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Now You're Thinking with Portals: Investigating Episodic Memory and Locomotion with Redirected Walking in Impossible Spaces

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Abstract

Natural walking locomotion in virtual reality (VR) allows intuitive movement through a virtual environment (VE), lower rates of simulator sickness, and increased immersion. However, it is limited by available play-space. Impossible spaces are VEs that use self-overlapping geometry to imitate larger play-spaces within a smaller area. Understanding how users interact with impossible spaces requires understanding how they perceive and remember VEs. However, it is unknown how impossible spaces impact users' memory. An experiment was conducted comparing 32 participants' memory from two conditions: natural walking in an impossible space and joystick movement in a similar non-impossible space. Participants were given up to 20 min to explore a virtual museum and were not instructed on what to remember. The experience was designed to allow participants to freely explore the VE at their own pace, allowing engagement duration to vary naturally. No significant differences were found between conditions for object or spatial memory; however, participants in the natural walking condition spent more time in the environment, revisited more areas, and were more confident identifying objects not encountered in the VE. This suggests natural walking in impossible spaces may be a viable alternative to traditional locomotion techniques.

Keywords: virtual reality; impossible spaces; locomotion; memory

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1. Introduction

Virtual reality (VR) offers compelling room-scale immersion, yet navigating large virtual environments (VEs) is constrained by the user's limited physical play area. Conventional locomotion techniques, such as joystick-based steering or point-and-teleport, allow players to traverse VEs while remaining stationary in the real world. As such, these locomotion methods require minimal real-world space but often diminish presence and increase the chance of simulator sickness compared to the natural option of physically walking [1].

A promising alternative is the use of *impossible spaces*: self-overlapping layouts that reuse the same physical play-space for multiple virtual locations [2]. Many implementations of impossible spaces, commonly referred to as a type of non-Euclidean space [3–5], rely

on the use of portals: virtual doorways that serve to indicate where, when, and how spatial transitions occur [3,6]. Other implementations may dynamically change parts of the environment [4] or move the player to a new environment [7]. In all cases, locomotion through impossible spaces can be designed to occur discreetly [3] or overtly [7], whereby users may or may not notice the transitions between overlapping environments.

Designing VEs using impossible spaces is an unconventional yet increasingly explored approach. Unlike traditional Euclidean layouts, impossible spaces require additional design consideration to maintain user immersion [6,7]. These spaces can be procedurally generated while still appearing seamless to users [3]. Moreover, their design can be so coherent that users often fail to notice when multiple virtual areas overlap within the same physical space [3]. Nevertheless, even with procedural generation, crafting such spaces demands significant design effort.

While impossible spaces may reduce simulator sickness and increase presence and favourable usability compared with controller-based locomotion [6,8], the cognitive consequences of these warped layouts remain an open area for study. Spatial and object memory are critical for learning, navigation, and game enjoyment. However, prior work shows that unnatural locomotion can impair these abilities [9]. Whether the same holds or is mitigated when users walk through impossible spaces is unknown. Frequent boundary crossings might even magnify the "doorway effect," where passing a threshold disrupts recall [10]. Clarifying these impacts on memory in immersive environments can be valuable for creating more effective tools for educators and psychologists [11,12].

To address this gap, this research compares impossible space walking with standard joystick-based locomotion in a comparable Euclidean VE. The following research questions are explored:

- ***RQ1:*** *In a VR environment, do users remember more about the path they traversed and the objects they saw when using natural walking locomotion in an impossible space compared to conventional controller-based locomotion methods in a similar Euclidean space?*
- ***RQ2:*** *In a VR environment, do users' traversed paths differ when using natural walking locomotion in an impossible space compared to conventional controller-based locomotion methods in a similar Euclidean space?*

This research reports on a between-subjects study with 32 participants assigned to one of the following: (a) joystick-based steering locomotion in the Euclidean space, as a control condition, or (b) natural walking in an impossible space, as an experimental condition. The findings provide practical guidance for designers of VEs who wish to expand the explorable space without sacrificing users' memory or comfort.

The remainder of this paper is structured as follows: Section 2 reviews prior research on VR locomotion, redirected walking, and episodic memory in virtual environments. Section 3 describes the design and implementation of the virtual museum environments used in this study. Section 4 details the user study methodology, including participants, procedures, and memory assessment tasks. Section 5 presents the results of this study, while Section 6 discusses these findings in relation to the existing literature. Section 7 outlines directions for future research, and Section 8 concludes this paper.

2. Related Work

This section reviews key areas relevant to this study. First, locomotion in VR is considered, focusing on the benefits, drawbacks, and design challenges of different movement techniques. Second, redirected walking approaches are reviewed, highlighting their potential and limitations for enabling natural locomotion in constrained spaces. Third, work on episodic memory in VR and impossible spaces is summarised to understand how these

environments may influence spatial and object recall. Together, these strands of research are synthesised to reveal the gap addressed in this paper.

2.1. Locomotion in VR

The field of research regarding the investigation of locomotion methods in VR is extensive. Studied methods include teleportation [1,13–15], smooth locomotion [1,13–15], other in-place movement [1,13–17], and motion-based control [1,17–20].

Boletsis conducted a systematic literature review on movement methods in VR and organised various methods of locomotion into four categories [21]. These categories are motion-based, room-scale-based, controller-based, and teleportation-based. Each category is defined by factors such as the physicality of the motion to activate the movement, how open/limited the movement is, or if the movement is continuous or discrete. Subsequent updated reviews have published findings that more accurately reflect the trends and properties of modern-day VR locomotion [22,23].

Natural walking is one of many possible locomotion methods in VR with various advantages and disadvantages [24], and it falls under the "room-scale-based" category [21]. Since initial work on locomotion in VR, natural walking has been preferred over other locomotion methods, including walking-in-place or virtually flying [16]. While this initial research was limited by the state of VR technology, especially with the need for cables between VR headsets and computers, more recent research has utilised standalone VR headsets for less restricted natural walking locomotion experiences.

Supporting this, one study found that walking locomotion in a large arena-sized area is preferable and considered easier to use than controller-based teleportation [25]. However, as most people do not have access to sufficiently large spaces, these findings may only be useful to a niche audience.

2.2. Redirected Walking

Various techniques to redirect natural walking in VR have been studied, involving taking advantage of impossible and non-Euclidean spaces [2,4,6,26,27], viewport redirection [28–33], and dynamic passive haptics [29,34,35]. The goal of redirected walking is to allow users to explore a VE that is larger than their play-space with natural walking, thereby bypassing traditional physical restrictions.

Redirected walking is defined in two ways, as being discrete or being continuous [36]. In one form, the users' position is redirected by discretely remapping the users' position. This is similar to how portals work in impossible spaces. However, redirected walking is also the process of smoothly and continuously remapping the path that the user naturally walks onto another virtual path. This is another method of natural locomotion, which also offers users the ability to move around in a VE in an immersive manner. However, this second form of redirected walking is often not viable as it requires the user to have specific room dimensions and is limiting to how the user can move.

Research investigating the benefits of impossible spaces, a utilisation of discrete redirected walking but without the constant redirection of viewports, revealed several benefits compared to standard locomotion methods [6]. Natural walking in impossible spaces was significantly more immersive than teleportation and joystick-based movement and had higher system usability scores than joystick-based and arm swinging movement; however, it led to an overall lower task completion time. While taking longer in a task-based application could be undesirable, in contexts such as museum-like exploration experiences, longer interactions or more exploration may be advantageous.

2.3. Episodic Memory in VR and Impossible Spaces

Previous work has investigated episodic memory in VR in a wide range of topics. These include how personal factors impact episodic memory in VR [37] and how VEs impact episodic memory in VR [38–42].

Episodic memory is defined as memory about dated events and any spatial/temporal links between memories [12]. Smith conducted a literature review on episodic memory in VR and found that various aspects of VR may impact episodic memory, such as simulator sickness, which may distract participants during experiences [12]. They also found that interacting with the VE may increase a user's ability to remember the layout of the environment; however, it may not influence object memory.

Daviddi et al. conducted an experiment on object memory where participants explored a virtual museum and were tested on how well they remembered various paintings in the museum [43]. They found that paintings which were observed by participants for longer were correctly remembered more consistently; however, a longer viewing time did not always result in less memory distortion.

Warren investigated the differences between non-Euclidean and Euclidean spaces on memory when naturally walking [5]. They conducted a study where participants had to navigate to an object within a limited time frame using wormholes to teleport around the environment. They found that participants in both conditions were able to correctly remember spatial path information to achieve their goal, suggesting that humans do not remember spatial paths simply as a Euclidean cognitive map but instead as a cognitive graph where paths are a collection of vertices and edges. Consequently, assumptions about navigation, such as the benefits of 2D minimaps during traversal of traditional Euclidean environments [44], may not directly translate to non-Euclidean contexts.

Vasylevska and Kaufmann [45] investigated how spatial perceptions were affected in self-overlapping VEs while using walking locomotion. They conducted an experiment comparing rooms with differing positions of doors leading to hallways, each using the hallway for unnoticeable transportation. They found that their metrics for spatial perception were influenced by the position and shape of the hallway traversed, especially when comparing hallways with curved walls and right-angle corners.

2.4. Summary

The existing literature provides valuable insights into locomotion in VR, redirected walking, and episodic memory, but it also reveals a clear gap. Most studies on locomotion focus on usability, presence, or simulator sickness [1,13,14] rather than on how different methods affect memory outcomes. Research on redirected walking has shown that impossible spaces can improve immersion and usability compared to joystick or teleportation [6], but these works did not examine their cognitive consequences, particularly in relation to memory performance. Meanwhile, episodic memory research in VR has demonstrated that interaction and exploration can influence recall [12,43], and studies on non-Euclidean spaces suggest that humans form graph-like representations of paths rather than Euclidean maps [5]. However, these prior works either did not involve impossible spaces or did not compare them directly to traditional Euclidean experiences, such as those using controller-based locomotion.

This leaves an important open question: while natural walking in impossible spaces has several benefits compared to established locomotion techniques used for Euclidean environments, but how does it influence spatial and object memory? Addressing this gap is crucial, since memory performance is central in applications of VR in education [11], psychology [12], and exhibit [43] contexts. Our study extends existing work by providing

the first direct comparison of memory outcomes between natural walking in impossible spaces and traditional controller-based locomotion in an equivalent Euclidean environment.

3. Design and Implementation

To answer the research questions, a VR application was designed in the context of a museum, which is explorable in Euclidean space with steering locomotion using a joystick or in an impossible space using natural walking. This application is immersive and intended for object and spatial memory testing. The designed application was used to carry out a user study with two conditions, exploring the museum using either natural walking or steering locomotion.

3.1. Locomotion

This subsection describes the hardware used to support locomotion, along with the locomotion types compared in this study and their respective steering components.

3.1.1. VR Hardware

The Meta Quest Pro was the target VR headset that the application was designed for. This headset allows for room-scale movement as well as controller-based movement. The weight of the headset is more evenly distributed than previous headsets, like the Meta Quest 2, and therefore feels more comfortable for players to wear. Additionally, the Quest Pro can run standalone applications that do not require the headset to be connected to a computer via cables. This avoids the chance that participants may tangle themselves with a cable during either condition of the experiment, making movement less restricted. The headset weighs 722 g and has the dimensions of 265 mm (L) $\times$ 127 mm (H) $\times$ 196 mm (W) when on the smallest fit setting [46].

3.1.2. Controller-Based Locomotion

Steering and teleportation are the two standard locomotion methods in VR. Of these two, steering, specifically with joystick movement, was selected for the control condition. This standard controller steering locomotion method was selected because it is easy and intuitive to use. This joystick-based movement is also continuous, which makes it more comparable to natural walking than teleportation and hence a more accurate comparison to the experimental condition. Researchers adjusted the joystick-based movement speed to approximately match the expected walking speed. Specifically, 2D input from the joysticks on the Quest Pro touch controllers was used.

The forward steering direction is relative to the head of the player. The maximum velocity is 2 m per second forward, which can be achieved within 0.083 s from rest by pushing completely forward on the joystick. Previous work has found this to be an acceptable speed to give the impression of self-propulsion [47]. The maximum velocity in the left, right, and backwards directions is half that of the forward direction movement. The left-hand Quest Pro controller handled movement, and the right-hand Quest Pro controller handled rotation. The participant could snap-rotate by 45 degrees in the direction they moved the joystick, either left or right.

3.1.3. Portals and Natural Walking

In the experimental condition, that is, the condition utilising natural walking locomotion, impossible spaces were used to increase the traversable virtual area. Various rooms of identical size were created, connected by portals. Portals within portal frames were the specific way that impossible spaces were created. These portals are essentially planes that project the view of another room onto the plane to appear as if the user was standing in that room. Once the user moves into the portal plane, they are teleported to the next room,

which has a copy of the portal projecting the previous room. This results in a seamless experience for the user in which they appear to simply walk through a portal to another area. This allows for paths to be spatially consistent. If a user travelled through several portals on a specific path they physically walked and then backtracked the same path, they would also backtrack on the same virtual path and end up where they started virtually. An example of how a portal would appear in the application can be seen in Figure 1. As can be seen, the floor through the portal appears different (as it is a different area in 3D space); however, the geometry maps perfectly as if it were overlapping and integrated into the current 3D area.

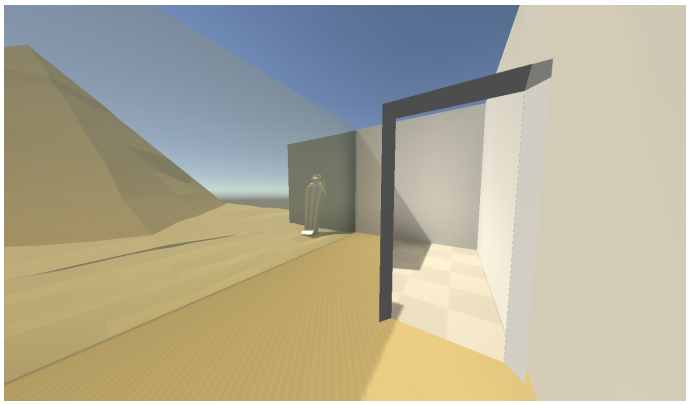


Figure 1. A portal in a room in the VE displaying a seamless view into another area of the VE, giving the impression of overlapping spaces.

Portals were used over other unnoticeable geometric overlapping techniques as they occupy minimal space and can be easily integrated into existing environments, therefore increasing parity between both conditions.

Figure 2 compares the locomotion path in control and experimental conditions using three rooms. While the VEs in each condition are almost identical, in the control condition, doorways are found between connected rooms, while in the experimental condition, doorways are replaced with walls and connected portals with frames placed on either side of where a doorway would have been. With an example of a user moving from the left room to the right room through the rooms, it is shown how portals are connected to each other and how portal placement is deliberately chosen to minimise the differences between paths traversed in both conditions inside the VE. It also demonstrates the relationship between the virtual path traversed during the experimental condition in the VE and the physical path traversed in the play-space. When travelling through a portal from room to room, the virtual path relative to the centre of the new room is rotated by 180 degrees. This allows a user to continue their path in a straight line within the VE while physically walking back and forth between points in a fixed-size play-space.

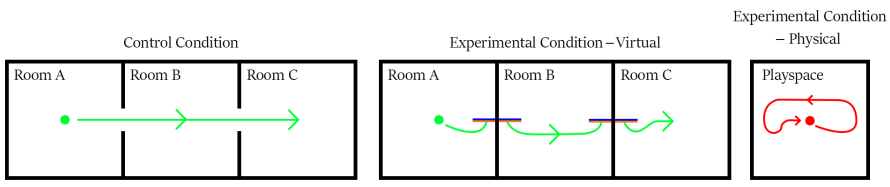


Figure 2. An illustrative example of a path traversed by a user during control and experimental conditions. Green lines show the path traversed in the virtual world, while the red line shows the path traversed in the physical world.

3.2. Virtual Environment

The selected context of the VE is a museum, as it allows for wide thematic variation in the rooms while remaining believable. For example, it would not be unexpected for the participant to walk from one room containing a dinosaur to the next room which may contains a series of paintings or other human-made objects. This allows the VE to remain immersive even with a vast array of differing room themes. Simultaneously, this allows for each room to be distinct and hence be more identifiable for the participants when they complete the spatial memory test at the end of the experiment.

In a standalone application, the Quest Pro is limited to rendering with its own hardware. As this is mobile hardware, to ensure that a consistently high FPS is met, the VE is constructed of 3D models that are in the "low poly" style so as not to overload the rendering capabilities.

3.2.1. Modular Room Design

An overview of the structure of a basic room in the VE can be seen in Figure 3. This demonstrates the basic template and idea of each room from a bird's-eye view, where any given room may be connected to up to four other rooms (one portal/door for each side of the rectangular room). Each room is 3 m wide and 6 m long. In Figure 3, the room shown is overlapped with the experimental and control condition rooms. The black rectangles represent the doors in Euclidean space, while the blue rectangles represent the corresponding portals in an impossible space. Note that while each room may have up to four portals/doors, no rooms in this study's museum are designed to have more than three doors.

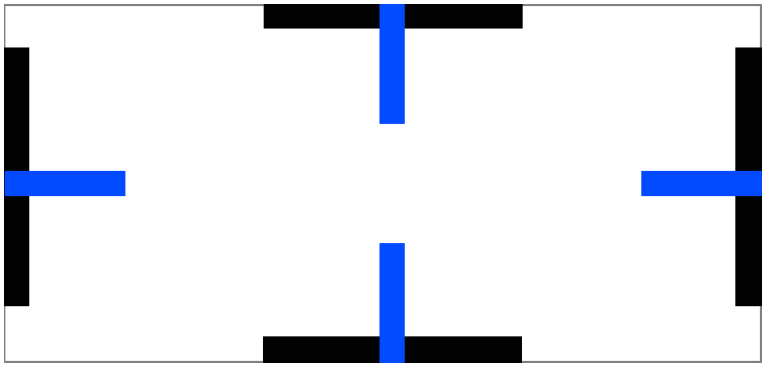


Figure 3. Top-down layout of a room in the VE. The lines in black show the placement of doors for a room in the control condition, while the lines in blue show the placement for the equivalent portals in the experimental condition. Everything else in the VEs remains identical to each other.

Portals were placed perpendicular to their Euclidean door counterparts. Over the alternative of parallel placement, this design choice ensures the distance travelled when moving from one room to the opposite is consistent compared to Euclidean travel. This is because each parallel portal would need to be placed far enough away from the wall to ensure users can step through it and then around it, which in turn brings two portals on opposite ends of the room closer to each other.

3.2.2. VE Layout and Themes

Figures 4 and 5 showcase a floor plan of the virtual museum. It contains a total of 20 rooms laid out in a grid, including a starting room marked by a blue cross and an end room marked by a green cross. Multiple overlapping paths can be taken from the start towards the end, with the possibility of looping back to previously visited rooms. This non-linear layout was chosen to allow us to measure whether traversed paths differ per locomotion

method used when users are given multiple options. Of the 20 rooms excluding the start and end, the 6 rooms marked with a red cross in Figure 4 are those guaranteed to be visited in a consistent order by participants traversing any possible path to the end. Objects in guaranteed rooms are used in object-related memory tests, while objects in non-guaranteed rooms are excluded.

Figure 6 shows an example of one of the rooms found in the virtual museum. Objects within the guaranteed rooms include a dinosaur skeleton, pyramid, signpost, mammoth, bird nest, and face on the wall. Other rooms included cherry blossom trees, clocks, paintings, a volcano, an aquarium, a giant ladybug, a sundial, statues, an ice cube, a pond, pots, and a beach. These objects were chosen based on their own feasibility or the feasibility of similar objects with regard to being displayed in a real museum. A bird's-eye view of the virtual museum can be seen in Figure 5, which is aligned with Figure 4.

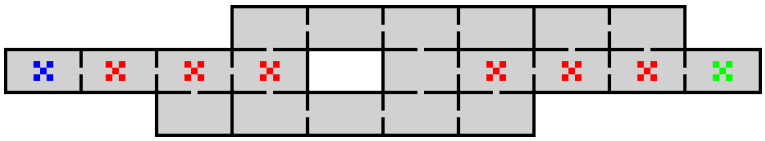


Figure 4. Floor plan of virtual museum. Participants begin at the blue cross and must make their way to the green cross. Rooms with red crosses are guaranteed to be visited by the participant as they traverse from the start to the end of the museum. Figure 5 shows a bird's-eye view of this layout.

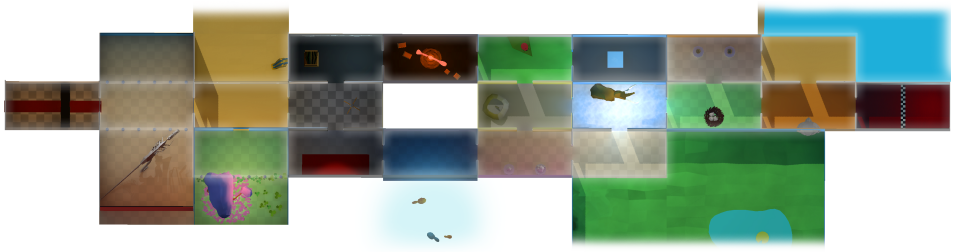


Figure 5. A top-down view of the VE that users explored using either impossible spaces and natural walking or Euclidean space and joystick-based movement. This figure displays how each room is connected to the others, including some of the area behind the windows in the rooms. Each room is the same size as the play-space in the non-Euclidean condition.



Figure 6. Dinosaur skeleton room within the virtual museum.

Sounds were intentionally excluded from the VR application. Although some of the objects in the museum may make sounds in the real world, such as the clocks, previous research has indicated that the addition of sounds may increase memory regarding objects in the VE compared to when no sounds are playing [12]. Therefore, the researchers chose to avoid this potential memory bias towards some of the tested objects.

The given task to participants was to reach the end room. Besides navigation from room to room, the VE has no other interactions for users. While previous work comparing controller and walking locomotions introduced tasks to complete with controller input [6], such a task was avoided for two reasons. Firstly, it is realistic to let users freely explore the museum without feeling pressured into completing any difficult tasks, and secondly, as controller-based tasks could be avoided, users in the experimental condition roamed the virtual museum without needing to hold controllers, hence taking full advantage of natural walking.

3.3. Implementation Details

To build the VE, a PC with an RTX 2080 graphics card and an i7-7800X CPU was used. A Meta Quest Pro was used alongside a USB-C link cable to connect to a computer for debugging.

The Unity game engine (version 2022.3.6f1) with C# was used for writing game logic, along with the Oculus Integration package (version 53.1) using the OpenXR back-end and Blender (version 3.0.0). The source code for the project can be found open-sourced on our GitHub [48].

4. Methodology

To evaluate the research questions, a user study with 32 participants was conducted. Participants were assigned to one of two groups: the experimental group or the control group. The experimental group took advantage of portals to enable natural walking in overlapping impossible spaces. The control group consisted of a very similar VE but where the portals were replaced with doorways such that the environment was completely Euclidean and non-overlapping. Joystick-based steering was used to move around in the control condition. An additional condition, including joystick-based movement in impossible spaces, was omitted in this study in order to only include conditions that designers of VEs may consider based on known advantages, but such a condition is recommended for inclusion in future work.

Participants were assigned to one of the two groups by a Latin-Square method. Out of all participants, 19 were male and 13 were female. Ages ranged from 18 years old to 60 years old, with a mean age of 23 years and a standard deviation of 8.29. It is important to note that while the researchers tried to sample from a diverse population, participants tended to be male and aged in their early 20s. This may influence how applicable the results are to the wider population.

To assess the user's baseline memory abilities, participants first completed a short visual–spatial memory test in the Pre-Study Questionnaire, which was an adapted spatial sequence test [49]. The results showed an average score of 8.97, with no significant difference between experiment groups. This shows that neither group should have any inherent significant difference in memory ability.

The structure and flow of the user study can be seen in Figure 7. After the initial Pre-Study Questionnaire is completed, the users were put into VR and told the following:

> *You will be exploring a virtual environment. You are in a museum, and you have between 5 and 15 min to find the "end" room. You will know it's the end room because there will be a finish line on the floor, and the experiment will end once you cross it. You will be assessed on memory. Are you ready to begin?*

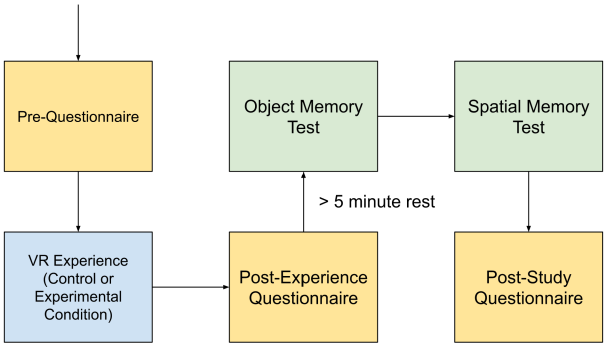


Figure 7. Overview of the user study.

The time range given for exploration was based on pilot testing of both conditions. Participants were not told specifically what to remember so as not to influence the difficulty of the memory tests and to replicate the many realistic scenarios where memory is not the primary focus of the VR experience and an instructor is not present to tell users what to remember.

Users then explored the VE. When they reached the end room and crossed the finish line, the VR stage of the experiment was completed. For users who took too long, they were told after 15 min to hurry to the exit, and the exploration stage ended if 20 min passed. Participants then took off the VR headset, and a 5 min timer was started. This ensured a consistent period of time between participants observing the VE and recalling it. Before this timer was up, participants were free to complete the first section of the Post-Experience Questionnaire, which contained questions about demographics and background. This section was designed to take a few minutes to "stall" for the 5 min rest period. If the participants completed this section within 5 min, they were asked to wait for the remaining time. Once the waiting time was complete, participants moved on to the object memory test.

The object memory test was adapted from Daviddi et al. [43]. In this work's version of the test, there are six "real" objects that participants really did see in the museum and 12 "distractor" objects that the participants did not see in the museum (as they did not exist in the environment anywhere). Six of these distractors are similar in either shape or colour to the six main objects; however, the other six distractors are not as similar to the main objects. Each object was presented to the user as an image of a 3D model, where the object was suspended against a black background. Each real object had 2 associated distractors which were positioned in the same way, and a similar camera angle was used to take the virtual photo. This was performed so that the image representations of the objects were fairly presented to reduce any perception bias. Below each of the 18 images presented during the test, participants were asked "Did you encounter this object in the museum?", and they answered either with a "yes" or "no", following by a 5-point Likert question with the text "Are you sure?" and a scale ranging from 1 (not at all) to 5 (completely). An example image of a real object compared with its corresponding two distractor images can be seen in Figure 8.



Figure 8. Examples of images displayed during the object memory test. The middle image displays the real object, and the left and right images display corresponding distractor objects.

Once the object memory test was completed, the spatial memory test began. Participants moved over to a whiteboard where image representations of each of the 20 rooms were randomly laid out on a table for them (not yet on the whiteboard). They were then told that their task was to draw a line on the whiteboard between any pair of rooms that had a direct connection (i.e., you could move directly from one room to another). The position and angle of the lines/rooms did not matter, only the semantic lines connecting them. This results in a node graph where each vertex is a room in the museum and each edge is a door/portal connecting the rooms. Additionally, participants were told that if they did not see any given room in the museum they could simply leave it to the side with no connections. Afterwards, a photo of the representation on the whiteboard was taken. This was then turned into an adjacency list representation of a graph to be analysed and compared against the true VE layout. An example of how a participant answered this memory test can be seen in Figure 9.



Figure 9. An example of a participant's answer for the spatial memory test. Rooms are represented by images, and connections between rooms are drawn with a whiteboard marker. These graph structures are then analysed and compared to the correct layout. The rooms in the bottom right have no connections, which is why the participant says that they do not remember the room at all.

After both memory tests were completed, participants filled out the Post-Study Questionnaire, including questions regarding feedback about the difficulty of the memory tests and optional written feedback about the application. Copies of each questionnaire can be found in the Supplementary Materials.

5. Results

Data collected from 32 participants in the user study was analysed to answer the two research questions. Additionally, other findings were also drawn from application-generated data and memory tests, as well as supplementary demographic and feedback questions. Due to the small sample size, only Mann–Whitney U significance tests between condition groups were considered for ordinal data. All significance tests were considered significant with a p-value of 0.05 or less.

5.1. Demographics

Demographic data consisted of multiple categorical and ordinal results. The Chi-square test for independence was used to compare categorical data between condition groups, and such data is marked with "-" in the second and third columns of the table. Table 1 displays these results.

The control condition had 3 participants who had never tried XR, 10 who had tried it one to two times, and 3 who had tried it three or more times. The experimental condition had two participants who had never tried XR, nine who had tried it one to two times, and five who had tried it three or more times.

The demographic results indicate consistency between each of the control and experimental groups, suggesting minimal impact from selection bias. The most significant inconsistency is the gender distribution overall and between groups, with 7 females and 9 males in the control condition, and 6 females and 10 males in the experimental condition. This should be taken into consideration when generalising to other groups.

Table 1. Demographics—difference in data metrics between participants in control and experimental conditions. "μ" = mean value, "*p*-value" = statistical significance of Mann–Whitney U tests (between ordinal data) and Chi-square tests (for categorical data), "-" = categorical data, "(1–5)" = 5-point Likert scale.

Metric	Control μ	Experimental μ	*p*-Value
Gender	-	-	1.0
Age (years)	22.8	23.8	0.484
XR experience	-	-	0.686
Joystick experience	-	-	0.881
Enjoys walking (1–5)	3.69	3.94	0.452
Enjoys museums (1–5)	3.88	3.50	0.570
Plays games	-	-	1.0
Baseline memory	9.00	8.94	0.909

5.2. Object Memory

As shown in Figure 8, object memory was tested by presenting an image of an item to the participant and asking them if they saw it and if they were sure of their answer. Items that were truly in the environment are referred to as "objects", while items that were not in the environment at all are referred to as "distractors".

Seen variables refer to the total number of times one of the six objects or 12 distractors were labelled as seen by participants. *Confidence* is answered from "not at all" (1) to "completely" (5) and is also the summation over all six objects or 12 distractors. *Weighted-seen* is similar to confidence but takes into consideration if the participant thought they saw the object or not.

Weighted-seen is a measure of the following:

$$\sum_{i=1}^{n} (x_i \cdot y_i - \max(0, y_i))$$

where x_i is the confidence of the answer of some object/distractor of index i, y_i is the answer they put if they had seen it or not ("yes" = 1, "no" = -1), and n is the number of objects (6) or distractors (12). A higher objects weighted-seen value means that the participants both correctly and confidently identified correct objects, while a lower distractors weighted-seen value indicates that participants both correctly and confidently identified the distractors as

fake. Table 2 presents a comparative analysis of the object memory testing metrics between the control and experimental condition groups.

Table 2. Object memory—difference in data metrics between participants in control and experimental conditions. "μ" = mean value, "*p*-value" = statistical significance of Mann–Whitney U tests, "*" = *p*-value below 0.05 threshold.

Metric	Control μ	Experimental μ	*p*-Value
Objects seen	5.69	5.69	0.81
Objects confidence	28.1	28.8	0.675
Objects weighted-seen	20.2	20.9	0.515
Distractors seen	2.5	1.12	0.129
Distractors confidence	43.6	50.8	0.026 *
Distractors weighted-seen	−28.3	−43.8	0.018 *

Only the "distractors confidence" and "distractors weighted-seen" metrics had significant differences between groups. The experimental group was 16.5% more confident on average about whether they did or did not see the distractors in the museum, and their "distractors weighted-seen", as a proxy for the level of incorrectness, was 54.8% lower.

5.3. Spatial Memory

Table 3 presents a comparative analysis of the spatial memory testing metrics between the control and experimental condition groups.

The following metrics were analysed from participants' node graphs, representing forms of correctness regarding door or portal connections between rooms in the museum. These included the number of *correct edges*, *incorrect edges* and *missed edges* of a user's node graph when compared to the ground-truth node graph.

As participants were specifically informed that the rooms they believed they did not visit could be left unconnected from the graph, modified versions of the previous three variables were also collected. These included a "visited" version, in which edges were not counted if the participant did not visit at least one of the two nodes (rooms) associated with the edge. Similarly, a "both visited" version was collected, in which edges were only counted if participants visited both nodes associated with the edge.

The following additional metrics were analysed from participants' node graphs, representing forms of correctness regarding how many door or portal connections exist for each room in the museum. These included the number of nodes with *correct degrees* and *incorrect degrees* in a user's graph when compared to the ground truth graph. As a sum over all nodes, other metrics included the *degree offset* and *degree difference*, the latter a sum of absolute differences.

Modified versions of these four degree variables were also calculated, including "visited" versions, in which nodes were only counted if the participant had visited the room associated with the given node. Two additional metrics were analysed from participants' node graphs, representing forms of correctness regarding paths between rooms. These included *end distance*, the shortest path from the start node to the end node for graphs including such a path, and *connected components*, the number of connected components containing at least one edge.

None of the spatial memory testing metrics were significantly different between condition groups.

Some participant graphs had to be specially interpreted by the researchers as lines drawn between nodes were not very obvious. This only occurred occasionally for control users, as they believed some rooms were corridors rather than distinct rooms. While not

strictly tested for, researchers observed that controller users tended to make grid-like graph patterns more often than portal users.

Table 3. Spatial memory—difference in data metrics between participants in control and experimental conditions. "μ" = mean value, "*p*-value" = statistical significance of Mann–Whitney U tests, "v." = node(s) visited.

Metric	Control μ	Experimental μ	*p*-Value
Correct edges	5.88	5.06	0.445
Incorrect edges	8.56	10.3	0.108
Missed edges	16.1	16.9	0.445
Correct edges (v.)	5.88	5.06	0.445
Incorrect edges (v.)	8.56	10.2	0.116
Missed edges (v.)	15.8	16.7	0.323
Correct edges (both v.)	5.12	4.69	0.676
Incorrect edges (both v.)	7.50	9.88	0.066
Missed edges (both v.)	14.1	15.8	0.115
Correct degrees	7.50	7.56	0.864
Incorrect degrees	12.5	12.4	0.864
Degree offset	15.1	13.2	0.297
Degree difference	21.0	18.1	0.205
Correct degrees (v.)	6.56	7.00	0.691
Incorrect degrees (v.)	11.2	11.6	0.954
Degree offset (v.)	13.8	12.3	0.316
Degree difference (v.)	18.9	17.1	0.241
End distance	8.69	10.7	0.243
Connected components	1.38	1.25	0.695

5.4. Traversed Path

Table 4 presents a comparative analysis of the traversed path metrics between the control and experimental condition groups.

Total time is a measure of how long participants spent in the VR experience. *Rooms visited* is a measure of the number of unique rooms visited. *Room transitions* is the measure of the number of times that a participant moved from one room to another. *Avg. speed* is the measure of the average speed a participant travelled at during the VR experience, and similarly, *Avg. angular speed* is the measure of the mean average angular speed of a player's head movement. This is an indicator of how often the participant moved their head/looked around.

Table 4. Traversed path—difference in data metrics between participants in control and experimental conditions. "μ" = mean value, "*p*-value" = statistical significance of Mann–Whitney U tests, "*" = *p*-value below 0.05 threshold, "s" = seconds, "m/s" = meters per second, "d/s" = degrees per second.

Metric	Control μ	Experimental μ	*p*-Value
Total time (s)	199	552	0.001 *
Rooms visited	17.8	18.9	0.043 *
Room transitions	35.9	84.4	0.002 *
Avg. speed (m/s)	0.926	0.562	0.001 *
Avg. angular speed (d/s)	41.6	59.7	0.001 *

All of the traversed path metrics were considered significantly different between condition groups.

Experimental condition users spent ×2.77 more time in the museum than the control condition users. Rooms were also visited or revisited ×2.35 more often by experimental condition participants. While experimental condition participants visited one more distinct room than control condition participants, this behaviour is likely explained by the fact that recording starts in the dinosaur room (the second room), and participants in the experimental condition often returned to the starting room to test how the portals worked.

5.5. Feedback

Table 5 presents a comparative analysis of feedback metrics regarding perceived difficulty of specific tasks between the control and experimental condition groups. Three questions asked participants whether they agreed that navigation, object recall, and spatial recall were easy with 5-point Likert scales, ranging from 1 (strongly disagree) to 5 (strongly agree). None of the Likert feedback metrics were considered significantly different between condition groups.

Table 5. Likert feedback—difference in data metrics between participants in control and experimental conditions. "μ" = mean value, "*p*-value" = statistical significance of Mann–Whitney U tests, "(1–5)" = 5-point Likert scale.

Metric	Control μ	Experimental μ	*p*-Value
Easy to navigate (1–5)	3.81	3.44	0.306
Easy object recall (1–5)	3.44	3.62	0.709
Easy spatial recall (1–5)	2.38	1.94	0.115

Additional thematic analysis was conducted on the free-answer questions completed by participants, in the hope of discovering further insights into some of the previous quantitative results. In particular, conceptual content analysis [50], extracting the frequency of themes with flexible categories throughout the coding process, was performed on the qualitative data to reveal common key themes. The questions asked what the participants did and did not enjoy about the application, along with suggestions based on perceived limitations and potential improvement, in the following format:

- *What did you like most about the application?*
- *What did you dislike most about the application?*
- *What were the biggest limitations of the application?*
- *What improvements would you like to see in the application?*

Thematic analysis from the first two questions revealed several categories of feedback, each groupable into a positive or negative light. Tables 6 and 7 present these grouped categories with the number of occurrences per condition group.

Table 6. Positive feedback—summary of frequency of the themes identified through thematic analysis of written feedback. "C" = control condition, "E" = experimental condition.

Metric	Count (C)	Count (E)
Interesting	2	1
Fun	2	3
Ease of use	4	0
Immersive	0	1
Virtual reality	4	3
Exploration	1	4
Locomotion method	1	1
Museum content or layout	6	9
Memory testing	0	2

Table 7. Negative feedback—summary of frequency of the themes identified through thematic analysis of written feedback. "C" = control condition, "E" = experimental condition.

Metric	Count (C)	Count (E)
Motion sickness or nausea	3	0
Physical discomfort	1	2
Hardware issues	2	4
Lack of informative text	2	3
Locomotion method	7	1
Navigation difficulties	3	7
Museum content or layout	5	5
Experiment ended early	1	0
Lack of interaction	2	0
Memory testing	3	0

Table 8 presents various categories of suggestions, extracted from answers to the third and fourth free-answer questions, from participants per condition group.

Table 8. Suggestion feedback—summary of frequency of the themes identified through thematic analysis of written feedback. "C" = control condition, "E" = experimental condition.

Metric	Count (C)	Count (E)
More realism	1	0
Informative text	2	1
Sounds or music	2	0
Improved graphics	1	3
Dynamic or moving objects	1	1
More range of movement	2	1
Interaction with objects	2	1
Navigation hints	3	1
Customisation options	1	0
More memory tests	0	1
Clearer instructions	1	2

6. Discussion

Overall, the results suggest that when participants are free to explore at their own pace, natural walking in impossible spaces does not impair memory and may increase engagement, as evidenced by longer time spent, more transitions, and increased confidence in rejecting unseen items. However, this increased engagement does not necessarily lead to improved recall and may also reflect greater navigational uncertainty.

6.1. Influence on Memory (RQ1)

Both objective metrics and subjective ratings indicate that natural walking in impossible spaces does not significantly affect users' object or spatial memory when time spent in the environment is flexible. While participants in the experimental condition were more confident when identifying distractor objects, this did not translate to greater overall object recognition accuracy. This supports previous work, which explored Euclidean space only, suggesting that differing interactions with a VE may not directly affect object memory if participants are not explicitly told what to remember during exploration [12].

6.2. Influence on Traversed Path (RQ2)

Participants in the experimental condition spent significantly more time exploring the environment and revisited rooms more often than those using joystick-based locomotion. These findings highlight a key behavioural difference between groups. One interpretation

is that users walking naturally may have been more engaged with the VE, as suggested by prior research associating natural walking with increased immersion in a task-oriented VR experience [6]. Alternatively, increased time spent may reflect spatial confusion or a lack of navigational clarity, particularly as thematic feedback showed that navigation difficulties were more frequently reported by experimental condition participants. Additionally, researchers observing participants noted that those in the experimental condition often appeared more disoriented within the VE.

The resulting difference in exploration time could also be partly explained by locomotion characteristics. Although joystick movement speed was calibrated to match an average walking pace, the inherent differences between controller-based and physical walking locomotion may have influenced total time. Experimental condition participants also showed greater angular speed, which could suggest higher engagement in visually scanning the environment. However, this increase is likely partly mechanical, as portal users were required to physically turn around when traversing opposite-end portals (Figure 2). Some participants even peered into portals to inspect the next room before entering, which both increased the number of recorded room transitions and required additional head rotation. These factors, combined with the extended time spent in the VE, suggest that experimental condition participants may have explored more extensively, possibly due to curiosity, disorientation, or the novelty of the portal-based layout.

6.3. Synthesis of Memory and Traversed Path Findings

Despite the increased exploration time, the results show no significant differences between groups in spatial memory performance or object recognition rates. One interpretation is that both groups performed memory tests as well as they could have given that additional time was not dedicated to recall because participants were not told what to remember. Another interpretation is that participants in the experimental condition needed more time to achieve similar memory performance and thus could have performed worse if they had used less time.

The similarity in spatial test performance between groups aligns with the cognitive graph theory of spatial memory [5], which suggests that path recall is influenced more by graph-like structures than by metric geometry. As the two environments shared an underlying graph structure, it is unsurprising that spatial recall was comparable, even with radically different locomotion methods. This study builds on this prior work [5] by demonstrating that locomotion type can influence how users explore the VE, even when the underlying structure remains constant. The observed differences in room revisit frequency suggest that users navigating impossible spaces may have adopted different exploration strategies, possibly driven by curiosity, disorientation, or the novelty of portals.

6.4. Additional Findings

Thematic analysis of participant feedback revealed further distinctions. Joystick users reported more discomfort and simulator sickness, aligning with prior findings that controller-based locomotion can increase cybersickness [6]. Conversely, while portal users rarely reported sickness, they more often mentioned difficulties in navigation. This trade-off reinforces the idea that impossible space design, while reducing sickness, introduces new cognitive challenges for users unfamiliar with such spatial distortions.

6.5. Recommendations for VE Designers

The results indicate that natural walking locomotion can be integrated with impossible spaces to replace traditional controller-based locomotion while still maintaining user memory performance. Designers who want to encourage longer interaction times, such as in exhibitions, educational environments, or therapeutic contexts, may find impossible

space layouts advantageous because they appear to foster deeper engagement. However, navigational ambiguity was more common among participants walking through impossible spaces, which suggests the need for directional aids, such as arrows or a map. In contexts where user comfort is a priority, walking in impossible spaces may be particularly suitable since participants reported fewer symptoms of motion sickness compared to joystick-based locomotion in equivalent Euclidean space. By carefully balancing these factors, designers can use impossible spaces as a practical and memory-neutral locomotion strategy that enhances both comfort and immersion.

6.6. Limitations

Despite efforts to maintain parity between conditions, several limitations remain. First, portals and doors were placed perpendicularly, resulting in different room-to-room viewpoints. This may have influenced perception and memory and could be clarified in future studies by introducing a third condition combining joystick-based locomotion with impossible spaces.

Second, joystick-based steering may not generalise to other Euclidean locomotion methods like teleportation. Although controller-based speed was calibrated to match walking pace, individual variation may have affected time spent in the museum and memory outcomes. While thematic analysis of written responses suggests that only controller-based locomotion caused cybersickness, consistent with previous findings [6], this study would have benefited from formally measuring cybersickness using a validated measure.

Third, the VE was constrained to 3 m $\times$ 6 m rooms due to physical space limits. Results may differ in environments with alternative play-space shapes or sizes. Additionally, portals were non-recursive for performance reasons, which may have reduced immersion by creating visible seams.

The sample was self-selected, with a mean age of 23, limiting generalisability to wider demographics. Moreover, factors such as age, familiarity with electronic products, prior VR experience, and exposure to different locomotion methods may be more influential on user experience than the locomotion methods tested.

Differences in memory outcomes may partly reflect time spent exploring rather than the locomotion method alone. Object memory tasks may have been too easy, while spatial tasks may have been overly difficult, masking differences between groups. Questionnaires were completed outside VR, which may have influenced responses [51].

Lastly, the implementation was highly specific. Object models and room themes were deliberately designed to be distinct but may not represent other VE designs. Furthermore, joystick-based locomotion within an impossible space layout was not tested, making it difficult to disentangle the effects of environment structure from those of movement method.

7. Future Work

The findings open several avenues for future research. First, future studies could isolate the effects of locomotion and environmental structure from exploration time by enforcing a fixed exploration period and instructing participants on what information to memorise. This would help clarify whether the lack of significant memory differences was due to the locomotion method or to variability in time spent exploring. Second, introducing a third condition with controller-based locomotion within an impossible space would help disentangle the individual and combined effects of locomotion method and spatial layout on memory performance.

Other promising directions include investigating long-term memory retention, exploring different types of VEs beyond museums, and varying portal placement, play-space configurations, object types, and the number of objects per room. Such studies could

reveal how specific design choices influence memory, engagement, and user experience in impossible spaces. Finally, we would like to investigate whether the locomotion (redirected walking in impossible spaces vs. conventional controller-based locomotion methods) has an effect on cognitive load [52–54].

8. Conclusions

A between-subjects experiment was conducted with 32 participants who explored a virtual museum either by naturally walking through impossible spaces or by using joystick-based locomotion in a geometrically similar Euclidean space. Participants were given flexible time (up to 20 min) to explore without being told explicitly what to remember.

No significant differences were found between groups in object or spatial memory performance. However, participants in the impossible space condition reported significantly greater confidence when identifying distractor objects, despite similar accuracy. Users in the experimental condition spent significantly more time in the VE and revisited more rooms than those using joystick-based locomotion. This extended exploration may reflect increased engagement, spatial confusion, or a combination of both. It may also partially explain their increased confidence in object judgments, particularly in rejecting distractors they were unlikely to have overlooked with the longer time they had.

These results provide insight into how locomotion and environment structure affect exploration and memory in VR. They extend cognitive graph models of spatial memory by showing that recall can remain stable when the environment's connectivity is preserved regardless of locomotion method. Importantly, they suggest that when users can control how long they explore, impossible spaces enabling natural walking can be used without impairing memory outcomes compared to traditional steering-based locomotion in Euclidean space. This reinforces their viability for designers seeking to enhance engagement and reduce motion sickness in contexts where both immersion and cognitive accuracy are important, such as education, psychology, or exhibitions.

In summary, impossible spaces may offer a promising alternative to traditional VR layouts by supporting natural locomotion while preserving memory performance, potentially improving accessibility, immersion, and design freedom in future VR experiences. Future work should aim to isolate locomotion and environment effects and examine memory outcomes across varied VEs and designs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/virtualworlds4030039/s1, Supplementary S1: Pre-Study Questionnaire; Supplementary S2: Post-Experience & Post-Study Questionnaires.

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