Improving Navigation in Virtual Environments

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Abstract

This research evaluates three VR navigation interfaces–walking and turning, teleporting to change position with physical rotation, and teleporting to change position and rotation–using a triangle completion task. For the triangle completion task, participants travel along two legs of a triangle in a virtual environment (VE), and are then asked to indicate the position at which they started. This project examines how their responses compare to their actual starting position, and thus the effects of body-based cues on VE navigability. It was predicted that participants allowed to physically walk and turn would be the most accurate, while participants using a controller to teleport to change their translation and rotation would be the least accurate. In addition, the experiment investigated whether the presence of landmarks can mitigate some of the disorienting effects of various navigation interfaces. It is expected that landmarks would aid navigation across different navigation interfaces. It was found that body-based cues did in fact affect spatial updating, with physical movement being an important predictor of navigation success. Those allowed to physically walk and turn performed better than those only rotating their body, and those who only had physical rotation performed better than those who solely used a controller to move and turn in the environment. However, contrary to the earlier proposed predictions, it was found that the presence of landmarks did not reduce errors. These findings suggest VE movement should match with body movement whenever possible to allow for the most successful navigation in VEs.

Improving Navigation in Virtual Environments

Introduction

The emerging field of virtual reality (VR) faces a unique challenge—creating a way for users to navigate through vast virtual environments given only a small tracked area in reality. VR developers have devised various types of navigation interfaces to circumvent this problem, but because many of these interfaces limit bodily movement and thus physical movement cues, they may make it harder for users to navigate and orient themselves in virtual environments (VEs). Disorientation then serves a barrier to immersion for VR users and developers. The current study investigates how common methods of navigation in virtual reality, coupled with landmarks, affect virtual environment navigability.

Current VR navigation interfaces use a combination of teleportation, joystick, and physical movement to allow users to move through a virtual environment. These navigation methods have varying levels of concordance with physical movement—concordance being the extent to which physical movements correspond to movement in the VE. Navigation interfaces range from completely concordant (user physically walks and turns) to partially concordant and completely discordant interfaces (some or all of virtual movement is based on controller input). Due to physical constraints, such as limited room size and tethered hardware, it is essential to create partially concordant interfaces for navigation. The evaluation of several navigation methods, as well as landmarks, will provide recommendations for developers to create more navigable virtual environments in addition to a better understanding of how these navigation methods affect spatial updating.

Literature Review

Previous research has examined the role of body-based cues and landmarks in aiding virtual navigation. Much of this research has focused on spatial updating, the process of keeping track of self-position and self-location when moving through an environment. Various studies have investigated how VE navigation interfaces that limit body-based movement cues affect spatial updating. Furthermore, studies have also looked at how landmarks affect one's ability to spatially update.

Effects of Body-Based Cues

Experiments with head-mounted displays (HMDs) have found that body-based movement is critical for successful spatial updating in a VE. Klatzky, Loomis, Beall, Chance, & Golledge (1998) investigated spatial updating using a triangle completion task, where participants walked along two legs of a triangle (the outbound path) before pointing back to where they started. When participants were allowed to physically walk and turn during the outbound path, they indicated where they started with more accuracy than those who were merely given visual information about their path through an HMD as a substitute for movement. When participants were allowed to physically turn but not walk, however, they performed comparably to those who physically walked and turned—indicating the importance of physical rotation in spatial updating (Klatzky et al., 1998). Rieser (1989) found similar results in a study where participants were asked to point to various objects from real or imagined headings. When participants were asked to imagine pointing to an object from a heading that was at a different orientation from their own (imagined rotation), it was far more difficult than pointing at an object from a different imagined position (imagined translation).

These conclusions demonstrate the importance of body-based rotation were called into question in other navigation studies. Ruddle and Lessels (2006) conducted an experiment where participants were asked to search boxes in a virtual room using one of several navigation interfaces. Similarly to Klatsky et al.'s (1998) findings, participants performed best when allowed to physically walk and turn. However, those who used a controller to rotate while physically translating performed poorly, indicating that rotational movement is not sufficient for spatial updating in VEs. Two studies, one by Riecke (2002) and the other by Riecke, Cunningham, and Bülthoff (2007) had participants perform navigation tasks in virtual environments projected on a curved screen. The studies found had the opposite findings of the Ruddle and Lessels study—physical turning was not necessary for participants to spatially update; visual information was sufficient.

Effects of Landmarks

Experiments have also examined how landmarks and visual information affect one's ability to navigate and orient in VEs. Landmarks are elements in the environment that provide visual information and context for the user, from far-off indicators (distal landmarks), such as mountains or buildings, to nearby indicators (proximal landmarks), such as furniture in a room. In the studies by Riecke and colleagues, landmarks were found to be helpful when comparing how well participants were able to navigate and orient themselves in landmark-rich environments (town or marketplace) versus featureless environments (infinite plains textured with randomly generated blobs or greyscale fractal patterns) (Riecke, 2002; Riecke et al., 2007). Other visual information can also help participants to orient themselves in virtual environments. Kelly et al. (2008) investigated the effect of room shape on spatial updating and found that participants had the poorest performance orienting themselves in circular or shape-changing rooms, but performed relatively well in square, rectangular, or trapezoidal rooms. The authors proposed that spatial updating was successful when the environment provided a stable environmental frame of reference which participants could use to orient themselves. Kearns, Warren, Duchon & Tarr (2002) found that visual textures on the floors and walls of environments could help users better approximate distances traveled in virtual environments, due to the enhanced optic flow.

Experiment Overview

This study had three aims. First, study the effects of the teleportation interface–a widely used, but not widely tested navigation interface–on spatial updating. Second, because previous studies on the necessity of physical rotation have been contradictory, look at how physical rotation versus virtual rotation affects one's ability to spatially update in virtual environments. Lastly, examine whether landmarks could help participants orient in VEs.

Methods

Stimuli and Design

The Unity game engine was used with the SteamVR plugin to create an interactive 3D environment for the HTC Vive. Participants were asked to perform a triangle completion task using three interfaces in two environments. Interface order and environment order were both counterbalanced to control for potential order effects.

Triangle Completion Task. Participants completed 72 triangle completion trials total (not including training), 12 for each of three movement interfaces in one environment then again in the same order for the other environment. Participants were guided through the triangle completion trial using a series of oriented markers that disappeared upon contact. Participants followed markers that guided them along two legs of a triangle. After reaching the last marker, participants were then asked to make a response indicating the position where they believed the path began.

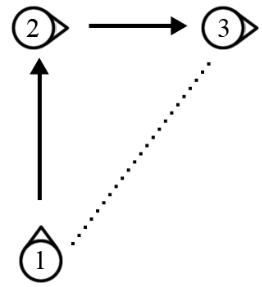

Figure 1. Triangle completion task.

A top-down view of a triangle completion task. Participants travel the path between markers in the labeled order, then indicate a path back to the origin (marked here by the dotted line)

Generating Triangles. The triangle completion task required participants to move along two legs of a path before pointing to the path origin. The first and second segments of the outbound path were chosen at random; the first length was 1.52, 1.68, or 1.83 meters, each being equally likely, and the second side length was 1.22, 1.37, or 1.52 meters, each being equally likely. These side lengths were chosen to create variation in triangle paths while still keeping within the constraints of the room size. The turn between the first and second segment was 22.5, 45, 67.5, 90, 112.5, or 135 degrees to the left or right (Figure 2); each pair of turn degree and turn direction was completed by each participant.

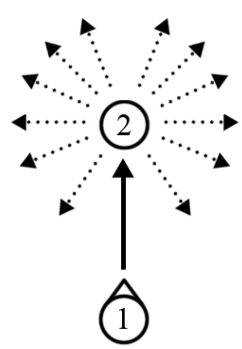

Figure 2. Possible turn angles.
A diagram of all possible angles relative to the first marker of the triangle, ranging from -135 to 135 degrees.

Guided Paths. Each point of the triangle was indicated by a marker placed within the space, with distinctive colors to indicate which leg of the triangle the marker denoted. The starting marker, which is green, and marker indicating the first leg of the triangle, which is yellow, had a given orientation and arrows that indicated the direction of the following marker, while the third marker, which is red, had the same orientation as the second. The starting marker always began oriented towards the center of the room. Start markers were placed at the sides and corners of the room with 8 total starting positions evenly distributed in the room. They were placed 3 feet from each wall when along the side of the room and 4 feet from each wall when placed in a corner to ensure participants would not move outside of the tracked space (Figure 3). No start position was repeated twice in a row to ensure participants did not get feedback as to how well their response matched their start position.

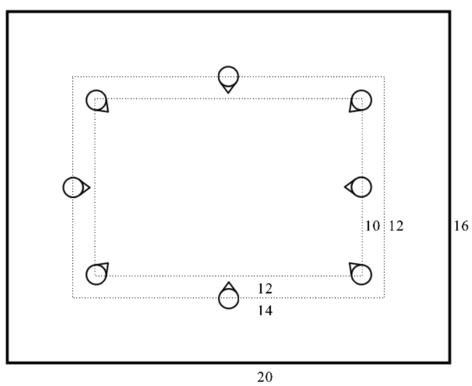

Figure 3. Start positions.

The eight possible starting positions for each triangle. Values indicate room dimensions (feet).

VEs. Two environments were created to test the effects of landmarks on VE navigation. The Landmarks environment (Figure 4) contained a variety of objects in the VE, both distal and proximal. Distal landmarks consisted of a bridge, building, mountains, and arch, spaced every 90 degrees, while proximal landmarks were common outdoor objects such as plants, trees, and benches. Proximal landmarks were closer to the participant but were placed outside of the walking area. Both the Landmarks and Landmark-Free (Figure 5) environments contained the same ground plane with a 2D grass texture and a plain blue skybox.

Figure 4. Landmarks

The Landmarks environment contains both proximal landmarks (tree and trashcan) and distal landmarks (arc) on an infinite grassy plane.

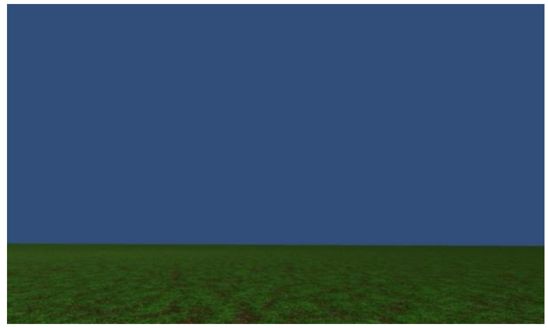

Figure 5. No Landmarks

The No Landmarks environment consists of an infinite grassy plane.

Procedure

Navigation Interfaces. There were three navigation interfaces that had various levels of concordance with body-based movement. The first was the Concordant condition, a completely concordant interface, where users were asked to physically walk and turn. Bodily movements had a one-to-one correspondence with movement in the virtual world. The second was the Partially Concordant condition, where participants physically rotated to turn in the virtual environment, but used a controller to change position in the virtual environment. The last was the Completely Discordant condition, where participants solely used a controller to change their position and orientation in the VE.

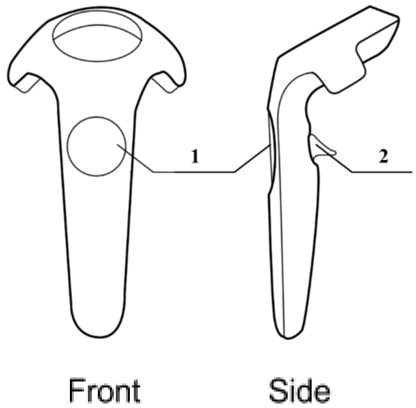

Figure 6. Vive controller.

1) **Touchpad**, used to change position in the Teleport-Physical-Turn condition and used to change position and orientation in the Teleport-Turn condition.
2) **Trigger**, used to indicate participant response

For the Concordant condition, participants translated and rotated in the virtual world by physically walking and turning, respectively. For the Partially Concordant condition, participants pressed down on the controller's touchpad (Figure 6) and pointed the controller at the ground to initialize teleportation. A target-shaped reticle (Figure 7) then appeared on the floor at the end of a laser coming from the virtual model of the controller. The position of the target was manipulated by pointing to different points on the ground. Upon release of the trackpad, the participant was translated to the selected location while facing the same direction that they were facing before the trackpad was released; virtual rotation occurred via body rotation. For the Discordant condition, participants pressed down on the trackpad and pointed at the ground to initiate teleportation. Instead of a target-shaped reticle as in the Partially Concordant condition, however, they saw a ring-shaped reticle with an arrow (Figure 8). By adjusting their thumb's position on the trackpad in a circular fashion, they could rotate the arrow on the ring and thus their future heading. For example, a finger position directly to the left of center of the trackpad corresponds to 90 degree rotation to the left while a finger position directly beneath the center of the trackpad corresponds to a 180 degree rotation. Like the Partially Concordant condition, the participant was moved to the ring's center upon release of the trackpad. The ring thus specified a new location and heading, and the participant was instantly moved to this location and heading on release of the trackpad..

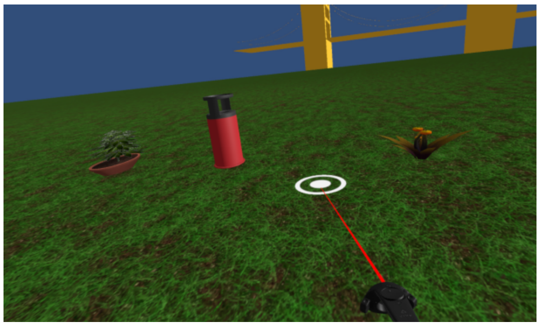

Figure 7. Partially Concordant

Participants teleport to the center of a disk with a radius of 37.5 cm.

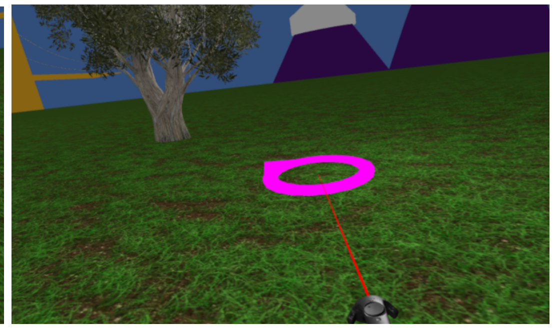

Figure 8. Completely Discordant

Participants teleport to the center of a disk with a radius of 93.5 cm. Their heading is also changed to match the arrow on the disk.

Training. Before triangle completion task trials for each navigation interface, participants completed training for that navigation interface. The training environment consisted of a textured plane without landmarks (Figure 9). Triangles were generated in the same manner as in the actual experiment except with two possible start positions and a turn of 56 degrees left or right. Participants completed triangle completion tasks twice in training, then continued to train until they stated they were comfortable with the navigation interface. Training was offered to participants before each block of twelve triangle completion trials.

Figure 9. Training environment.

Participants trained in in an environment consisting only of a textured plane

Response. Participants were asked to indicate the position of the origin marker using the trigger on the Vive controller (Figure 6). To indicate the origin, participants were asked to hold down the trigger, which spawned a response reticle, move the reticle onto the origin, and then release the trigger (Figure 10). The measures of error were signed turn error and absolute distance error. In addition, response time–the time between arriving at the end of the second leg of the triangle and pointing to the path origin–and path trajectory were measured. One participant had absolute error responses more than 2.5 standard deviations above the mean, thus their responses were not included in the statistical analyses.

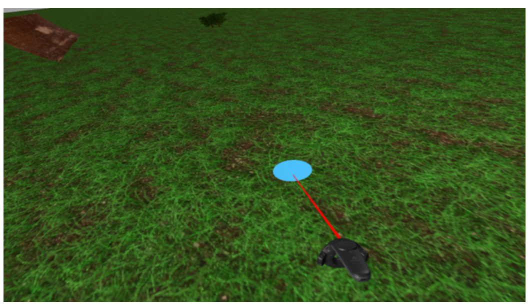

Figure 10. Response

Participants respond in the triangle completion task by hovering a disk with a radius 19.5 cm radius to their point of origin and releasing the trigger

Results

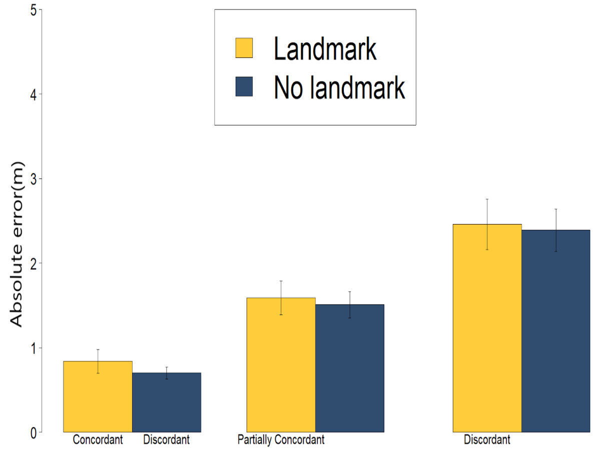

Figure 11. Absolute distance error across interfaces.

Bar graphs indicating measured absolute errors across the different navigation interfaces.

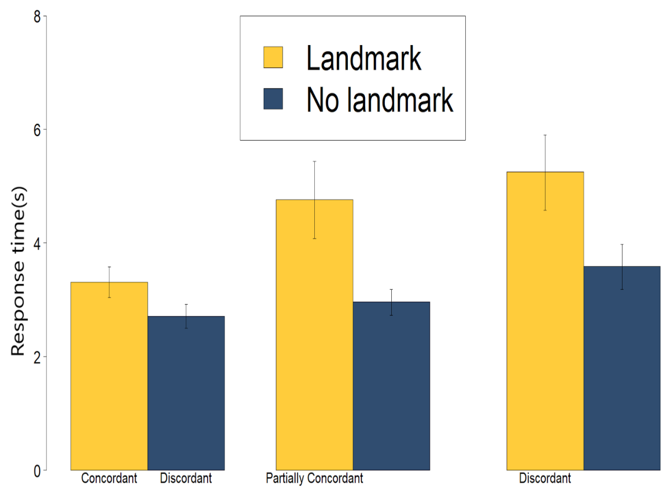

Figure 12. Response time across interfaces.

A top-down view of a triangle completion task. Participants travel the path between markers in the labeled order, then indicate a path back to the origin (marked here by the dotted line)

Absolute errors were analyzed in a 2 (VE: landmarks or no landmarks) x 3 (interface: concordant, partially concordant, or discordant) repeated measures ANOVA. Only the main effect of interface was significant [$F(2,22)=29.502$, $p<.001$]. The concordant interface produced significantly smaller errors than did the partially concordant interface [$F(1,11)=15.245$, $p=.002$], which produced significantly smaller errors than the discordant interface [$F(1,11)=36.616$, $p<.001$]. The main effect of VE was not significant [$F(1,11)=0.399$, *ns*], nor was the interaction [$F(2,22)=0.522$, *ns*].

Response times were also analyzed in a 2 (VE) x 3 (interface) repeated measures ANOVA. The main effect of VE was significant [$F(1,11)=25.45$, $p<.001$], as was the main effect of interface

[$F(2, 22)=6.25$, $p=.007$]. Response times were significantly faster in the concordant than the partially concordant and discordant conditions, which did not differ from one another.

Conclusions

When navigation through a virtual environment, triangle completion errors were worse when teleporting compared to walking. Furthermore, teleporting to change position and orientation was worse than teleporting to change position and rotating the body to change orientation. These differences were unaffected by whether or not the VE contained landmarks. The main recommendation that can be made to designers of VEs is to allow body movement associated with walking and turning when possible. Future research will investigate whether other environmental cues, such as a structured room or a familiar environment, can mitigate the negative effects of teleporting.

Acknowledgements

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