

The Effect of Impossible Spaces on The Choice of Locomotion Techniques

Mason Hawver

Evan Voogd

hawve005@umn.edu

voogd004@umn.edu

University of Minnesota - Twin Cities

Minneapolis, Minnesota, USA

Abstract

One of the most commonly researched topics in Virtual Reality is locomotion, or the set of methods that can be used to move a player around in space. The most natural, walking physically in a space, is optimal, but given the limited amount of space available to most users, it is not realistic in many spaces. Impossible spaces have been developed as a way to overlap the user's space to result in them being able to access a higher proportion of the map without having to rely on less realistic, non-walking locomotion techniques. While prior research has established that impossible spaces can be implemented with little detriment to the user experience - maintaining presence and spatial awareness while not being detectable by users unless the overlap is extremely high - little research has been conducted into seeing whether or not impossible spaces actually accomplish their primary goal of reducing user reliance on these alternative methods of locomotion. We conducted an experiment, where users traverse through two similar environments to see if overlapping space resulted in them decreasing their usage of alternative locomotion techniques - in our case, joystick-based locomotion and teleportation-based locomotion. We find that impossible spaces significantly decrease the amount of time users spend using joystick-based locomotion while not having a significant impact on the number of times a user teleports.

Keywords

Virtual Reality, Impossible Spaces, Unity, Locomotion, Non-Euclidean Spaces

1 Introduction

The best form of locomotion in VR is natural walking because it allows a user to naturally move around in a virtual world in the same way they would in the real world. However, not everybody has a large open space for them to achieve this. To overcome this, developers have included joystick locomotion and teleportation, so the user can move around in any virtual space in a constrained physical space. There have been other, more subtle techniques to address this like curved walking paths, but we want to explore the technique of using non euclidean virtual impossible spaces to pack more virtual space into the physical space available to a user. To construct a non-euclidean space in VR we have connected many disjoint euclidean spaces together with seamless portals. This allows rooms to overlap each other, effectively increasing the usage of physical space.

There have been past works exploring the use of non-euclidean spaces in VR, but they mostly test the level of disorientation that a user experiences based on different levels of overlap between spaces. For instance Suma et al introduces the concept of impossible spaces while testing the maximum overlap that can be achieved without it being noticed by users [16]. Other studies found that non-euclidean spaces have a negligible impact on presence [9], while preserving spatial orientation [8], and navigational abilities [3]. While these studies prove the feasibility of impossible spaces in terms of reducing any negative impact on user experience, the question remains on if the additional complexity of building impossible spaces is worth the effort. Building impossible spaces requires the developer to visualize how these disjoint spaces connect with each other, complicating the level design process exponentially as the number of spaces increases. Additionally, impossible spaces in VR require an additional camera being rendered for each eye to display the portal, so it further intensifies the already high computational requirements of VR applications. Thus, it is important to see if an application uses impossible spaces, does it reduce the user's use of less realistic controller-based locomotion methods? Will a user use head tracking, joystick, or teleportation locomotion more with or without non-euclidean spaces? Additionally, we have plotted out a user's motion through time and evaluated the differences in their trajectories in normal spaces vs non-euclidean spaces.

With the above data, our goal is to determine a general idea of how impossible spaces affect user behavior, such that developers can choose whether or not the benefits of implementing them in their projects outweigh their additional complexity of implementation and computational requirements.

2 Related Work

2.1 Alternate methods of increasing reliance on natural walking

Impossible spaces were not the first method employed within the VR space to accomplish the general goal of increasing user reliance on natural walking. It is important to also be aware of these other methods, especially due to the lack of studies comparing their relative effectiveness at accomplishing this goal.

2.1.1 Treadmills. Perhaps the oldest class of method to increase reliance on natural walking is the treadmill, where the user walks on a moving platform, so they can walk naturally without leaving their usable space.

One of the earliest methods in this class does not involve a physical treadmill at all. "The Virtual Treadmill", proposed by Slater

et al, involves the user walking in place within an environment, moving in the direction they face[14]. However, this method was not particularly successful at mimicking natural walking, with as many participants finding use of a mouse more natural than the virtual treadmill as found the virtual treadmill more natural.

With this in mind, the goal shifted from mimicking a treadmill to developing different treadmills and treadmill-like devices to allow a user to move within space. One of the earliest such devices was the Torus Treadmill, developed by Iwata, which uses several smaller treadmills attached to each other to create an infinite, torus-shaped walking surface[5]. Movement using the Torus Treadmill was more accurate than joystick-based locomotion methods, and users were able to maintain stability without any devices such as safety harnesses. However, the device was fairly large (2m by 1.8m) compared to its small moving surface (1m by 1m). Additionally, due to this small movement surface, the user was limited to a maximum speed of 1.2m per second, on the slower end of the average walking speed. Additionally, the small walking space limited the stride distance of users, resulting in them taking smaller steps than they would using natural walking.

Iwata later refined the Torus Treadmill into the CirculaFloor, a series of moving panels that also simulates an infinite surface by moving the panels into the direction of the user's motion[6]. This system required significantly less space than the Torus Treadmill, but further worsened the walking speed problem, with a maximum speed of only 0.33 meters per second. One final treadmill-adjacent method developed by Iwata, the String Walker, moved away from flat surfaces altogether and instead utilized four strings connected to each of the user's shoes, pulled by a system of motor-pulley devices to keep the user within the center of the device[7]. However, this system required a fairly large space to implement (4m by 6m) for a relatively modest increase in walking space over the Torus Treadmill (a circle with a diameter of 1.8m).

One later omni-directional treadmill is the CyberWalk, which used a similar approach to the original Torus Treadmill, albeit with a larger footprint for walking space (4m by 4m) and a greater proportion of the total footprint taken up by said walking space[15]. The greater walking space additionally allowed a much faster maximum speed than either of Iwata's device, allowing a maximum speed of 2m per second, which is generally enough to accommodate the average walking speed.

2.1.2 Redirected Walking. Another method of increasing reliance on natural walking that predates impossible spaces is redirected walking, proposed by Razzaque[12]. In redirected walking, the scene gradually rotates around the user. By imperceptibly rotating the scene while the user is in motion, the user turns themselves in order to preserve their orientation. Over time, the user can be redirected away from restrictions in usable space, e.g. a boundary wall or a pole. One goal of redirected walking, which is common to all techniques attempting to increase reliance on natural walking, is attempting to minimize cybersickness. Razzaque proposes to keep the frequency of rotation below the visual-vestibular crossover frequency, minimizing the difference between the motion seen by the user's vision and the motion felt by the user's vestibular system, as this has been found to be a major cause of cybersickness. Through careful tuning of this redirection frequency, Razzaque was able to

accomplish this goal, with an SSQ score (Simulator Sickness Questionnaire) with a 75th percentile one-third of that of a traditional controller-based locomotion technique.

With this, it's clear how redirected walking can be seen as a precursor to impossible spaces. Both aim to reduce cybersickness (and theoretically increase presence) by increasing the user's reliance on natural walking. However, redirected walking is not without its flaws, as it can only be seriously employed in a larger space, as Razzaque found that the detection threshold while walking is only approximately 1 deg/s. In a fairly large space for a home user of approximately 10ft. by 10ft, a user walking at an average pace can reach the opposite end of a room in approximately 3 seconds. With only 3 degrees of rotation achieved in this timeframe by redirected walking, it's clear that, in smaller spaces, it is not a sufficient method by itself to increase reliance on natural walking.

2.2 Early work in impossible spaces

As discussed in the introduction, Suma et al. introduced the concept of impossible spaces to the VR literature, describing the theory/implementation behind them, and running an experiment to determine the maximum amount of overlap that an impossible space can contain before it is noticed by a user[16]. The paper found that this overlap is around 56% for "small rooms" (tested with a room with the dimensions 3.66m by 7.32m) and 31% for "large rooms" (tested with a size of 9.14m × 9.14m). Additionally, the paper hinted at future research into how impossible spaces affect user perception of space, finding that users' perception of distances within impossible spaces are equivalent to if the spaces did not overlap, even if the level of overlap was high enough to be noticeable by users.

Robb and Barwulor expanded on this investigation into the perception of space, conducting an experiment to see how impossible spaces impact users' ability to remember the locations of objects[13]. Unsurprisingly, participants had a harder time keeping track of objects in overlapping spaces versus non-overlapping ones, no matter the percentage of overlap. Based on this, they theorized that subconsciously users must be adapting their mental model of spaces based on perceived differences in sizes of objects/rooms and the size of real world equivalents of simulated spaces.

2.3 Presence within impossible spaces

Mayor et al. investigated the impacts of impossible spaces on presence, conducting quantitative tests and qualitative surveys with users after the experiment[9]. The experiment found that impossible spaces have no significant effect on presence compared to traditional euclidean spaces. Despite this finding, some researchers have seen opportunity in impossible spaces as a way to increase presence. Theoretically, in experiences that do not require a high level of spatial awareness, it would be easier for the user to have a higher level of presence in an impossible space versus a traditional euclidean space, as their locomotion would be closer to that of the real world. One such paper was Murray and Vigentini who attempted to optimize impossible spaces to increase presence[10]. In their preliminary findings they found that participants preferred locomotion within an impossible space versus a euclidean space,

along with the unintended benefit of decreasing the users' cybersickness (referred to as Visually Induced Motion Sickness in the paper).

2.4 Spatial awareness and pathfinding within impossible spaces

Another avenue of research in assessing user experience within impossible spaces was provided by Jaksties et al, which assessed how well users could maintain spatial awareness and knowledge of their orientation within impossible spaces.[8] To do this, they built a "magical tower" VR game, where the player must find four hidden items throughout an impossible space, and return them to the starting location. Accomplishing this task requires the user maintaining a mental model of the space, as the puzzles require knowledge of their orientation. They found that players were able to maintain knowledge of their orientation, and were not particularly frustrated by the map.

Spatial awareness within impossible spaces is an area of research within psychology as well. Research within this field dates back to at least the 1980s, with Golledge and Hubert's research on the concept of mental maps[2]. Golledge and Hubert were not studying non-euclidean spaces directly, but rather attempting to model how the human, or more generally mammalian, brain holds a "mental map" of its surroundings. They theorized that these mental maps did not match traditional euclidean geometries, and instead inherently contain folds, tears, and most importantly warps. While this predates Suma et al's introduction of impossible spaces by 30 years, the fact that, even when exploring euclidean spaces, the mind inserts warps - equivalent to portals within an impossible space - into their mental map suggests that the brain should be equipped to handle the non-euclidean mental maps required to maintain spatial awareness within an impossible space.

More recently, Warren theorized that even the sorts of non-linear transformations on euclidean space suggested by Golledge and Hubert do not properly represent humans' mental maps, instead they are better modeled by graphs[18]. Crucially, what this means is that the spatial information encoded by mental maps in the human brain do not follow a euclidean coordinate system, instead they are modeled by a graph, with nodes and edges, augmented by angles/edge lengths to mimic a euclidean system. This provides an even clearer rationale for navigation within impossible spaces in VR than Golledge and Hubert - impossible spaces themselves can be thought of as graphs, with the portals between disjoint spaces being represented by edges. In fact, Walker supported his hypothesis in this paper by building an impossible space. In this experiment, he built two similar virtual mazes - one euclidean, and one with a "wormhole", analogous to what we refer to as portals. The portals not only changed the location of the user, but also rotated the user 90 degrees, to throw off their sense of orientation as well. Even with this, users were able to navigate the maze under both conditions (although they took a less direct route than that of the euclidean group). Additionally, aligning with previously discussed research, users did not notice the wormhole. With this research, we have a psychological foundation for how humans can maintain spatial awareness and navigate successfully within impossible spaces.

Warren's hypothesis was further supported by Murry and Glennerster, who conducted a similar experiment, while focusing more on deviation from the optimal path rather than simple completion versus incompleteness[11]. Specifically, they compared two different models of decision-making for when a user entered a junction - a simple "shortest-distance" model where they choose the path that aligns the closest to the euclidean direction of the target, or the rewarded-choice model where they make similar decisions to what progressed them successfully earlier on in the maze. The study found that the rewarded-choice model better explained user behavior in impossible spaces, showing that users tend to make decisions at junctions (nodes in a graph of the impossible space) that mirror previously successful decisions. This further shows how navigation can be natural within impossible spaces, as users can be trained into making correct pathfinding decisions by consistent level design, mirroring prior successful decisions even if they disagree with the decision with the apparent shortest euclidean distance.

One final iteration of the pathfinding experiment was conducted by Hylten, who took a more prescriptive approach, analyzing if impossible spaces degraded players' pathfinding to an extent that it would be inadvisable to be used within a VR game[3]. Hylten conducted a similar experiment to the previous two studies, with the user attempting to traverse two mazes, one euclidean, one non-euclidean. Interestingly enough, Hylten found that users of the non-euclidean maze completed the maze faster (albeit just above the significance threshold) than the users of the euclidean maze. With this in mind, Hylten advised that game design could be advanced by incorporating impossible spaces without a detriment to their navigational abilities.

3 Project Overview

With prior research supporting that impossible spaces could be implemented with little to no detriment to user presence or spatial awareness, we moved to answer the question: is the challenge of implementing impossible spaces worth it? Or more precisely, how well do impossible spaces solve the problem of limiting the user's use of unrealistic, cybersickness-prone locomotion techniques such as joystick-based locomotion or teleportation?

3.1 Problem Definition

To answer this question, we first need to formally define impossible (or non-euclidean) spaces. An impossible space is a space that cannot exist in a euclidean system, and can instead be modeled as multiple disjoint euclidean spaces that the user is teleported between. This can be accomplished either using portals that show the user the side they will be teleported to or replicas of the opposite side beyond the teleportation point. In our implementation, we chose to use portals, as they are easier to implement with higher levels of overlap. To implement our project, we used the Unity game engine[17] and its built-in XR development tools. In our implementation, we built several disjoint maps within the same scene, and the user was teleported between them using portals.

3.2 Portal Implementation

Our portal implementation can be thought of in two, relatively independent, components. The first is the visuals of the portal, or

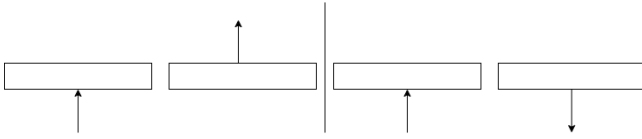


Figure 1: Left side denotes the most common portal teleportation arrangement, right side denotes our desired portal teleportation arrangement.

how the user sees their perspective on the other end of the portal before entering. The second is the teleportation, moving the user to and from the portal. The visuals went through several iteration, with the final iteration being based on a publicly available tutorial[4]. The teleportation implementation for the portals was created by us, as most portal implementations are designed in a way that we found unsatisfactory. This can be visualized in Figure 1. In most implementations, the user is teleported to the opposite face of the portal than the user entered. In an impossible space implementation, this is undesirable, as the opposite face will generally be a wall, so the user must reverse orientation.

The portal is set up as a cube with a Box Collider and an attached Portal script. The rendering for all portals is handled by a separate Portal Camera object, with one camera for each eye, allowing stereoscopic depth in the portal in VR.

3.2.1 Visuals. The visuals of every portal is handled by the Portal Camera object. The portal camera possesses a reference to the first portal the user encounters in each pair of portals, as well as a camera for each eye. The portal is rendered using two Render Textures for each portal, one for each eye.

For each frame, first, the Portal Camera finds the closest portals to the user, to avoid unneeded rendering of far-away portals. Next, the stereo projection matrix of each eye of the main camera is copied over to the projection matrix of the respective portal cameras. Next, the camera sets the texture for the closest portals to the respective Render Texture for each eye, as well as setting the output render texture for the portal to its respective texture.

Next, the portal cameras are moved to their relative location with respect to the user's eyes. First, the portal cameras are moved to the position of the main camera. Next, the position of the main camera relative to the near portal is calculated. This is adjusted so it is rotated, so that it is relative to the opposite plane of the portal, instead of the near plane, and then this is translated to the corresponding position of the linked portal. This transformation ensures that the camera is rendering what the user will see as they exit, due to our unorthodox teleportation arrangement shown in Figure 1.

Once this relative position has been calculated, the relative rotation must also be calculated. This is done similarly to the position, where the rotation relative to the near portal is calculated, flipped to point at the far plane of the portal, and then translated to the corresponding position relative to the linked portal.

Finally, the projection matrix of the portal must be calculated. Firstly, a clip plane is calculated, with a normal opposite to the normal of the front plane of the linked portal, and an in point positioned in front of the linked portal, ensuring that the clip plane

is a developer-scalable distance in front of the linked portal to prevent the camera from showing the linked portal on the portal's surface. This plane is then represented in world space, and then transformed into the camera's space.

Once the clip plane has been calculated, the oblique matrix is calculated next. First, the inverse matrix of the main camera's projection matrix is calculated, and this matrix is multiplied by a vector to determine the plane's projection space alignment. Next, the earlier derived clip plane is scaled, and it is used to adjust the projection matrix to move the clipping plane into the earlier calculated position. This resultant matrix is oblique, meaning it accounts for the developer-tuned clipping plane to avoid rendering the portal. Finally, the portal camera's projection matrix is set to this oblique matrix, and the camera is told to render.

3.2.2 Teleportation. The teleportation is triggered by the user entering into the Box Collider of the portal. To prevent clipping the face of the portal before teleportation, the Box Collider is placed slightly outside of the actual mesh of the portal itself. This, along with the "Is Trigger" flag, allow the portal to be triggered by the user entering the portal by either physically walking or using their joystick.

One challenge we encountered when developing the teleportation is that physically walking does not update the transform position of the XR Origin, while using the joystick does. This meant, when we used the Box Collider using the collision event, we were able to teleport when the user entered the portal using a joystick, but not when they walked into it. To fix this, instead of waiting for a collision event, upon each call to Update, the portal checks to see if the camera is within the bounds of the box collider, as the Camera transform position does update upon the user walking.

Once the portal has detected that the user has entered the portal, the portal calculates where the camera intersected with the front plane of the Box Collider. This position, in local coordinates, is converted to the equivalent position in the linked portal. Essentially, if the user enters in the left side of the portal, they're teleported to the left side of the linked portal.

Next, the orientation of the user is calculated. The portal first calculates what angle the user is looking at relative to the portal, and then calculates what angle the camera should be pointed at relative to the linked portal. After this, the camera is further rotated another 180 degrees so they're facing away from the linked portal.

The last step from the user perspective is actually teleporting the user. Using the intersection point calculated earlier, two further transformations are made. The first, is a small push in the direction normal to the linked portal's face to ensure that the user isn't teleported into the Box Collider of the linked portal, resulting in a teleportation loop. The next adjustment is to subtract 0.85 from the position in the y-axis. This is because the XR Origin's MoveCameraToWorldLocation function adjusts the y-axis to account for the camera offset. However, as the camera offset is already accounted for by finding the intersection with the Box Collider, we subtract this value to undo this effect.

The final step is not related to teleporting the user, but instead to prevent camera artifacts between the linked portals. In our implementation, two linked portals cannot be rendered at the same time, as it results in artifacting due to only using two cameras for

all portals. To solve this, we only render one portal at a time, so we must disable the Renderer of the portal the user entered, enable the Renderer of the linked portal, and swap the Portal Camera's reference to the entered portal with that of the linked portal.

3.3 Map Design

The Euclidean map was designed as a simple square layout, consisting of four rooms arranged linearly along the perimeter of the square. Participants progressed through each room in sequence before reaching a central area, which featured a natural environment. This nature area, complete with grass and trees, was deliberately designed to attract users, leveraging humans' innate appreciation for greenery. Each room was furnished with interior decorations intended to distract users and serve as a basis for post-task questions about their experience. These distractions aimed to ensure that participants focused on their exploration rather than consciously considering their choice of locomotion.

The non-Euclidean map retained the same linear progression as the Euclidean map, with users traveling through four rooms in the same order before reaching the central nature area. However, the four rooms preceding the center were spatially compressed and overlapped using portals, effectively fitting the virtual layout into the same physical space as the Euclidean map. Remarkably, most participants did not immediately notice the portals, even when the geometry appeared impossible at a glance. It was only upon walking through them that subtle rendering artifacts became apparent, an issue still under refinement. Additionally, minor differences in room interiors were introduced in the non-Euclidean map. These changes encouraged participants to search for discrepancies between the two maps, further distracting them from deliberate decision-making about their locomotion methods.

3.4 Experiment

3.4.1 Experiment Setup and Design. The purpose of this experiment was to study the effect of non-Euclidean virtual environments on users' locomotion. Two groups of participants were tested:

- **Control Group:** Participants explored a normal VR level and answered questions about the theme of each room. This task aimed to distract them while allowing the collection of locomotion data.
- **Experimental Group:** Participants were shown the same normal level but then tasked with exploring a non-Euclidean VR level. In this level, virtual space was compressed into physical space, fitting several rooms into the same physical area. Participants were asked to spot minor differences in decorations or interiors between the two levels.

Participants were free to move naturally, teleport, or use the joystick for continuous movement. Movement data was categorized as follows: Time spent using the joystick, Time spent walking, The number of times participants teleported (teleportation was instantaneous and thus excluded from time measurements).

3.4.2 Hypotheses and Expected Results.

- **Hypothesis 1:** In the experimental group, participants would spend relatively more time walking compared to

using the joystick, due to the compact nature of the non-Euclidean space.

- **Hypothesis 2:** Participants in the experimental group would teleport less frequently than those in the control group, as the environment required less movement between rooms.

Expected Results:

- The experimental group would exhibit a higher ratio of walking time to total movement time compared to the control group.
- The experimental group would perform fewer teleportation actions compared to the control group.

4 Results

4.1 Statistical Analysis

Overview of Statistical Method:

To compare the control and experimental groups, we used a two-sample t -test, a standard statistical method to evaluate whether the means of two independent groups are significantly different. The test assumes the data is approximately normally distributed and calculates the t -statistic using the formula:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

Where:

- $\bar{x}_1, \bar{x}_2$: Mean values of the two groups.
- s_1^2, s_2^2 : Variances of the two groups.
- n_1, n_2 : Sample sizes of the two groups.

The resulting t -statistic reflects the size of the difference between the group means relative to their variability.

Hypothesis 1: Relative Time Spent Walking

We calculated the ratio of walking time to total movement time for both groups and performed a two-sample t -test. Using the data from Table 2:

$$t(4) = 5.46, \quad p = 0.0027$$

Where:

- The degrees of freedom $t(4)$ are determined by the formula for independent t -tests, which combines the sample sizes of both groups ($n_1 + n_2 - 2 = 4$).
- The p -value indicates the probability of observing the data under the null hypothesis (no difference between groups).

Since $p < 0.05$, we reject the null hypothesis. The experimental group spent significantly more time walking relative to joystick use.

Hypothesis 2: Number of Teleports

We conducted a two-sample t -test on the number of teleports:

$$t(4) = 1.36, \quad p = 0.123$$

The larger p -value indicates insufficient evidence to reject the null hypothesis. There is no significant difference in teleportation frequency between groups.

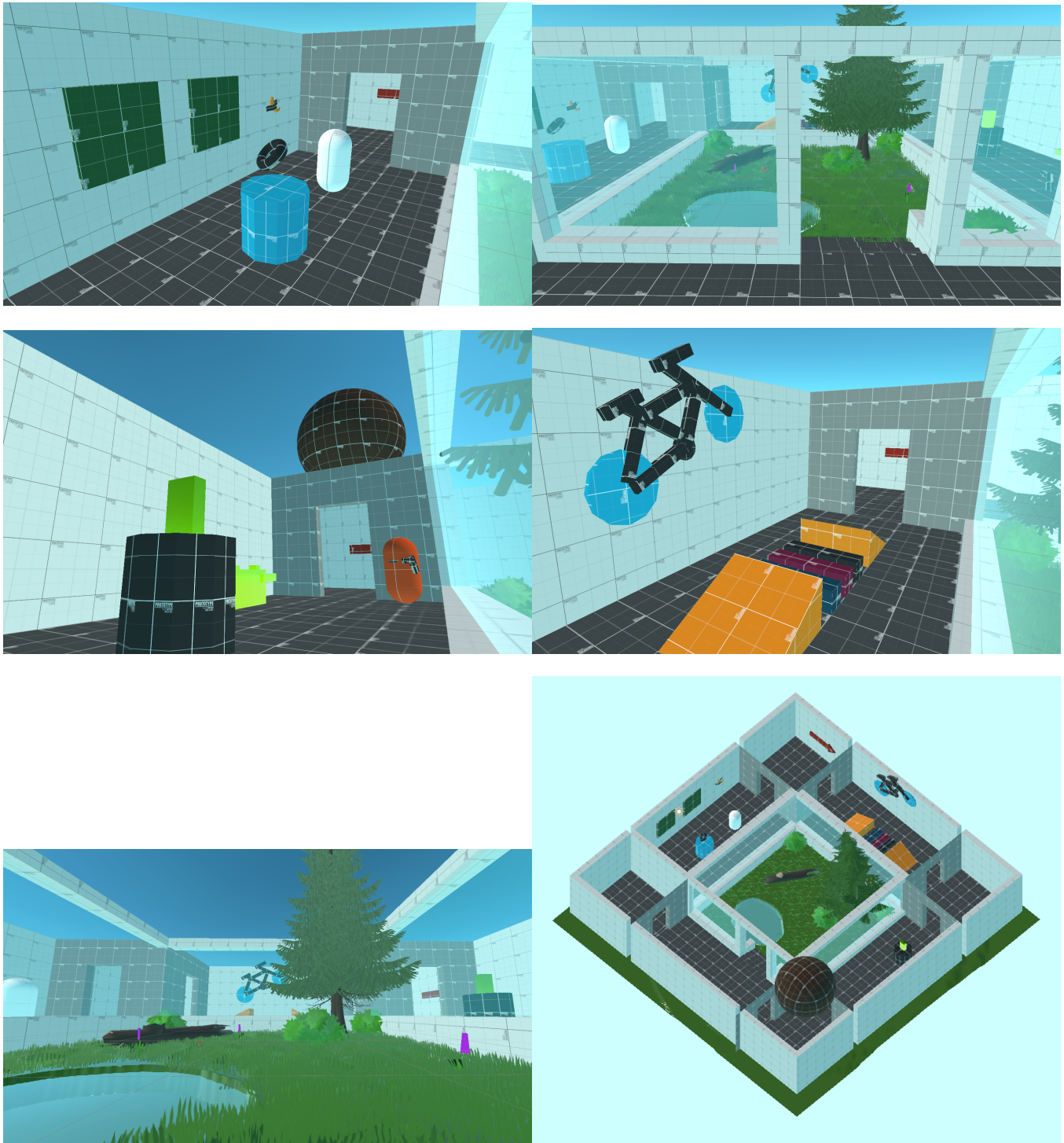


Figure 2: Images of the euclidean control map. Final image presents a complete picture of the map layout.

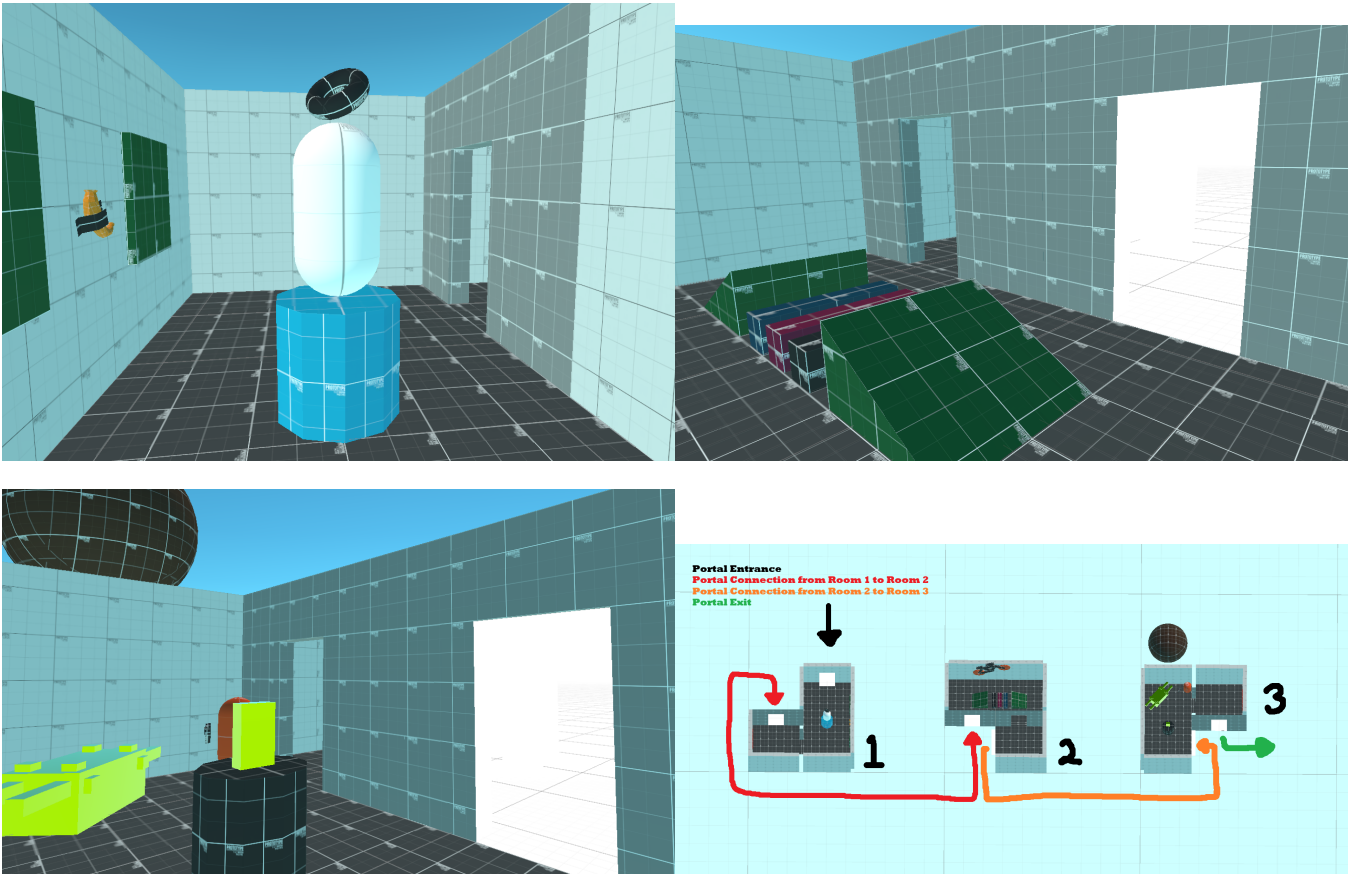


Figure 3: Images of the non-euclidean map. Final image presents a complete picture of the map layout, where the arrows represent linked portals.

Participant	Joystick Time (s)	Walking Time (s)	Teleports
Control 1	25.1	46.9	3
Control 2	29.9	37.0	6
Control 3	32.0	78.0	7
Experimental 1	13.0	105.0	6
Experimental 2	7.0	127.0	0
Experimental 3	12.0	95.0	1

Table 1: Raw data collected from participants.

Statistic	Control Group	Experimental Group
Mean Joystick Time (s)	29.0	10.67
Mean Walking Time (s)	53.97	109.0
Mean Ratio (Walking Time / Total Time)	0.638	0.908
Mean Teleport	5.33	2.33

Table 2: Summary statistics for the control and experimental groups.

4.2 Conclusion

Hypothesis 1: We have rejected the null hypothesis. Participants in the experimental group spent relatively more time walking in the non-Euclidean environment.

Hypothesis 2: We did not have sufficient evidence to reject the null hypothesis. There was no statistically significant difference in teleportation frequency between the experimental and control groups.

These results suggest that the compact, non-Euclidean nature of the experimental environment encouraged more natural locomotion (walking). However, teleportation behavior, being instantaneous and less influenced by space constraints, was not significantly affected. This implies that, in impossible spaces, users replace joystick-based locomotion with natural walking as their method of choice for traversing smaller distances, while teleportation retains its advantages in traversing larger distances. Future experiments with larger sample sizes could provide deeper insights into locomotion behaviors in non-Euclidean environments.

5 Limitations and Future Work

There are a few minor limitations with our implementation that differ from some other implementations of impossible spaces. Firstly, our portals teleport the user very slightly forward from the perspective they see when looking into the portal to avoid falling into a teleportation loop. This means that the user can sense a small shift in their perspective, hinting at the existence of the portals. We do not believe this should affect our results significantly, as our goal was unrelated to the detection of the portal, such as the many earlier studies attempting to detect a level of overlap. A related limitation of our teleportation mechanism is that a user cannot throw an object through a portal, and must carry it through, although this should not have affected our experiment as we designed it to avoid this user behavior, and no user attempted to do this throughout our trials. Another limitation discussed in our results section is that we had a small number of participants with only $n = 3$. Having more participants would increase the statistical power of our tests, giving us clearer results.

While we believe that these limitations to our experimental design are limited enough to not affect our ability to find an answer to our research question, we do believe that further questions could be answered in a similar problem space. For instance, as discussed in the related work section, impossible spaces are not the only technique available to attempt to increase user's reliance on natural walking. Comparing the efficacy at achieving this goal between impossible spaces and other technologies such as redirected walking or treadmills could be a potential avenue of research. On a similar note, combining these technologies could also be an interesting angle. How much of an overlap can exist between rooms if the user is using an omni-directional treadmill? Does redirected walking increase cybersickness more when used in conjunction with impossible spaces? As virtual reality gains higher adoption through more affordable devices such as the Meta Quest 3S, making VR experiences that can accommodate a variety of room sizes becomes more and more important, so knowing which techniques can support this goal the best is extremely useful.

On that note, another interesting direction to push impossible spaces research is using procedural generation to fit a map to a user's usable space. The map used in our experiment was designed to be as traversable as possible through solely natural walking in the specific test space, but this is unfeasible at scale for commercial games. Using procedural generation to fit a map to a specific room could provide an opportunity to bring this to everyday users, increasing the value of impossible spaces. At least one paper [1] has proposed an algorithm for accomplishing this task, although it worked with a relatively simple maze, and did not attempt to keep consistent elements like would be expected in a video game. Building on this to attempt to preserve elements could be an interesting direction to take impossible spaces.

6 Division of Work

Mason was in charge of building the impossible spaces, designed and conducted the experiment, and wrote the Results section and the "Map Design" and "Experiments" sections of the Project Overview section. Evan was in charge of portal implementation, wrote the rest of this report, and edited/typeset the $\text{\LaTeX}$ document of the report.

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