. There was a significant effect of technique on 'difficulty of understanding' ($F(2,34)=5.67$, $p=0.008$, $\eta^2=0.25$) with post-hoc pairwise comparisons[1] only revealing differences between Teleport and Free techniques ($p=0.005$). There was a significant effect of technique on 'difficulty of operation' ($F(2,34)=19.74$, $p<0.0005$, $\eta^2=0.54$) with post-hoc pairwise comparisons[1] revealing differences between Node and Teleport techniques ($p=0.32$) and the Free and Teleport techniques ($p<0.0005$). There was a significant effect of technique on 'effort required' ($F(2,34)=5.34$, $p=0.01$, $\eta^2=0.24$) with post-hoc pairwise comparisons[1] revealing differences between Free and Node techniques ($p=0.01$). There was a significant effect of technique on 'tiredness' ($F(2,34)=5.91$, $p=0.006$, $\eta^2=0.26$) with post-hoc pairwise comparisons[1] revealing differences between Node and Free techniques ($p=0.005$). There was a significant effect

[1] Bonferroni corrected.

of technique on 'feeling overwhelmed' ($F(2,34)=8.64$, $p=0.001$, $\eta^2=0.34$) with post-hoc pairwise comparisons[1] revealing differences between Node and Free techniques ($p<0.0005$) and the Teleport and Free techniques ($p=0.006$). There was no significant effect of technique on 'frustration' ($F(2,34)=0.91$, $p=0.41$, $\eta^2=0.05$), 'feeling in control' ($F(2,34)=1.86$, $p=0.17$, $\eta^2=0.10$), or 'enjoyment' ($F(2,34)=1.71$, $p=0.20$, $\eta^2=0.09$).

Table 3. Usability Scores

	Node		Free		Teleport	
	M	SD	M	SD	M	SD
Difficulty in Understanding	2.17	1.32	1.64	0.99	2.47	1.23
Difficulty in Operation	1.97	0.97	1.53	0.77	2.67	1.12
In Control	3.53	0.21	4.00	0.18	3.83	0.16
Required Effort	2.33	1.29	2.14	1.02	2.89	1.24
Tiredness	1.67	0.99	2.42	1.34	1.86	1.07
Enjoyment	3.28	0.21	2.83	0.24	3.31	0.18
Overwhelming	1.89	0.94	2.86	1.40	2.06	0.86
Frustration	2.03	1.158	2.06	1.33	2.39	1.13

4.1.4 Usability Interaction Effects

The usability measures above were subsequently examined for interaction effects with group (expert, novice) and gender (male, female). An interaction effect was found with group for 'feeling in control', and repeated measures ANOVAs by group revealed a significant effect of technique for the expert group only. Post-hoc pairwise comparisons[1] revealed differences between Node and Free techniques only ($p=0.005$). A second interaction effect was found with group for 'tiredness', and repeated measures ANOVAs by group revealed a significant effect of technique for the expert group only. Post-hoc pairwise comparisons[1] revealed differences both between Node and Free techniques ($p=0.005$) and the Node and Arc techniques ($p=0.024$). No other interactions with group or gender were found for the usability measures.

Table 4. Ranking Scores

	Node		Free		Teleport	
	M	SD	M	SD	M	SD
Ease of Use	2.17	0.81	2.28	0.78	1.56	0.69
Comfort	2.36	0.64	1.56	0.77	2.08	0.84
Presence& Immersion	1.67	0.72	2.47	0.77	1.86	0.76
Motion Sickness	1.44	0.50	2.75	0.60	1.86	0.71

4.1.5 Ranking Data

Ranking positions for 'ease of use', 'comfort', 'presence and immersion' and 'motion sickness' were converted to point scores (3=first, 2=second, 1=third) and a series of Friedman tests were performed to compare scores for the three techniques (Node, Free and Teleport). The means and standard deviations are presented in table 4. There was a significant effect of technique for 'ease of use' ($\chi^2(2,n=36)=10.89$, $p=0.004$) with post-hoc Wilcoxon Signed Rank Tests[1] revealing a difference between the Teleport and Free techniques ($Z=-3.11$, $p=0.002$) and the Teleport and Node techniques ($Z=-2.52$, $p=0.12$). There was a significant effect of technique for 'comfort' ($\chi^2(2,n=36)=12.06$, $p=0.002$) with post-hoc Wilcoxon Signed Rank Tests[1] only revealing a difference between the Free and Node techniques ($Z=-3.31$, $p=0.001$). There was a significant effect of technique for 'presence and immersion' ($\chi^2(2,n=36)=12.72$, $p=0.002$) with post-hoc Wilcoxon Signed Rank Tests[1] only revealing a difference between the Teleport and Free techniques ($Z=-2.48$, $p=0.013$) and the Free and Node techniques ($Z=-3.10$, $p=0.002$). There was a significant effect of technique for 'motion sickness' ($\chi^2(2,n=36)=32.72$, $p<0.0005$) with post-hoc Wilcoxon Signed Rank Tests[1] revealing a difference between the Teleport and Free techniques ($Z=-3.50$, $p<0.0005$) and the Free and Node techniques ($Z=-4.91$, $p<0.0005$).

4.1.6 In-Game Measures

Data was recorded for all 6 trials for each technique, but the first three trials were treated as training in each case and not included in the analysis. Three dimensional plots of the participant's movements are shown in figure 4.

One-way repeated measures ANOVAs were performed to compare 'average time' and 'average distance' for the last three tasks using each of the three techniques (Node, Free and Teleport). The means and standard deviations are presented in table 5. There was a significant effect of technique on 'average time' ($F(2,34)=6.37$, $p=0.005$, $\eta^2=0.29$) with post-hoc pairwise comparisons[1] revealing differences between Node and Free techniques ($p=0.045$), the Node and Teleport techniques ($p=0.006$) and the Free and Teleport techniques ($p=0.045$). There was no significant effect of technique on 'average distance' ($F(2,34)=2.05$, $p=0.15$, $\eta^2=0.12$). Interaction effects with both group (students, staff) and gender (male, female) were subsequently found to be non-significant for both 'average time' and 'average distance'.

A (non-parametric) Friedman test was performed to compare 'number of aborted trials' for the three techniques (Node, Free and Teleport). This revealed a significant effect ($\chi^2(2,n=36)=12.67$, $p=0.002$) with post-hoc Wilcoxon Signed Rank Tests[1] revealing a difference between the Free and Teleport techniques ($Z=-2.38$, $p=0.017$) and the Free and Node techniques ($Z=-2.54$, $p=0.011$).

Table 5. Game measures for the last three tasks

	Node		Free		Teleport	
	M	SD	M	SD	M	SD
Average Time	28.24	13.52	34.37	17.26	49.39	44.00
Average Distance	0.37	0.42	0.63	0.55	0.40	0.48
Aborted Trials	0.08	0.50	0.75	1.54	0.11	0.53

5 Discussion

The results provide evidence to support our first hypothesis that rapid, continuous movement between nodes produces lower levels of motion sickness than free locomotion. Both oculo-motor and nausea clusterings were lower for the *node* technique than the *free* technique and ranking data placed *node* below *free* in terms of causing motion sickness. Fewer aborted trials were also observed for the *node* technique than the *free* technique and the *free* technique made participants feel more overwhelmed. Whilst this may be considered a surprising result given the rapid movements involved, this was all also true for the *teleport* technique, so we come to consider our second hypothesis.

The results do not provide evidence to support our hypothesis that node-based locomotion produces greater feelings of presence than teleportation. No differences were found between the three conditions in any of the presence clusterings. However, we would have expected users to report greater feelings of presence in the *free* condition than the *teleport* condition, so this may indicate problems with sensitivity of the modified instrument. We only included questions which were relevant to the REVEAL prototype at its early stage of development, but this ignored a range of factors (such as audio and physical interactions) considered relevant to creating a feeling of presence. It could be argued that our prototype was simply not rich enough to accurately measure presence at this stage. However, it's notable that this study was the first time many participants had used virtual reality, and the experience may have simply been too overwhelming to discern subtle differences in feelings of presence (a little like asking someone who has never seen a wheel whether they feel more relaxed in a car or a train).

The ranking data did show higher scores for 'presence and immersion' for the *free* technique, but the *free* technique also made participants feel more overwhelmed than both the other two techniques, and more tired than the *node* technique. Both measures of simulator sickness were also highest for the *free* technique. All this goes some way to explaining why the number of aborted trials was also highest for the *free* technique. Interestingly, the *free* technique made the expert group feel more in control than the *node* technique, but not the novice group. This last finding may point towards the students' much greater level of previous experience with videogames. However, given the apparent differences between the two groups in this particular respect, it was surprising that more interaction effects with group weren't found. Overall the lack of group differences supports the premise that the node technique is appropriate for a wide range of users.

Our analysis of usability found that the *teleport* technique was more difficult to understand and required more effort to use than the *free* technique, and was the most difficult to operate. Ranking scores for 'ease of use' were also lowest for the *teleport* technique. Participants reported issues controlling the arc in confined spaces. Graphical visualisation of all the locomotion paths logged for the Arc technique revealed star-like patterns around many of the task target points. This revealed how participants were repeatedly overshooting the targets and having to turn around and try again multiple times. Several participants reported that pointing their head at their feet (to achieve small movements) was difficult and uncomfortable.

6 NODE PLACEMENT

Our analysis of the in-game measures found that the average time taken was lowest for the *node* technique followed by the *free* and then the *teleport*. While this is hardly a fair comparison, it does demonstrate the efficiency of the *node* approach compared to the others. However, these nodes needed to be individually placed by hand within the scene. The REVEAL framework supports the placement of nodes within a 3D environment via a PhyreEngine editor plugin which allows the nodes to be visualised as a series of connected volumes (see figure 4). The manual placing of this kind of scene-based data is common in games, and it is only a minor part of the overall data added manually to REVEAL's scenes to create an environmental narrative game. Nonetheless an automated approach may be more appropriate for other contexts [43].

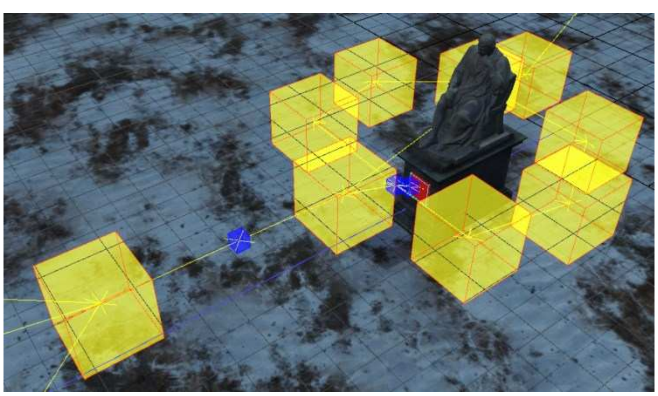

Figure 4: Node placement using the REVEAL framework

Node-based approaches have a number of additional practical advantages over free movement. They significantly reduce the collision detection requirements for a virtual environment, as they limit the positions and transitions that a user can occupy. Collision detection is a processor-intensive process which can be a significant source of bugs, so this could be an important advantage for applications with limited development budgets. This same limitation also provides the game designer with an additional means of guiding and controlling the player's attention through the game, which is often helpful in the context of games.

7 FUTURE WORK

A subsequent study could attempt to address the limitations of this work in a number of ways. A richer virtual environment used alongside the complete presence questionnaire may help to discern differences in users' feelings of presence. The reliability of a validated instrument may simply not hold for a partial version of the questionnaire. However, it could be that more objective measures of presence are required. Tests of the user's spatial recollection of the environment could prove pertinent, either outside of the game, or by asking the user to recall and re-locate items they saw in other parts of the house.

The *teleport* mechanic used in this study would be improved through the use of a controller to position the movement arc, rather than the headset. Although the headset was intuitive and hypothetically provided greater precision, it does not have the range of movement required for controlled nearby locomotion.

8 CONCLUSIONS

This study has evaluated an untested virtual reality locomotion technique based on rapid, continuous movement between nodes and shown that it is appropriate for novice users. Furthermore, our data suggests that rapid movement in very short bursts (<300ms) doesn't produce any greater feelings of motion sickness than teleportation. This is not an intuitive finding and one which deserves a greater level of focus within the literature.

While this study was unable to demonstrate any benefits over teleportation in terms of user's feeling of presence, there are additional practical benefits to a node-based approach for collision detection and game design. On the basis of our work we would recommend a node-based approach to projects aimed novice users and/or when development budgets are limited.

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