EVALUATING EMBODIED NAVIGATION IN VIRTUAL REALITY ENVIRONMENTS

Contributors

Justin Berry, Yale University
Johannes DeYoung, Yale University
Lance Chantiles-Wertz, Yale University
Jack Wesson, Yale University
Stephanie Riggs, Sunchaser Entertainment

Abstract

Virtual reality has become more accessible and affordable to the general public in recent years, introducing the exciting potential of this technology to new audiences. However, the mechanisms of navigating within a virtual environment have primarily been constrained to handheld input devices akin to gaming controllers. For people unfamiliar with traditional gaming input devices, VR navigation devices are not intuitively mapped to real-world modes of locomotion and can be frustrating and disorienting. Designers have largely focused on utility (the ability to efficiently accomplish a task) to the detriment of usability (ease of use). The industry lacks an intuitive, universal method of navigation that can be easily learned by novice participants.

Dr. Jakob Nielsen identified five factors that impact usability in human-computer interactions (HCI): learnability, efficiency, memorability, errors, and satisfaction. Previous research in virtual environment locomotion incorporated teaching time periods where the researchers explained the control devices to participants. We believe that this neglected one of the key usability factors in human-computer interactions: learnability, or the ability and ease to accomplish a task the first time a user encounters it.

Our research focuses on comparing existing modes of navigation (game controller based) with a mode of controller-less embodied navigation between two demographics based on Nielsen's usability factors. We test our results within communities of self-identified gamers and non-gamers, evaluating navigation modes designed for joystick control pads, trigger-based teleportation, and controller-less embodied navigation. Our research inquires whether embodied navigation enhances usability in accordance with Nielsen's usability factors, specifically enabling easier access and engagement for inexperienced subjects, compared with controller-based modes of navigation.

CCS Concepts

Human-centered Computing → Interaction paradigms → Virtual Reality

Keywords

Embodied Navigation; Active Locomotion; Virtual Environments; Interfaces; HCI

Introduction

Navigation is the act or process of ascertaining one's position and steering, directing, or finding a way through space. Typically in VR this relates to the set of controls a participant uses to go from one area to another. Controls, in this context, mean buttons or triggers that are embedded in the associated hardware, such as HTC Vive or Oculus controllers. Unfortunately, for users that are new to VR and do not have a background in gaming, the process of figuring out which buttons to press and in which order is an abstraction. By eliminating hardware controllers and leveraging natural, embodied navigation methods, we hypothesized that acclimation time could be reduced and satisfaction increased.

To test our theory, we created a simple room-scale VR navigation system based on the relative position of a subject within a virtual environment. Because this form of navigation is intuitive and controller-less, we hypothesized that it would offer simpler means of on-boarding. By reducing acclimation time, participants would spend less time learning how to operate controllers to navigate a virtual environment and spend more time immersed in the VR experience. We anticipated that the quality of the VR experience would be enhanced through embodied navigation, resulting in greater levels of satisfaction and a greater sense of immersion.

Typically, room-scale VR utilizes a finite play area, defined by end user sensor hardware configuration. In this study, the room-scale was set to a 10-foot square sensor hardware installation, which defined a real world bounding box for the virtual play area and all forms of movement that happened therein. For disambiguation, we define users participating in VR experiences as subjects.

Commonly, VR experiences enable subjects to move within a virtual play area through hardware motion tracking within the limits of the sensor hardware configuration. Within this bounding box, two types of movements are enabled: the first movement is the localized, physical movement of the subject that is captured by motion sensor hardware and mapped onto virtual space, within the play area defined by the real world bounding box; the second movement involves the global translation of the play area itself within a virtual environment. Henceforth, we will describe these two modes as localized movement and global translation.

Our model of embodied navigation was developed in the Unity 3D engine (v. 2018.1) for the HTC Vive headset. The navigation algorithm utilizes localized movement data to drive the global translation of the virtual play area. In our model, the subject is surrounded by two concentric radii, a small radius and a large radius. The small radius is described as a zone of stillness (ZOS), where only localized movement is enabled. Once the ZOS border is surpassed the entire play area is translated within the global environment, where speed corresponds to distance outside of ZOS border and translation direction corresponds to radial direction from center of ZOS. The ZOS was established to primarily allow for head rotation without corresponding global translation. This model aligns with the natural movement of looking around while standing in place, where as the global translation of the Play Area corresponds to looking while walking.

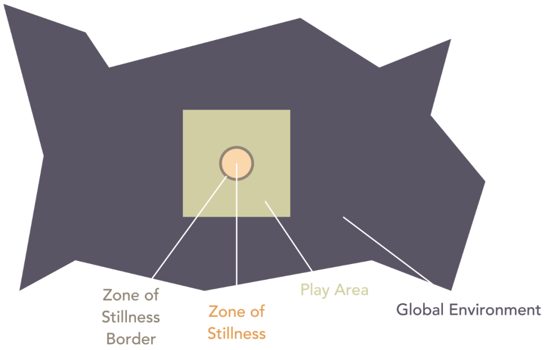

Figure 1. Zone of stillness / Play area diagram

Our algorithm takes the subject's distance from the center on both axis and then subtracts it by the ZOS radius. We then use this as the global translation speed of the play area along each axis. Global translation only occurs if the subject is outside of the ZOS.

In our model, the subject's position vector (distance from subject center) is first separated into its "x" and "z" vector components (Unity coordinate system). The individual components vectors are normalized to retrieve the magnitude of the vector (how large of a distance they are from the center position regardless of positive or negative coordinate direction). This value is then subtracted by the value of the radius of the ZOS. This calculation prevents a jump in acceleration that would otherwise result from the speed corresponding to the distance from the subject center rather than from the ZOS perimeter. The new value of distance subtracted by zone distance is multiplied by the sign of the unit vector of the original subject position vector.

$$(\frac{V_x^2}{|V_x|} - |s|)\frac{V_x}{|V_x|}$$

This is used to reintegrate the subject's localized movement direction along its axis. This calculated value is equalled to the subject's new speed along the corresponding axis after being multiplied by a scaling factor. All of this is only done if the subject is outside of the ZOS.

Through this form of navigation we amplify a person's natural movement. To navigate local space, subjects walk as they do in daily life. To navigate distant space, the subject's walk is amplified by the embodied motion mechanic. The walk is boosted.

This form of navigation offers an alternative to game-based point-and-click, joystick, and track-pad navigation controllers. Instead of abstracting, or in some cases obfuscating, natural participant movement through these controller methods, it emphasizes natural intuitive motion and becomes embodied navigation.

Methodology

We hypothesized that embodied navigation would enhance user experience in VR and reduce on-boarding time for people unfamiliar with gaming controllers and existing VR hardware, and increase overall satisfaction in both gamers and non-gamers. To test this hypothesis, our methodology deployed three random mazes of equal difficulty, in which subjects were tasked to navigate via three distinct navigation methods (embodied motion, teleportation, and joystick control). This method allowed us to test our custom mode of navigation against two commonly deployed modes of navigation in current VR hardware and software development. Three mazes were utilized as test controls, with each maze sharing common attributes of scale and wall count. While the maze path varied between each of the three maze designs, the paths consisted of equal path units across all designs.

Testing was conducted within a 10'-square physical bounding box, defining a common play area for all trials. Mazes were generated using a pre-existing random maze generator called Maze Magician. Each maze block scaled to one-meter real world scale and each maze shared a constant overall grid size, 15 units square. Constant maze wall heights set to five-meters. Physical space and aesthetic attributes were designed for uniformity and consistency across all trials and subjects, with maze coloration rendered in an unobtrusive white albedo. Environment lighting was common across all trials, with ambient lighting, two directional lights, and ambient occlusion to uniformly light all maze surfaces and effectively denote intersecting maze walls without creating atmospheric landmarks. Starting point orientation was applied uniformly across virtual and physical spaces for all trials. An X on the physical floor of the test environment marked the subjects' starting position. All subjects were oriented in the same starting direction. Constant spawn points were maintained for each virtual environment at the start of each trial. Similarly, the finish line was denoted by a standard checkered flag laying in a demarcated orange square, common across all trials.

Subjects were asked to self-identify their experience with gaming controller hardware and Virtual Reality on a Likert-type scale, rating a value of 1 as little-to-no experience or frequency of use, and a value of 5 as high experience or frequency of use. For testing purposes, subjects ranking ≥ 3 values in gaming controller hardware experience were classified as **Higher Frequency Game Controller** (**HF GCXP**) subjects, while subjects ranking ≤ 2 values in gaming controller hardware experience were classified as **Lower Frequency Game Controller** (**LF GCXP**) subjects. Likewise, subjects ranking ≥ 3 values in Virtual Reality experience were classified as **Higher Frequency VR** (**HF VRXP**) subjects, while subjects ranking ≤ 2 values in Virtual Reality experience were classified as **Lower Frequency VR** (**LF VRXP**) subjects.

Results were tested quantitatively through timed completion rates, and qualitatively through Likert-type user experience surveys. Usability evaluation for each form of navigation was designed to be measured in accordance with HCI metrics of learnability, efficiency, memorability, errors, and satisfaction. Proctors administered testing with common testing scripts, and without explanation of the navigation mode mechanics that were being evaluated.

Three mazes and three modes of navigation were sampled across matrixes, where subjects evaluated navigation modes in three separate trials that distinctly combined one mode of navigation with one of three sample mazes. Navigation modes (E)mbodied, (J)oystick, and (T)eleportation were systematically paired with each maze sample. Navigation mode and maze pairings were cycled between subjects to ensure that each navigation mode was fairly tested against each maze sample. Between each trial, subjects were given a survey to rate their experiences. All qualitative user experience data was surveyed according to a Likert-type rating scale, measuring key factors of enjoyment, familiarity, confidence, and comfort, as well as users' feelings of navigation accuracy, sense of immersion, spatial awareness, and navigation precision. Subjects' prior experience with game controllers and Virtual Reality were measured on scale of 1 to 5, with the value of 5 being most familiar with popular gaming hardware and Virtual Reality interfaces.

Quantitative results were obtained from timestamps on trial recordings. Subjects started their trials in an open atrium area for each maze sample. Subjects were instructed to use the atrium area as a space to acclimate and learn the navigation method and cross the start line into the maze at will. The acclimation period is defined as the time between when the subject was situated in the HMD and when they elected to cross the start line into the maze. There were no time limits established and no guidance on use of controllers were given by proctors during this period of time. After the measured acclimation period, subjects entered the maze and navigated to aforementioned finish line. Our study measured the time that each subject spent acclimating to VR conditions in the atrium area, as well as maze navigation duration.

Time began to elapse in the atrium as soon as the maze appeared in the subject's headset. If there appeared to be interruptions, either because of technical difficulties (problems with controllers, discomfort with HMD) or because of misunderstanding of permission (not knowing they were permitted to begin), duration in atrium was adjusted to the time spent focused on navigation and maze. Time ended in the atrium once subjects entered the maze. Time spent in the maze began immediately upon maze entry. Proctors were able to effectively determine transitions through birds-eye orthographic screen capture of each subject's navigation. In the event of a subject teleporting from the atrium directly into the interior of the maze, the turning point occurred immediately upon their interior teleportation.

Time spent in each maze ended once the player either: (1) collided with the finish line in embodied navigation or joystick navigation or (2) teleported near the finish, attempted to teleport in (but could not because finish zone was not accessible), then proceeded to teleport closer. In the event that a subject teleported very close to the finish line and they - or the proctor - assumed completion, time spent in the maze ended once the subject attempted their final teleportation. In the event that a subject was not close to the maze end but assumed completion, time ended after their final teleportation.

Results

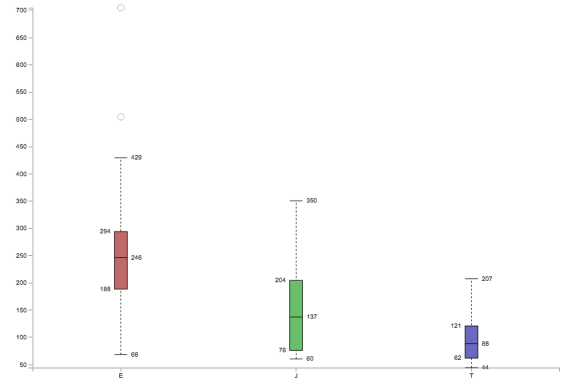

Figure 2a. Timed maze navigation averages; (E) = red, (J) = green, and (T) = blue

(T) Acclimation	34 seconds
(T) Navigation	97 seconds
(J) Acclimation	52 seconds
(J) Navigation	153 seconds
(E) Acclimation	123 seconds
(E) Navigation	260 seconds

Figure 2b. Timed acclimation period and maze navigation averages across all modes of navigation

Twenty-seven subjects participated in the study. Time samples for acclimation and maze navigation were averaged separately for each navigational mode. Our testing results yielded the fastest acclimation and maze navigation results for the (T)eleportation model, followed by (J)oystick, with (E)mbodied navigation yielding the slowest timed results. Qualitative user experience varied across **HF/LF GCXP** and **HF/LF VRXP** subject classes. **HF GCXP** and **LF GCXP** subject classes yielded the highest user satisfaction averages for embodied navigation across both classes in sense of Immersion. Our results also demonstrated the highest user satisfaction averages for embodied navigation for **HF GCXP** subjects in the categories of Spatial Awareness, Familiarity, and Confidence. Embodied navigation and joystick navigation tied for highest user satisfaction average in the **HF GCXP** Acceleration category.

Figure 3. HF / LF GCXP user satisfaction averages; (E) = red, (J) = yellow, and (T) = blue

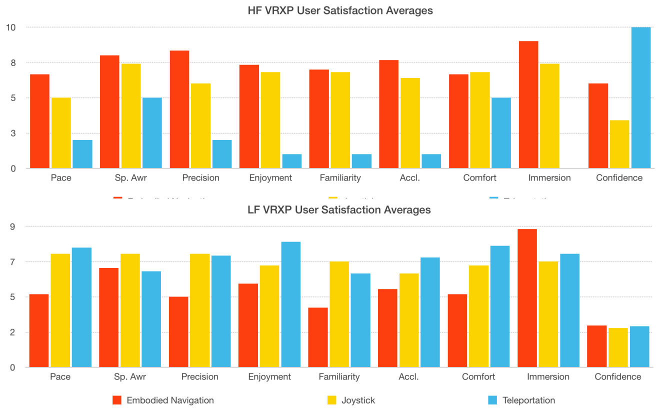

Figure 4. Timed maze navigation averages; (E) = red, (J) = yellow, and (T) = blue

In both **HF VRXP** and **LF VRXP** subject classes, embodied navigation ranks highest user satisfaction for sense of Immersion. Among **HF VRXP** subjects, embodied navigation ranks highest user satisfaction for Pace, Spatial Awareness, Precision, Enjoyment, Familiarity, and sense of Acceleration. Among **LF VRXP** subjects, embodied navigation ranks highest for sense of user Confidence. Teleportation and joystick navigation rank higher user satisfaction among overall **LF VRXP** subjects, with a slight subject preference for teleportation. Embodied Navigation ranks highest user satisfaction among overall **HF VRXP** subjects.

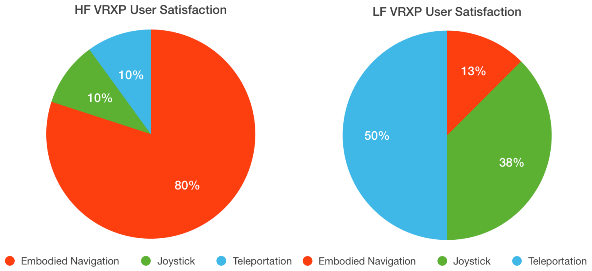

Figure 5. General HF / LF VRXP user satisfaction averages; (E) = red, (J) = green, and (T) = blue

Discussion

Contrary to our initial hypothesis, both acclimation and maze navigation times took the longest with our mode of embodied navigation. Our proctors observed notable subject curiosity in the embodied navigation model, which might correlate to increased durations in this particular mode of navigation. This notion is supported by the fact that subjects noted significant attributes of greater user satisfaction in the embodied navigation model. While timing serves as a sound qualitative measure, it is not necessarily a clear indicator of success when factored against qualitative user satisfaction metrics like enjoyment and immersion, which favor embodied navigation. We also recognize that cultural correlations for joystick and teleportation that exist outside of the world of gaming might further bias subjects toward these more familiar modes of operation. Further research is warranted to determine possible correlations between quantitative and qualitative measures, and cultural bias corollaries.

Data for **LF GCXP** and **VRXP** subjects averaged across our user satisfaction studies clearly favors existing modes of teleportation and joystick control, while **HF VRXP** subjects favored embodied navigation. In our pursuit of further research, we want to consider the merits of a normalized, universal velocity across these modes of navigation. For instance, constructing a limiter for the Arc length on the teleportation mechanic, and reducing the speed of the joystick controller, to scale appropriately with the embodied navigation speed. By "racing" the three navigation modes in a straight line to generate a speed multiplier that standardizes the average speed of each model, we could likely create more interesting results overall, across and between the separate modes of navigation. Our experimental data supports a trend towards abundant high user satisfaction scores for immersion across all three modes of navigation. However in Figure 6, we also note a considerably high Immersion score for embodied navigation, which had eight reports of a 10-grade (maximum) score on the user satisfaction scale for Immersion.

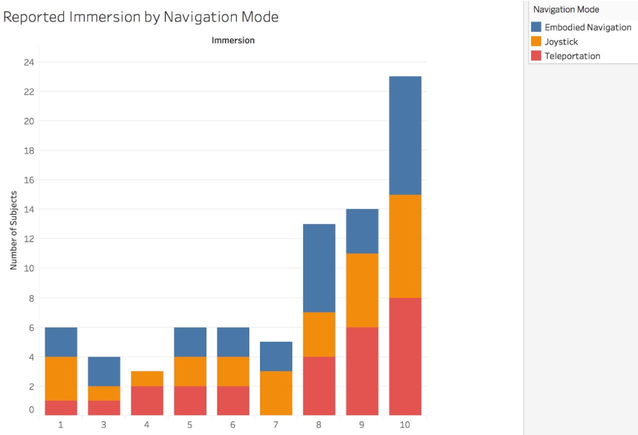

Figure 6. Immersion scale reports; (E) = blue, (J) = yellow, and (T) = red

Additionally, we want to address the limitations that were structurally present in the study. Due to a limited subject pool, we faced challenges in our sample sizes for each of our experimental groups. Additional subjects would accommodate our desire to consider further explorations into embodied navigation. Specifically, an increased sample size would allow for subsequent sub-classification of subjects into different modalities to investigate key variables of interest (e.g. the size, speed, acceleration curves, etc.) that dictate and alter the mobility and control settings of our embodied navigation model.

Conclusions / Further Research

While we anticipated our research would reflect that a current VR development bias toward gaming controller-based locomotion prevents accessibility and enjoyment for subjects in the **LF GCXP** and **LF VRXP** classes, we were interested to note that LF subjects rated higher user satisfaction in existing modes of VR navigation, while HF subjects gave embodied navigation higher ratings. Further research might explore cultural correlations outside of the gaming and VR experience that inform these biases.

We anticipated that embodied navigation would reduce on-boarding time (learnability, comprehension and execution of navigation method), resulting in improved maze navigation speeds. Clearly this was not supported by our data. Qualitative measures, however, do support increased user satisfaction and improved spatial awareness in the embodied navigation model. These findings suggest that embodied navigation may also serve memorability, warranting further research in this area.

Our study addressed many core interests regarding the applicability of our findings across a diverse, varied set of subjects. Our subject pool met our desired compositions for age, gender, gaming familiarity, and prior virtual reality exposure. In further research, we may wish to address variables of size and speed of acceleration curves that determine underlying mobility factors in our embodied navigation model, to explore their potential to reshape the reception of embodied navigation among a similarly diverse pool of subjects.

References

Abraham.M. Hashemian and Bernhard.E..Riecke. “Rotate and Lean: Does Leaning towards the Target Direction Improve Virtual Reality Navigation?” Models and Representations in Spatial Cognition Workshop, Tübingen, Germany. iSpace Lab, School of Interactive Arts + Technology, Simon Fraser University. 2017.

Ernst Kruijff, Bernhard E. Riecke, Christina Trepkowski, and Alexandra Kitson. “Upper Body Leaning can affect Forward Self-Motion Perception in Virtual Environments”. ACM SIGCHI Symposium on Spatial User Interaction (SUI ‘15). Bonn-Rhein-Sieg University of Applied Sciences, Sankt Augustin, Germany; Simon Fraser University, BC, Canada. 2015.

Alexandra Kitson, Abraham M. Hashemian, Ekaterina R. Stepanova, Ernst Kruijff, and Bernhard E. Riecke. “Lean Into It: Exploring Leaning-Based Motion Cueing Interfaces for Virtual Reality Movement”. ACM IEEE Virtual Reality 2017. Bonn-Rhein-Sieg University of Applied Sciences, Sankt Augustin, Germany; Simon Fraser University, BC, Canada. 2017.

Jacob B. Freiberg, Alexandra Kitson, and Bernhard E. Riecke. “Development and Evaluation of a Hands-Free Motion Cueing Interface for Ground-Based Navigation”. Simon Fraser University, BC, Canada. [Date].

Ernst Kruijff, Alexander Marquardt, Christina Trepkowski, Robert W. Lindeman, Andre Hinkenjann, Jens Maiero, Bernhard E. Riecke. "On Your Feet! Enhancing Vection in Leaning-Based Interfaces through Multisensory Stimuli". ACM SIGCHI Symposium on Spatial User Interaction (SUI '16). 2016.

Alexandra Kitson, Bernhard E. Riecke, Abraham Hashemian, and Carman Neustaedter. "NaviChair: Evaluating an Embodied Interface Using a Pointing Task to Navigate Virtual Reality". ACM SIGCHI Symposium on Spatial User Interaction (SUI '15). 2015.