Virtual Reality Navigation Within Confined Spaces and its Impact on Immersion

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CCS Concepts: • **Hardware** → Emerging simulation; • **Human-centered computing** → **Virtual reality**; *Gestural input*; *User centered design*; *Usability testing*.

Additional Key Words and Phrases: Locomotion, limited spaces, immersion, contradictory architecture, impossible spaces

1 INTRODUCTION

Immersive experiences within virtual reality (VR) have captivated audiences worldwide, offering unprecedented opportunities for exploration and engagement. Yet, within this expansive landscape of virtual realms, there exists a distinct gap in our understanding of navigation from a user's limited confined space and its impact on their immersion. Confined spaces, characterized by constrained dimensions and intricate designs, present a unique challenge for users to navigate and interact within virtual environments. This study aims to bridge this gap by investigating the immersive potential of navigating VR from confined spaces and its broader implications for user experience design.

VR immersion goes beyond mere entertainment by holding profound implications for various industries and fields. In education, immersive VR experiences can transport students to historical events, scientific phenomena, or cultural landmarks, fostering greater retention of complex concepts and deeper understanding. Healthcare can also benefit from VR simulations, wherein medical professionals hone their skills in safe and controlled training scenarios. Moreover, in therapy and rehabilitation, traditional therapeutic approaches can be complemented with immersive experiences that facilitate exposure therapy, pain management, and motor skills rehabilitation.

The motivation behind this project stems from the recognition of the profound influence that spatial constraints can exert on user immersion and engagement within virtual environments. While extensive research has been conducted on navigation in open-world settings, the dynamics of navigation from confined spaces remain relatively unexplored. Understanding how users navigate and interact within vast virtual environments from confined spaces is essential for optimizing the design of VR experiences across various domains, including gaming, education, simulation, and therapy. By uncovering the nuances of confined space navigation, we aim to unlock new avenues for creating more captivating and immersive VR environments, enriching the user experience, and broadening the applications of VR technology.

The findings of this study have the potential to improve the design and implementation of VR experiences across several domains. The development of dynamic and challenging gameplay mechanics can be enriched by a deeper understanding of how users navigate confined spaces. Diverse learning styles and education preferences can be better accommodated for in immersive VR learning environments. Furthermore, VR-based therapeutic interventions can use optimized navigation to enhance treatment effectiveness for those struggling with mental health disorders, physical rehabilitation, and phobias. Overall, this research has far-reaching implications for shaping human experience in the future of VR technology.

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2 RELATED WORK

While numerous studies have explored the principles of redirected walking and locomotion in VR, our research addresses a critical gap by focusing on individuals facing spatial constraints when attempting to immerse themselves in these virtual environments. Existing literature has extensively examined the effectiveness of redirected walking techniques and various locomotion methods, yet mostly fails to adequately consider the unique challenges encountered by users with limited physical space. By delving into this under-explored area, our study aims to provide valuable insights into how individuals navigate and interact within VR when confined to constrained environments, thus contributing to a more comprehensive understanding of immersive experiences in such contexts.

2.1 Locomotion

VR Locomotion refers to the methods of movement used for traversal within a VR environment. Costas Boletsis [1] reached several significant findings in their literature review on the topic. Eleven VR locomotion techniques were observed, with most being focused on physical interaction. Past research was also found to be heavily focused on improving VR from technological metrics, which has overshadowed other aspects of user experience. The most commonly used locomotion techniques include natural walking [27], touchpad, touchpad with joystick [2], and arm-swinging [10].

Daniel Christopher Locher and James Edward Gain [15] claimed that locomotion is integral and indispensable for user interaction within VR environments. Their research compares the most commonly used techniques in terms of performance and user experience. Task completion times were found to be fastest to slowest in the order of touchpad, touchpad with joystick, natural walking, and arm swinging. Natural walking was found to be the best in terms of system usability and immersion despite its mediocre task completion speed. In a similar study by Jiwon Lee et al. [13], walking in place has distinguished its better immersion than gamepad or gesture-based input devices. Frameworks have been developed to better classify locomotion. One such framework is LoCoMoTe, which compares themes including navigational decisions, technique implementation, and modalities [4].

Immersive VR environments risk harming some aspects of learning required in locomotion. A study on VR learning by Gustav Bøg Petersen et al. [21] saw many aspects of user learning improved due to being in VR, but negative relations were derived for declarative memory using embodied learning. In other words, there is a risk of a lack of congruence between body actions and content learned in the many techniques for VR locomotion.

Despite the potential drawbacks, there is potential for future applications to benefit users in relevant real-world contexts. Work has begun in developing VR nature walk experiences, which can provide access to the restorative properties of a real nature walk for those with limited time and availability [23]. Alexandre Gordo et al. have also begun incorporating VR for locomotion rehabilitation by allowing physiotherapists and patients to be in the same environment [8]. Their system called Locomotiver received positive feedback for its ease of customization, optimization of their methods, and improved diagnosis ability. Tools for VR rehabilitation have started to see use, with one study using VR for gamified neck rehabilitation [24]. More potential VR locomotion tactics could be learned from development in the field of mobile robotics, which includes several strategies and techniques for navigation. Adopting these in two simulated adapted redirected walking artificial potential field concepts has led users to experience faster exploration but led to a lower distance between resets [17].

2.2 Contradictory Architecture and Impossible Spaces

Changing how a VR setting is presented can change the user experience for better or worse. Previous research by Tiffany Marques et al. [18] has yielded positive experiences in the field of VR impossible spaces. For example, Jannik A. I. H. Neerdal et al. [19] demonstrated that proper use of self-overlapping environments results in seamless transitions. Multiple partial virtual environments were overlapped in a small space, while only one was displayed to the participant at a given time. Participants were likely to overestimate the perceived virtual area size and the vast majority of participants did not notice transitions during their experience. Techniques have also been developed to prevent presence-breaking experiences, such as by having narrow transition paths block the user's vision during rendering [7].

Another factor worth considering when designing a VR setting is whether the environments are indoors or outdoors. For example, a study by Jose Luis Saorin et al. [25] found that spatial perception, orientation, and immersion for users are lower in closed VR environments than in open ones. Elaborate system designs can encounter problems in user recognition. Niklas Steinhauser et al. [26] found in their study that a lawn sprinkler system expressed in VR could not be made easier to understand than physical expressions for users despite the possibility of more different representations.

2.3 Redirected Walking

A study by Mathieu Lutfallah et al. [16] compared immersion levels while changing locomotion techniques and architecture designs. The mean distance between resets was always increased using redirected walking, with greater increases on trials with overlapping architecture. Half of the participants were not able to recognize when the room layout was changed to overlapping, with less than half of the participants correctly identifying which trials used overlapping. Further work has also been conducted to reduce the number of required resets during traversal, such as by guiding the user to optimal directions with a two-arrow indicator [30]. Others were able to develop a mapping-based algorithm that decomposed the virtual path and mapping segments into smoothed curves, resulting in sped-up navigation and reduced distortion for users [22]. A study by Huiyu Li and Linwei Fan [14] advanced the field by introducing methods to enable real-walking roaming in virtual and real spaces of different space sizes and boundary shapes.

Further research from Eike Langbehn and Paul Lubos [11] applied the concepts of redirected walking and impossible spaces using a curved corridor. Redirection gains are toggled in overlapping rooms such that detection thresholds are not reached. Participants were not able to detect overlapping of the rooms. A single table from the physical world was represented as multiple virtual tables such that participants failed to recognize their similarity. Work to adapt redirecting walking methods to accommodate multiple users has recently seen success in a user study [29]. Attempts to introduce optical flow-generating vection for improving user immersion have had mixed results, as lacking familiarity with VR seemed to have an adverse effect on the user's curvature gain threshold [12]. Potential alternatives to redirected walking have been considered, with redirected teleportation resulting in taking less time, but inputs felt less natural, and less of the available tracking space was used [20].

2.4 Cybersickness and Immersion

VR Immersion has been proven to increase positive perceptions of various systems [3]. Minimizing cybersickness to improve immersion is one effective strategy for designing new VR experiences. A study by Simon Davis et al. [5] has categorized possible cybersickness symptoms in four sub-scores. A Nausea-related sub-score (N) is composed of symptoms including sweating, burping, stomach awareness, increased salivation, and nausea. The Oculomotor-related sub-score (O) is made up of symptoms including eyestrain, headache, fatigue, difficulty focusing, and eyestrain. A Disorientation-related sub-score (D) includes symptoms such as vertigo, blurred vision, dizziness with eyes closed, and dizziness with eyes opened. Combining results from these sub-scores gives a Total Score (TS) that represents the user's overall severity of cybersickness.

Further research has been conducted to evaluate VR cybersickness. A study by Kota Hoshino and Michael Cohen [9] has identified movement using teleportation with a VR controller thumbstick to have a greater risk of cybersickness than alternatives such as using smartphone orientation with arm swinging. Typical user experience evaluations include post-hoc questionnaires or surveys, with new technologies such as eye-tracking data allowing for a further drive towards improvements [6]. Pilot studies with eye-tracking have been able to produce data viable for quantifying immersion and presence [28], but such data is not able to fully evaluate the complex experiences of users in VR.

3 METHODOLOGY

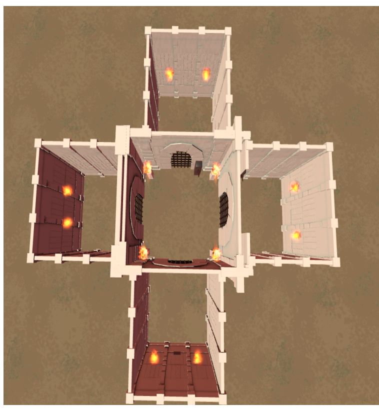


Fig. 1. Joystick scene.

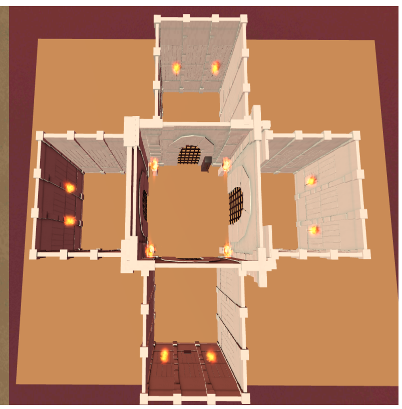


Fig. 2. Full teleportation scene.

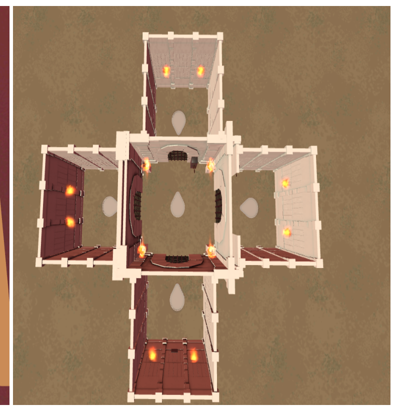


Fig. 3. Redirected walking scene.

3.1 Participants

All participants in the experiment were recruited voluntarily. A total of eight individuals took part in the study, comprising a diverse range of age groups, spanning from elementary school students to adults in their 40s. All participants were literate with computers and technology, although they had limited prior exposure to VR environments.

3.2 Interface

The experiment utilized a Meta Quest 3 VR headset with 128GB storage capacity, providing participants with an immersive virtual environment. The software employed for this experiment was a Unity project created using editor version 2022.3.21f1. The desktop used to run the application during the trials was equipped with Windows 11 Home, a 13th Gen Intel(R) Core(TM) i9-13900Ks CPU @ 3.2 GHz, an NVIDIA GeForce RTX 4090 GPU, and 64GB of memory at a speed of 6000 MHz.

3.3 Procedure

The tasks were clearly described before the participant was to embark on a trial: the goal of the participant was to find and interact with the dragon egg as fast as they could. The participants were told that in order to find the dragon egg they would need to go through every room by interacting with the levers that opened the doors, and then interact with the button in the final room for the altar with the egg to appear. There are three scenes, each designed to accommodate a different method of locomotion. The participant was told beforehand which locomotion method they were using for the trial and how it works, instructed on how to interact with the key objects, and that they were going to be asked about their experience afterward. Upon entering the scene the participant was allowed to familiarize themselves with the virtual environment and method of locomotion from within the starting area of the trial; Timing began only when participants interacted with the first lever, and the time concluded upon completing the task or reaching a predetermined time limit. Metrics were recorded for the trial immediately after completion through a questionnaire about the previous experience. Participants were instructed to perform to the best of their abilities and were required to continue the trial upon any errors. Errors were not recorded, only completion time up to the time limit, where if they weren't finished they would be asked to stop.

The experiment consisted of multiple trial repetitions, with each trial focusing on a different locomotion method. Figure 1 shows the map design for the Joystick method, which is the base-level design assuming freedom of movement through the use of a joystick, where the user would be instructed to remain seated for the duration of the trial and use only the controllers for movement. Figure 2 shows the map design for the full teleportation method, which is the base-level design with a change to the floor so that users can teleport anywhere that isn't obstructed by an object. The participant was instructed to remain seated for the duration of the trial, instructed on the details of teleportation within the map, and was only given the right controller to remove the chance of alternative techniques. Figure 3 shows the map design for the redirected walking method, where the user would physically walk through the level but use the teleportation pads to move between rooms. The user was provided a 6ft x 6ft space to traverse with the boundary preset into the VR headset, given only the right controller to prevent accidental joystick movement, and instructed on how to use the teleport pads, only while standing on another teleport pad, in order to allow the user to fully explore every room of the scene without physically running out of room. Short rest breaks were allowed and encouraged between trials to minimize fatigue and ensure participant comfort. During the trial, participants were encouraged to finish with as few breaks as necessary within a reasonable time limit.

The time per trial varied depending on the complexity of the navigation task and the locomotion method being evaluated but was limited to five minutes per trial. Detailed records of the time taken for each trial were maintained for analysis. Total time for the experiment encompassed the duration of all trial repetitions, rest breaks, and additional briefing and debriefing sessions. This structured approach ensured that participants were guided through the experiment systematically, with considerations for their comfort, and overall experience within the virtual environment.

3.4 Experiment Design

The experiment investigates the impact of different locomotion methods on user immersion within confined spaces for an expansive virtual reality (VR) environment, focusing on the independent variable of the locomotion method. Participants are exposed to various locomotion techniques, including full teleportation, walking with redirection techniques, and joystick, with each method serving as a distinct condition. The dependent variables include measures of immersion, VR motion sickness, frustration, and task completion time, collected through questionnaires administered after each trial. The control variables include the size of the level, where each room was the size of the physical space allotted for the user, the size of the physical space for the user, being 6ft x 6ft which was the size of one room of the level, and the base design of the level so that the only difference would be the required changes for the different locomotion techniques; Additional control variables include the time limit of 5 minutes for the user to complete the task and the procedure for each trial. The purpose of the experiment is to determine how different locomotion methods affect user immersion and engagement within the limited physical space of the VR environment. The study employs a within-subjects design, allowing participants to experience and evaluate multiple locomotion methods, thereby minimizing individual differences and increasing the reliability of the findings. By systematically manipulating the independent variable and measuring its effects on the dependent variables, the experiment aims to provide insights into optimizing locomotion techniques for enhanced user experiences in VR environments.

4 RESULTS

After each trial was completed, participants rated their experience of motion sickness, frustration, and immersion on a scale of 1 to 5 where a larger number correlated to a larger amount of that feeling being present in their experience. The averages of these scores were used to compare the methods of locomotion for their impact on these metrics.

4.1 Joystick

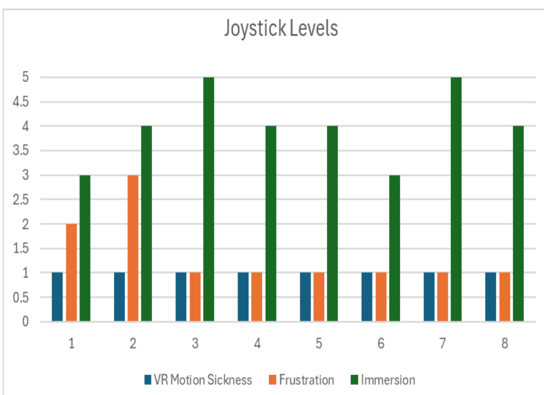


Fig. 4. Survey results after completing the scene traversal with the joystick.

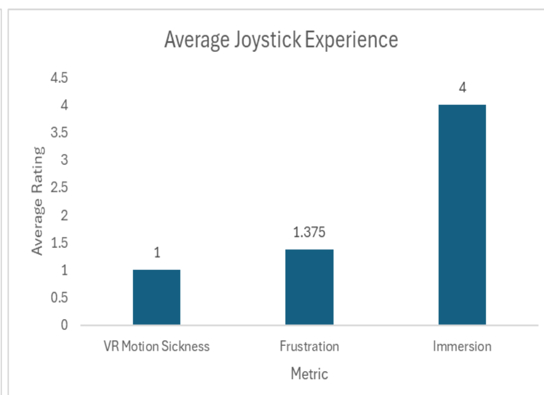
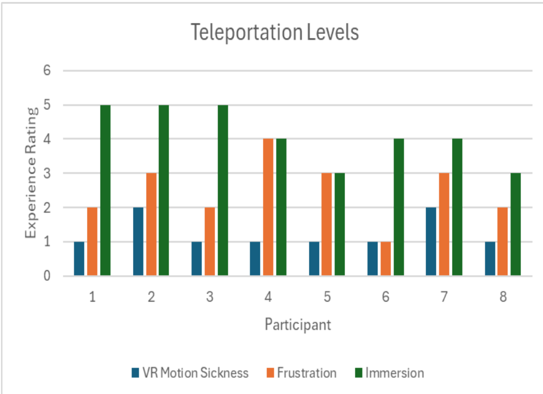


Fig. 5. Average rating from joystick experience.

The joystick trial involved participants sitting in a chair and navigating the scene while only utilizing their left joystick for movement. Participants noted their feelings of VR motion sickness, frustration, and immersion as seen in Figure 4. All participants gave a rating of 1 for motion sickness meaning that they did not experience any. Frustration values ranged from 1 to 3 to display out of 5 how frustrated they were. Immersion ratings from our participants ranged from 3 to 5 with 5 being completely immersed. Averages of these ratings, as seen in Figure 5, show that the average motion sickness rating was 1, the frustration average rating was 1.375, and the immersion average rating was 4.

4.2 Teleportation



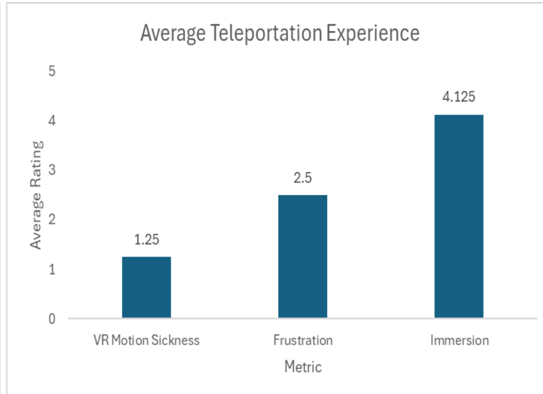
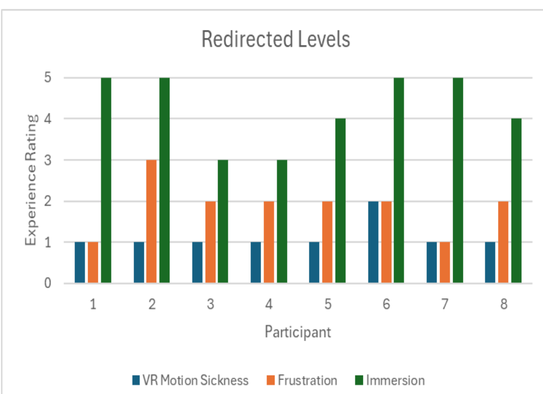


Fig. 6. Survey results after completing the scene traversal with the joystick.

Fig. 7. Average rating from teleportation experience.

The teleportation trial involved participants sitting in a chair and navigating the scene by teleporting to different locations on the floor. During this trial participants only had the right controller available to them. Participants were asked to scale their feelings of VR motion sickness, frustration, and immersion from this trial as seen in Figure 6. Teleportation had motion sickness results of either 1 or 2, frustration reported between 2 and 4, and immersion rated between 3 and 5. The averages of these values are depicted in Figure 7 with averages of motion sickness of 1.25, frustration averaging 2.5, and immersion averaging 4.125 from the experiences of the participants.

4.3 Redirected Walking



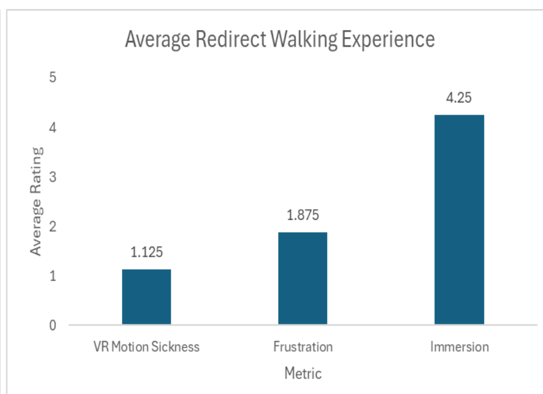


Fig. 8. Survey results after completing the scene traversal with redirected walking.

Fig. 9. Average rating from redirected walking experience.

The redirected walking trial had participants starting in the middle of a 6ft x 6ft room and only having access to the right controller. Participants were instructed that they could teleport between pads but were told only to do so from standing on the pad in the middle of the room they were currently in. While performing this trial, participants were told to move close to the physical objects they were interacting with and to only move with physical movements besides teleporting between rooms. The experiences of the participants were recorded in a survey and looked at in Figure 8.

The motion sickness for this trial was rated between 1 and 2, frustration was rated between 1 and 3, and immersion was rated between 3 and 5. The averages of this were taken and put into Figure 9 to be used to compare to the other locomotion methods.

5 DISCUSSION

Our results show that each VR locomotion method has its own set of advantages and drawbacks. Participants using redirected walking reported the highest levels of immersion with middling feelings of motion sickness and frustration. When they used joystick locomotion, participants expressed the lowest levels of frustration and motion sickness but also felt the least immersion. Teleporting for movement had participants report middling feelings of immersion but the greatest amounts of motion sickness and frustration. Speeds of navigation were in the order of teleportation being slowest, redirected walking being faster, and joystick being fastest. These results suggest that any of these methods of locomotion are viable given the developer's goals.

The results of our study give a better idea of how to get the most out of redirected walking. Expansive environments are a good fit for this method of locomotion in that users physically walking will become engrossed in the setting with seamless navigation. Real-world simulations would also benefit from redirected walking because walking through the virtual world as you would in a physical space allows for experiences that closely mimic real-life situations. A VR open-world exploration game is one example where redirected walking is an appropriate choice of locomotion. An architectural design simulator in VR would similarly benefit from being able to walk around as you would in real life. Other VR situations might be poorly suited to the inclusion of redirected walking. A surgical training simulation would require precise movement control and hand-eye coordination, which might be better suited to more focused and controlled locomotion. Those with mobility issues, physical disabilities, or motion sensitivity are unlikely to have good experiences in redirected walking.

Teleportation in VR has different factors to consider. Those new to the method of locomotion had higher feelings of frustration and motion sickness with slower task completion times than those with more practice, introducing a barrier of entry for widespread use of the technique. Users with more experience in VR would instead have fast task completion times with less motion sickness. Considering a need for practice, teleportation can be a good fit for fast-paced experiences or experiences involving limited physical space. Inclusive VR experiences would benefit from teleportation because those with motion sensitivity, mobility issues, or physical disabilities would have an easier time using teleportation than alternatives. Puzzle-solving games could use teleportation to create surreal experiences impossible in real life. Moving with teleportation is worse suited for open-world exploration games or narrative-driven games because teleportation disrupts the flow of the experience.

Joystick-based locomotion in VR also has unique aspects worth considering. This locomotion method is more familiar to those who have gamed on older consoles and devices. Also, this method is faster than teleportation and redirected walking in small settings (depending on the environment's settings). Longer use, typically associated with larger environments, has a significant risk of inducing motion sickness and reducing immersion. A traditional gaming experience, such as a platformer, created for VR would better replicate the experience of older games by using a joystick. A difficult tight space navigation game would also benefit from the high degree of control over movement included with a joystick. However, a vertigo-inducing environment such as one with dizzying aerial maneuvers should avoid joysticks due to a high chance of discomfort through their use. Some VR environments use unpredictable or dynamic terrain, which would be less enjoyable when experienced with a joystick.

5.1 Future Work

There are several yet unexplored areas to continue off from our research that seem promising. One direction that can be furthered is utilizing more methods of redirected walking to be compared to. In our project we only utilized overlapping spaces via teleportation; There are many other methods of implementing redirected walking that should be studied such as impossible spaces, curvature gain, and dynamic scaling. Another direction that should be developed is additional methods of locomotion. There are many promising VR locomotion techniques that we haven't included such as arm swinging, gesture-based locomotion, voice commands, or even gaze-based navigation.

6 CONCLUSION

In this project, we ran a study where eight participants performed three trials each, navigating the three slightly altered versions of the same level, each designed to accommodate a different method of locomotion, all designed to allow the participant to navigate the entire area despite limited physical space. One level was designed for movement through a joystick, one for teleportation, and one for redirected walking. The participants participated in every trial, navigating through the level with the appropriate navigation technique, opening the doors by interacting with levers, summoning the dragon altar by interacting with the button, and finishing the level by interacting with the dragon egg. By timing the participant from the switching of the first lever until the interaction with the egg we were able to determine how well each locomotion technique did for basic usability analysis. Immediately after the participant finished each trial they filled out a survey that gave information on their feelings of VR motion sickness, frustration, and immersion.

The main takeaway of changing VR locomotion techniques was that no single technique is better in every possible situation. Environment developers maximizing task completion speed, minimizing frustration, or minimizing motion sickness should consider joystick locomotion. Developers wanting to maximize immersion should consider redirected walking. Those improving their experiences in other aspects or minimizing tradeoffs should consider teleportation. Further work could evaluate these locomotive methods using more participants and a more elaborate and consistent level design.

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