Technical Report, University of Nicosia

Steering versus Teleport Locomotion for Head Mounted Displays

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ABSTRACT

We compared the ability to navigate from one point to another in a virtual environment using Gaze-Directed, Pointing and Teleport locomotion. Participant's start position and destination was shown to them on a map at the beginning of each trial. Participants also had to deviate from their route to collect 'Pokémon' tokens: testing their spatial updating ability. Subjective reports base on a standard simulator sickness questionnaire revealed that the two steering methods resulted in increased levels of motion sickness as compared to teleporting. In terms of performance, teleporting resulted in faster traversal times, as expected, but surprisingly was just as effective in allowing users to complete their journey, showing that user disorientation was not an issue. The only failing of the teleport method was that it increased the likelihood of missing collectable tokens en route. These results suggest that restricted variants of the teleport method should be explored for use in commercialized VR applications in which real walking is not necessary.

Keywords: virtual reality; navigation; spatial updating; locomotion; immersive gaming; motion control; steering.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities H.5.2 [Information Interfaces and Presentation]: Interfaces—Input devices and strategies I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality;

1 INTRODUCTION

Hardware requirements for a Virtual Reality (VR) system include sensors for tracking of users head and body, a display for sensory feedback, and a means of user interaction for grabbing objects and for initiating locomotion through the depicted 3D virtual environment. VR systems come in many varieties depending on how they implement these requirements. For example, the VR CAVE system situates the user in a 'room' consisting of back-projected screens and tracking of head movements is used to update their view of the virtual world [1]. In head-mounted display (HMD) systems the user wears the visual display on their head and the position and orientation of the user in physical space are tracked by sensors and coupled to a virtual camera in the scene. This close coupling between movements of the user's body and concomitant sensory feedback contributes to the impression of immersion within the depicted virtual environment and immediately the user may forget their physical surroundings and feel that they are situated in the virtual world instead [2].

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A key component of VR interaction is that of locomotion, or the control of movement through the virtual world. Tracking of user's bodies means that, to a limited extent, they can perform real walking through a virtual scene. However, virtual worlds, as the name implies, may be vast and require the traversal of large distances to be experienced or to complete a given task. VR systems on the other hand are limited by the extent of the physical space in which the simulation occurs. In the CAVE, for example, these are the distances between the projection walls. For HMDs, the restriction is the extent of the tracking area and the size of the physical space in which the user is contained. The challenges for methods of locomotion therefore are that they should allow the traversal of distances larger than the physical space of the system while being comfortable, relatively effortless and without interfering with the objectives of the task. This latter requirement relates in part to the locomotion method being able to support the same spatial awareness that we would expect in the real world.

In order to preserve and exploit the naturalness of real walking researchers have devised numerous imaginative devices and techniques that allow free walking while maintaining the user's position within an enclosed space. Such methods include treadmills, which allow walking on a moveable surface [3,25,26], and walking in place [23,39] in which walking is 'mimed' and interpreted by computer to determine pace and direction. This emphasis on real walking is based on evidence from several studies which suggest that only through real walking can a user maintain spatial updating and therefore spatial awareness [27]. However, other studies indicate that the important component of real walking, as far as spatial awareness is concerned, is the sense of physical rotation of the body, whereas a sense of translation is not as important [19]. Real walking can also cause fatigue, especially when large distances must be traversed during a simulation. Furthermore, recent advances in VR displays have resulted in dramatic reductions in the cost of VR systems making them affordable for home and classroom use. This has in turn resulted in a flurry of development activity aimed at the commercialisation of VR for home and educational use. If VR is to be commercialised, then hardware requirements should be kept to a minimum. Real walking devices are costly and fewer users may be prepared to play immersive games for an extended period if this involves excessive physical activity. We therefore also need to explore other methods of locomotion that are cheap, expedient, do not induce fatigue, are enjoyable to use and which still maintain reasonable spatial awareness.

The locomotion metaphor most often used in traditional computer games is that of *Gaze-Directed* simulated walking. This belongs to a class of locomotion techniques known as steering, in which smooth motion is achieved using a joystick or button presses on a keyboard. The user orients their 'gaze' (heading) and makes translations only in this direction. It is expedient and easy to use and therefore was adopted by non-immersive desktop VR systems [5,8]. Because the view into the virtual world is relatively small it makes sense to change heading and move only in that direction: movements in directions other than the gaze direction may cause collisions with objects in the scene. The Gaze-Directed method has also been incorporated into immersive systems. However, immersive systems use sensors to track the orientation of the users' head. They can therefore use head and body rotations to change gaze direction directly instead of using a controller, which is only required for translation. The ability to make independent head movements while walking provides an alternative travel method to Gaze-Directed locomotion. This is facilitated by P*ointing*, another steering method, in which the user indicates their direction of travel by pointing with a tracked hand-held device while being free to look wherever they like [5,8]. Pointing is more akin to real world locomotion. A recent extension of the Pointing method which has found favour with developers is the *Teleport* method. Teleporting dispenses with smooth motion and instead the user points to some location in the environment using a tracked controller and is instantly transported to that location. Teleporting is believed to reduce the likelihood of motion sickness (cybersickness) in VR. All these methods are easily implemented in commercial VR architectures using minimal hardware and users are only required to stand and rotate their bodies in the direction they wish to travel, thereby reducing the possibility of fatigue.

In this paper, we compare these latter three methods with respect to navigation and spatial awareness in VR. Our comparisons are made based on objective performance variables but we also place strong emphasis on the degree to which each method induces cybersickness. Any visually perceived movement in VR, without concomitant sensory feedback from the body can result in motion induced nausea. We therefore also compare these methods by the results of a standard cybersickness questionnaire. Before we describe the experiment we briefly review some of the background research concerning spatial awareness issues in virtual environments and some of the locomotion methods devised to enable VR navigation.

2 BACKGROUND

2.1 Spatial Cognition in VR

Virtual worlds are built to be navigated and navigation is a combination of two components, wayfinding and locomotion [6,7]. The process of wayfinding encompasses the cognitive skills that allow people to orient themselves in 3D space and to get from one place to another. Darken [46] categorised three types of wayfinding behaviours

- Naïve search
- Primed search
- Exploration

VR applications usually involve at least one of these behaviours. Thorndyke [9] identified three types of knowledge that people may gain and use from such behaviour: survey knowledge, procedural knowledge and landmark knowledge. Survey knowledge is geocentric in nature and develops over a prolonged period of familiarization with an environment. Procedural knowledge characterizes a given space by memorized egocentric sequences of actions that must be followed to get from one place to another. Finally, landmark knowledge records distinctive objects or buildings that have a particular location in space in relation to other objects. It can be used in conjunction with procedural knowledge to aid navigation.

Survey-type knowledge may also be acquired directly from a map [10, 11]. This process is beneficial in that it reduces the time required to familiarise oneself with an environment. However, distance estimation and orientation judgements have been found to be inferior in individuals who have gained their spatial knowledge in this manner [10, 12]. Also, survey type knowledge derived only from maps is still somewhat egocentric in nature, being dependent on the orientation of the user in relation to the map used to learn the environment [14]. This orientation-dependency was studied by [13] in terms of map design. They found that in order to facilitate efficient map use, the map must be congruent with the environment it represents. This is illustrated in the forward-up equivalence principle, which states that the upward direction of a map must correspond with what is in front of the viewer for them to make efficient use of it and proceed from where they are to where they wish to go. If the user's position, as specified on a map, is not congruent with the environment in front of them then cognitive effort (in the form of imagined rotations) is required to navigate to their destination. This is something that people find difficult to do [44, 12] and we make use of this in our experiment described below.

Locomotion methods should not impede normal cognitive function. Initial experiments that studied navigation in VR found that it was more difficult than in equivalent real world scenarios, e.g. [14, 15]. It was found that subjects readily become disorientated and lost their way. This was initially attributed to impoverished visual cues in VR compared to the real-world [16]. Other research suggested that visual fidelity is not entirely the problem. Instead, it has been argued that the lack of proprioceptive and vestibular feedback during locomotion makes navigation in virtual environments more difficult [17, 18, 19]. Proprioceptive feedback informs us of the position and orientation of our limbs and head. Vestibular feedback gives us a sense of linear acceleration (translation) and rotation in space. It has been shown that observers are capable of reconstructing complex displacements of the body using just proprioceptive and vestibular inputs alone, e.g. [45, 46]. It may therefore be that such non-visual cues contribute to successful navigation and when they are lacking, as in some VR systems, this leads to diminished spatial cognitive performance. According to [20] the main ability that is lacking in VR systems is spatial updating. Spatial updating is the dynamic process of adjustment of a cognitive map based on one's movements within an environment. For example, if we started from a given point in space and walk directly ahead, make a turn and walk directly head for some distance, we would be able to pin-point our original start position. Performing this as an experiment with objective measurement of errors in pin-pointing one's original start point [20] found that only with real walking did subjects perform the test relatively accurately. When this procedure is based on imagined translation and rotation or, more relevant, when it is performed in a HMD with simulated walking and rotation, there are systematic errors suggesting lack of path integration, or spatial updating. These results suggest that spatial updating is sub-served by non-visual proprioceptive and vestibular cues. This in turn has important connotations for the design of VR motion control as we shall see in the next section.

2.2 Types of Motion Control Methods

The previous discussion suggests the importance of allowing real body movements in VR systems designed for tasks requiring spatial cognition. This is not to say that spatial awareness is completely lacking when movement through virtual space is implied solely by visual cues. This is evidenced by the many people who play and enjoy 3D computer games using only a mouse, keyboard and joystick. However, it does appear that spatial awareness may be reduced and many published 3D adventure games provide aides such as maps to show the player where they are. Locomotion in VR has been influenced by the techniques used in computer games. However, the ability to track the position and orientation of the user's head, hands and body has also inspired many novel and pioneering techniques that go well beyond the abstract steering methods used in computer games (see [37] for review). Locomotion techniques may be classified as follows:

- Physical Walking or miming. These methods involve actual walking, walking in place with the aid of a treadmill or redirected walking. In other methods the user 'mimes' the actions necessary to control their movements through space.
- Steering. The continuous movement and rotation in space using a movement metaphor. Can be either gaze-directed or pointing.
- Target-based locomotion. The destination is first chosen by the user using a pointer and they are teleported to that position instantaneously.

If the user is wearing a HMD with positional tracking, then natural walking can be implemented without a locomotion interface. Such a system however is limited by the area across which a user can be tracked reliably, the length of the cables and the size of the physical space surrounding the user. Current technology for general usage (e.g. in the home) supports head-tracking, and therefore walking, within a space of 4.5 x 4.5 meters (e.g. HTC Vive[11]). For exploration of large spaces in VR and for immersive gaming, physical walking appears impractical, although developments of the Immersive Deck[22] with wireless tracking through whole buildings looks promising.

To counteract these limitations of real walking some researchers have proposed two different types of solution that preserves proprioceptive cues. The first is redirected walking, e.g. [40, 38], in which the virtual world is imperceptibly rotated around the user's head as they explore a potentially infinite environment whereas in reality they are walking in a curved path within a limited tracking area. The second is omni-directional treadmills [3, 25, 26] in which multiple rollers are used to detected the movement and direction of the user's feet during walking in order to update their view of the scene.

In miming-based methods the user makes gestures of walking while standing in place. Their movements are tracked by sensors and interpreted to update their view of the scene. For example, [23] used a neural network classifier to interpret body movements while users mimed walking. A similar method was employed by [39] and [24] made comparisons between different immersive travel methods, including walk-in-place, in interfaces designed especially for children.

All these methods share a common problem: performing walking movements for long periods of time causes fatigue. If VR systems are to be commercialised, then unnecessary movement requirements should be kept to a minimum. The other alternatives for locomotion are the steering and target selection methods. There are two main types of steering-based methods: gaze-directed and pointing [5, 28]. With gaze-directed locomotion the user can rotate their head and/or body and start moving in the direction in which they are looking. The pointing method is similar but the direction of translation is independent of the direction of gaze: the user is free to look around and the direction of locomotion is chosen by pointing in a particular direction using an orientation tracked controller.

While these two methods reduce the possibility of fatigue they also reduce some of the cues that aid spatial awareness; although the user can make rotational changes there is no sense of translation. There is also an increased risk of cybersickness. Cybersickness has always been a problem for VR and consists of symptoms including nausea, disorientation, headaches, increased sweating and eye strain [33, 34, 35]. There is still some debate about the causes of cybersickness and the means of eliminating it [47] but cybersickness is related to motion sickness experienced by travellers in vehicles such as cars and trains. The compelling experience of self-motion while the user is actually at rest, also called vection, is believed to underlie cybersickness.

Target-based locomotion eliminates the possibility of vection by removing the smooth motion involved in steering methods. For instance, Teleporting allows the user to select their destination and they are instantly transported to that point at the click of a button. The destination is usually chosen as the intersection between the ground and a projected beam emanating from a tracked controller. Because there is no vection in this case it is hypothesized that there would be no associated cybersickness. However, this method may suffer from the same problems as the steering methods in as much as it does not provide proprioceptive and vestibular inputs. Moreover, there are no visual flow cues either which might result in greater chances of users becoming disorientated in VR. We explicitly test this possibility in our experiment described below. First, we consider previous comparative experiments relating to locomotion in VR.

2.3 Comparisons of Motion Control Methods

The influence of real walking on spatial cognition was highlighted by a series of experiments by [18, 27] in which participants performed a search task in a room-sized virtual environment. The experiments compared gaze-directed travel using either a desktop display, a HMD with joystick, or physical walking using a HMD. They found that only in real walking with HMD was performance comparable to the same task conducted in the real world. The other locomotion methods resulted in more errors. The conditions employed in these experiments differed in the amount of body-based information provided: In the first scenario (desktop display) no body-based information was provided, whereas gaze-directed travel with HMD provided rotational body information only and, finally, the free walking condition provided both rotational and translational body information. This and other studies, e.g. [29,49], provide evidence that there are cognitive benefits attributable to physical walking in a virtual environment when the application involves spatial awareness and spatial problem solving.

Addressing these issues, [19] performed the same experiment as in [18, 27] but requiring participants to wear a HMD in all conditions. Body-based information was none, rotation only or rotation and translation (real walking). They found that although walking with a HMD produced the best results, rotation only performance was comparable to real walking and better than having no body-based information at all. This suggests that allowing a user to perform physical rotations while inside a virtual environment is more beneficial than allowing them to translate by real walking.

The results of [19] suggest that a combination of head-tracked orientation changes with translation controlled using a hand-held device may be the most versatile means of locomotion which still supports spatial awareness. This, for example, can be accomplished using a steering or target-based method. The pointing, Gaze-Directed and Teleport methods have previously been subjected to comparative evaluations. Asking users to walk along a line to a target object [21] found that the Gaze-Directed method produced slightly better performance in terms of speed and accuracy. However, this difference was not statistically significant. In another task, in which participants had to move to a point relative to an object, they found that the Pointing method produced better performance. These experiments utilized a sparse virtual environment consisting of rectangular spaces defined only by concentric lines. Each method appeared to have its advantages and disadvantages. The authors noted that more significant differences between the two motion techniques might be found with more complex navigation tasks and in richer 3D contexts. Such a scenario for example might involve someone steering themselves along a city street with all the visual cues that we normally experience in the real world. Using more realistic scenes and a realistic wayfinding task [48] found a significantly better performance in terms of speed and accuracy for a Pointing method as compared to a Gaze-Directed in a CAVE-like display.

Finally, in relation to the Teleport method, [21, 22] compared teleporting with the two steering methods with respect to spatial awareness. They reported that the Teleport method resulted in participants becoming disorientated after each transition. This may be attributed to a lack of spatial updating ability as user's displacement to the target location is instantaneous whereas in the real-world movements are gradual allowing us integrate distance travelled. This is pity because the method is a fast and accurate way of moving around. Furthermore, there may be the added advantage of reducing or

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[1] https://www.vive.com/eu/

[2] https://www.illusion-walk.com/

Figure 1. Schematic diagrams of the 3 ‘desert cities’ used in the experiment showing the start locations (green) and destinations (red). These are *not* the maps seen at the beginning of each trial. The maps used in the experiment (Fig. 3) showed only the region of the city that included the start and end locations and were generated from a ‘live’ orthographic projection camera situated above the city.

eliminating cybersickness. We were therefore motivated to perform a rigorous comparison between teleportation and the two steering methods is a realistic wayfinding task to see if disorientation and cybersickness is an issue.

2.4 Quantifying Cybersickness

Cybersickness is related to visually implied motion through a virtual scene. This motion in turn is determined by the method of locomotion. It is therefore necessary to include a measure of cybersickness in a comparison of motion control. Quantifying the degree if cybersickness is usually done by a questionnaire that probes associated symptoms. The most commonly used questionnaire was devised by [34] who used a series of factor analyses to identify sixteen symptoms. When using a questionnaire, each item is rated with the scale of none, slight, moderate or severe. The 16 symptoms were found to cluster into three categories, oculomotor, disorientation and nausea. The oculomotor cluster includes eyestrain, difficulty in focusing, blurred vision and headache. The disorientation cluster includes dizziness and vertigo. The nausea cluster includes stomach awareness, increased salivation and burping. A weighted average of these three factors comprises the Total Score, which reflects the severity of the symptoms for an individual and can be used to assess the likelihood that a VR system will cause cybersickness.

3 EXPERIMENT

We wanted to make a comparison between Gaze-Directed, Pointing and Teleport methods in a primed search navigation task requiring spatial awareness and spatial updating for successful completion. In particular, we wanted to address the following:

- Whether there are advantages in using the pointing method with a HMD, as was previously found in the CAVE.
- Whether the two steering methods increase the likelihood of cybersickness as compared with teleporting.
- Whether the teleport method increases the likelihood of users becoming disorientated in comparison to the steering methods.

We devised a task that required the user to navigate from a given start position to a destination shown to them on a map at the beginning of each trial. This use of maps was an expedient way to allow participants to form knowledge of the spatial layout of the environment without extensive learning in advance. A similar map-based method has been used in [48].

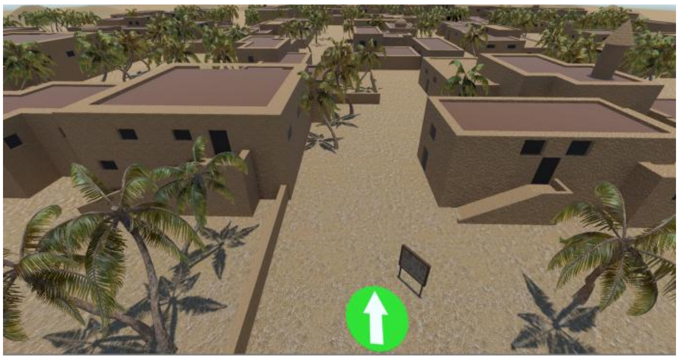

Figure 2. View of one ‘city’ from above and behind the start position showing the map and direction to target. These disappeared as soon as the participant moved out of the circle.

Because participants vary greatly in navigation abilities a repeated measures experimental design was used. Repeated measures designs, often referred to as within-subject designs, require the same subject to perform all conditions of the experiment: in our case, they would use all three locomotion methods. The main problem with this type design is possibility of an effect of learning and therefore appropriate randomisation of conditions had to be performed. The advantage however is that there is less variability in the data and fewer participants could be employed.

To reduce the effects of random variables within each trial, multiple trials were used and performance variables averaged. In order to generate multiple trials a 3D model of a desert city consisting of self-similar buildings was used. This allowed us to create 3 different cities with different configurations of buildings for repeated trials (see Figure 1). The destination was always exactly in the middle of each city. In order to vary the difficulty of the task the start positon, as shown on the map, was either directly below, to the left, on top and to the right of the final destination. Thus, if the customary way of viewing a map with the ‘you-are-here’ at the bottom is 0° then the other positions where located at 90°, 180° and 270°. In ego-centric terms the final destination was always directly ahead of the start direction, and the ‘beeline’ distance was identical (approx.. 100m). However, different buildings impeded direct walking to the target and participants had to navigate around them. Therefore, the total distance was different for each route.

As a further test for spatial-updating we also required participants to collect ‘tokens’ that they observed along each route. These tokens were ‘Pokémon’ type characters (Figure 3), approximately 1m high, and positioned away from, but within viewing distance of, the route to

Figure 3. View of a map and two Pokémon. The start location is indicated by a green circle and the destination in red.

each target. Spatial updating would be required to collect each token and continue their route to the target. There were exactly 5 tokens visible for each route. These became visible only when the participant was close enough (10m). Similarly, the final target destination was only made visible when the user came within 20 meters, thus testing participant's *memory* for the target's position rather than allowing its presence to guide their movements.

Because the Teleport method allows long leaps from one location to another the fact that participants had to collect tokens en route served to restrict extra-long leaps. Long leaps were also restricted by the presence of buildings: Teleports through or into buildings were not permitted. Nevertheless, it was expected that the Teleport method would produce faster route navigations than the steering methods, which were restricted to a speed of 3m/s. The latter was chosen based on our own subjective impressions of comfort and the fact that maximum walk speed for 20-30-year-olds is around 2.5m/s [36].

Table 1. Implementation of the three locomotion methods.

	Pointing	Gaze-Directed	Teleport
Method of Implementation	Direction of motion is the horizontal projection of a vector emanating from the front of the controller.	Direction of motion is the horizontal projection of a vector emanating from the front of the HMD.	Destination is the intersection of a ray emanating from the front of the controller and the ground plane.

3.1 Design

The objective performance measures used were the number of successful trials, the time taken to reach the destination and the average number of tokens collected for each condition. Because the routes consisted of navigations around different buildings, the optimal route times were different for each route. We therefore used average recorded time for each condition in the analysis.

We used a between-subject repeated-measures design in order to limit the effects of inter-subject differences in performance and response biases in the questionnaires. The three locomotion methods formed the three conditions of the experiment. In order to make fair comparisons between conditions we used random presentation of the same three cities for each condition. However, the cities were rotated 90 degree clockwise about their centre for each new condition: thus, the final condition performed by participants used the same cities as the first but rotated by 180°. Order effects were eliminated by altering the order of the conditions for each new participant according to a Latin square design.

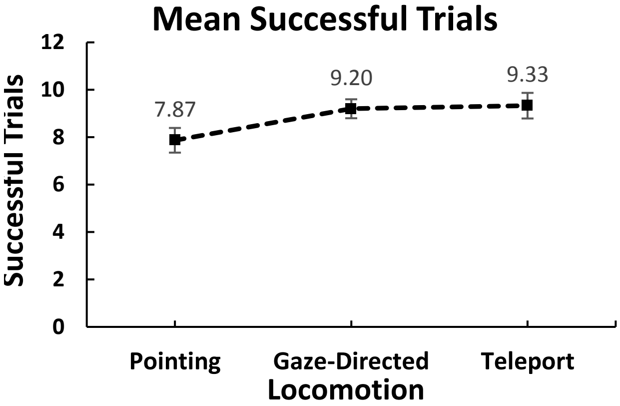

Figure 4. The mean number of successful trials for each method of locomotion. Participants completed12 trials in total for each condition.

To summarize, the experiment consisted of three conditions (Pointing, Gaze-Directed and Teleport) and each condition was tested by three different scenes (cities) whose presentation order was randomized between subjects. Each scene consisted of four trials with four different start positions around the same target, presented in random order.

3.2 Participants

Eighteen participants were recruited by advertisement. The mean age was 24 years, median age was 22 years. 11 participants were male and 7 were female. The majority (>90%) were students and had regular interaction with computers, but the minority (<10%) had prior experience with VR technology.

Participants gave informed consent to the data collection and agreed to visit the lab for testing on three separate occasions. Tests for each condition were performed on different days with no more than a two-day intervening gap between tests. All tests were completed over a three-week period.

3.3 Setup

The VR display used was a HTC Vive HMD with a resolution of 1080x1200 pixels per eye and 110° field of view. Each of the two screens of the HMD had a refresh rate of 90Hz. User input was achieved with a single hand-held controller, a virtual depiction of which was also visible in the virtual environment. The position and orientation of the display and the controller were tracked within a space of 3 square meters, although the participants were not required to make physical translations. The head and controller tracking was based on a lighthouse system with lighthouses placed at opposite ends of the tracking area and approx. 4 meters apart. A positional tracking accuracy of 2mm has been reported for this system[3].

The virtual environment was rendered by a Windows 7 workstation with Intel Core i5-4690K 3.5GHz CPU & 8GB RAM with NVidia GeForce GTX 970 GPU with 8GB on-board memory.

The Unity3D game engine was used to create the game level design with lighting, buildings, terrain, trees etc. In total 11 scenes were created: 9 scenes for the different trials (3 conditions x 3 cities), 1 practice scene and 1 experiment scene in which each session started. Custom C# scripts controlled the flow of the experiment. We used an

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[3] http://www.roadtovr.com/analysis-of-valves-lighthouse-tracking-system-reveals-accuracy/

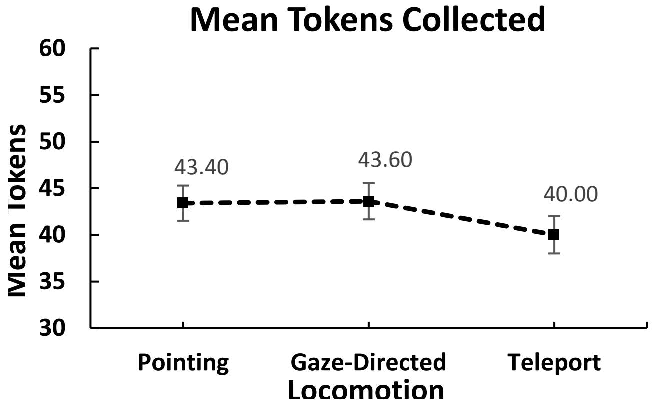

Figure 5. There were 5 tokens available per trial therefore the maximum number of tokens that could be collected was 60.

Experiment class to control the onset of the practice and test scenes, and a *TrialManager* class to control each scene including loading of appropriate locomotion controls, randomisation and presentation of trials and data collection. The SteamVR SDK[4] was used to handle display of the scene as well as handling the tracking data from the sensors and user interaction from the hand-held controller.

The Pokémon characters and the buildings of the 3D environment were derived from a public domain source. The buildings were adjusted for our purposes using the graphical editor 3DS Studio Max. These models were chosen because they had simplistic self-similar detail and could be positioned 'Lego-style' to restrict user movements. For each start-stop pair, there was only one viable route that would lead users to the target location.

3.4 Procedure

Each test began with participants reading written instructions explaining the task and how to perform locomotion using the current locomotion mode. The HMD was then fitted and adjustments made for inter-pupillary distance, and clear focus by adjustment of the eye-screen distance. The participant then had the opportunity to practice using the locomotion technique in a demo scene. This consisted of 5 token Pokémon characters randomly positioned within a 20m virtual space. Participants navigated to each character and 'collected' them by passing over them. When all practice tokens were collected, they proceeded to the main test.

Each trial consisted of the following: One of the four routes was chosen at random without replacement and the subject's virtual position was changed to the start of the route and their orientation was changed so that they were facing towards the direction of the target. To the participants' right they could see a map of their route. The map was dynamically generated by a virtual camera situated above and in front of the participant. The orthographic image that the camera produced was just large enough to show the location of the start platform (shown in green with an arrow indicating the correct direction) and the location of the target (shown as a red disk). Participants were instructed to memorize the route from the start location to the target location and collect any tokens that were visible along the route. As soon as they moved out of the start region it disappeared, together with the map. They then had to proceed as quickly as possible to the target destination collecting tokens en route. If after 120 seconds they had not reached the target location, they were informed by text display that they had failed and to wait for the next trial which proceeded automatically. Immediately following each test a cybersickness questionnaire was administered. The questionnaire was derived from [34]

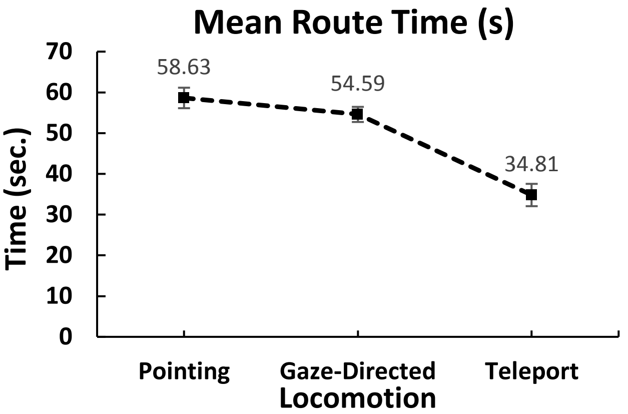

Figure 6. Average time taken to complete each trial. The maximum time allowed was 120s. Data shown only for successful trials.

Table 2. Cybersickness mean scores (n=15).

	Pointing	Gaze-directed	Teleport
Nausea	36.0	21.0	10.8
Oculomotor	23.8	18.7	13.6
Disorientation	39.0	29.7	24.1
Total	36.4	25.4	17.5

4 RESULTS

Three participants (all female) dropped out of the experiment after the first or second condition complaining of nausea and their data was discarded from the analysis.

We consider first the post-test survey. Averaged scores are shown in Table 2. According to [34] scores for the nausea scale range from 0 to 200, scores on the oculomotor scale range from 0 to 159, scores on the disorientation scale range from 0 to 292, and total simulator sickness scores range from 0 to 235. The higher the score, the greater the cybersickness. A total score of less than 10 indicates minimal symptoms, whereas a total score over 20 indicates a problem simulator [41]. Table 2 indicates that Pointing resulted in the highest level of cybersickness and Teleport the least. The average score for the Pointing method is indicative of motion sickness which carries a high likelihood that a user would terminate their use of a VR simulation [50]. We performed a repeated-measure ANOVA with mode of location as repeated-measures factor with three levels. The result revealed that the mode of locomotion was significant [F(2,28)=3.68, $p<0.05$]. Post hoc comparisons using the Fisher LSD test indicated that the Teleport method produced significantly lower cybersickness scores than the Pointing method. There was no statistical difference between Gaze-Directed locomotion and either the Pointing or Teleport methods.

In terms of performance Figure 4 shows the mean number of successful trials averaged across all subjects for each of the three conditions. Each participant performed 12 trials using each of the three locomotion methods. The Pointing method resulted in fewer successful trials than either of the other two modes. A general linear models repeated-measures ANOVA showed that the mode of transport had a significant effect on success rate [F(2, 28)=5.65, $p< 0.01$]. A Fisher LSD post-hoc comparison of means showed that the pointing method produced significantly lower success rates than both the gaze-directed or teleport methods (mean diff -1.33 and -1.47 respectively), and that the gaze-directed and teleport means were not significantly different (mean difference= -0.13) from each other.

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[4] http:// *www.**steamvr**.com/*

A similar analysis was performed on the total number of tokens collected (regardless of eventual outcome). The reader should remember that the experiment for each locomotion mode involved exactly the same environments (displayed differently on the maps) and token positions. Figure 5 shows that the two steering methods resulted in similar performance and better than the Teleport method. A repeated measures ANOVA was conducted to compare the effect of mode of locomotion on tokens collected. There was a significant effect of locomotion on tokens collected at the p<.05 level for the three conditions [F(2,28)=3.74, p=0.036]. Post hoc comparisons using the Fisher LSD test indicated that the mean tokens collected for the teleport method (M=40, SE=1.99) was significantly lower than those collected using the Pointing (M=43.4, SE=1.89) and the Gaze-Directed (M=43.6, SE1.94) methods. The latter were not significantly different from each other.

Finally, we consider the time taken to complete the routes. Here we consider only trial times for successful route traversals averaged across the three scenes (each consisting of four routes) for each condition. Figure 6 depicts the average traversal time for each mode of locomotion and shows that the Teleport method allowed subjects to complete the routes in approximately half the time required by the other two methods. A within-subjects repeated measures ANOVA indicated that locomotion mode significantly affected average trial time [F(2,28)=40.56, p<.005]. A post hoc analysis of means showed that the mean time for Teleport (M=34.8,SE=2.74) was significantly different from the means for Gaze-Directed (M=54.59,SE=1.85) and Pointing (M=58.63,SE2.5). The latter two modes were not significantly different from each other (mean difference =4.04, SE=2.83, p=0.16).

5 SUMMARY & DISCUSSION

There are many ways in which a user may interact with a VE but perhaps the most important is the ability to navigate through it. Navigation is a combination of wayfinding and locomotion and since our wayfinding abilities are developed in the real world from an early age locomotion for VR should enable and exploit the cognitive machinery that we have at our disposal. Although real walking is therefore the best way to do this it may not always be feasible and, as we have mentioned, it may not even be necessary. Effective spatial updating may still be possible as long as bodily rotations are enabled [19,20,46]. In a head and body tracked VR system there are many ways to do this. In this paper, we have compared three such methods. Our results, in terms of performance in finding a target position specified on a map, shows that even with the worst performing method participants could find the target on 66% of trials. This was the case even though we deliberately violated the forward up equivalence principle of map use by depicting the user start position at 90°, 180° and 270° offsets around the target as depicted on the maps. In these offset cases participants had to employ more cognitive effort to form their route knowledge, thereby making the task more difficult.

In terms of our comparison of the three methods of locomotion, our initial prediction was that the Pointing method would be most successful in the wayfinding task. This is because it is more natural (after all, we often walk in one direction while looking in another), and because recent tests have shown it to be more effective than Gaze-Directed locomotion [48]. This experiment was similar to the one reported here, however the display used was a CAVE. The CAVE does provide a larger field of view than the HMD used in the current tests and this could be a contributing factor. A restricted field of view may have caused participants to employ a different strategy to that used in the CAVE [30]. We believe, however, that the difference is more likely related to the relative level of cybersickness experienced. Although the cybersickness scores for the Pointing and Gaze-Directed conditions were not statistically different, those of the Pointing method were consistently higher in all sub-categories and the final score. A participant who is experiencing high levels of nausea and disorientation is not going to perform very well in wayfinding and this may be the principle contributing factor to this result.

The teleport method, as expected, allowed participants to navigate faster to their destination than either of the steering methods but surprisingly it produced comparable results in terms of successful navigations. This is not to say that users did not get lost using teleporting. Our observation of the participants performing the trials was that they did, on occasion, become disorientated, particularly after disengaging from their route to collect a token. However, in some cases they still had enough time to backtrack to the point where they made a wrong turn.

There was also less evidence of cybersickness using the Teleport method compared to the steering methods. Nausea scores for the Teleport method were one third those for the Pointing method. Again, some care must be taken in interpreting this result as the Teleport method required less time and therefore less opportunity for our participants to feel discomfort. Nevertheless, these results suggest that steering using a HMD elevates cybersickness and furthermore that the primary reason for this is the vection produced by smooth motion with a display that allows only restricted field of view.

Our results suggest that Teleport locomotion does not result in substantial disorientation. The mean sub-score for Disorientation in the cybersickness survey was lowest for Teleport locomotion (Table 2). Disorientation is often maintained as the main problem with teleportation methods. However, our results show that participants were able to successfully navigate to their destinations with teleporting equally as well as with Gaze-Directed locomotion and better than with Pointing. The main problem with teleporting that we observed was that users have a propensity to miss detail. In our case the tokens that had to be collected en route. In application, this can be handled, perhaps, by restricting the size of teleport leaps. Indeed, we observed that a few participants adapted to the method by making rapid yet small teleport leaps. However, developments in this field ongoing. In order to maintain awareness of the environment during a teleport leaps the game developer *id Software LLC* have developed a variant of teleporting known as Dash Teleport in which, instead of moving instantaneously to a new location, the user selects the leap destination and is propelled there with accelerated movement. This 'warp-speed' movement may reduce any element of disorientation and allow the user to see detail in between. However, its propensity for inducing cybersickness is yet to be assessed.

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