Perception of a Spatial Implausibility Caused by Seamless Covert Teleportation

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Abstract: This paper investigates human perception of spatial implausibility through seamless teleportation in circular and hexagonal closed-loop corridors. Spatial implausibility refers to virtual spaces that deviate from Newtonian Euclidean geometry rules, while seamless teleportation involves changing the user's position in the virtual world without their awareness. In this work, the impression of implausibility is generated by subtle teleportation of the user within these corridors, thereby allowing them to unconsciously skip certain sections of them. Different levels of this "implausibility" are presented by varying the percentage of skipping within these corridors, specifically 0%, 15%, and 30% of the corridor's overall length. These implausibilities are assessed through a within-subject study on naive participants to determine their perception of spatial implausibility. Our findings indicate no significant difference in the detection rates between the two corridor shapes. Interestingly, most participants interpreted the manipulation as a change in the environment's shape or size while only few could perceive the teleportation and the skip. This paves the way for future research to leverage this technique for subtle spatial manipulation.

1 INTRODUCTION

A crucial and integral aspect of any virtual reality (VR) experience is the locomotion technique used to navigate virtual environments (VEs). Immersive and engaging VEs come to life through the seamless movement and exploration through effective locomotion techniques. By providing users with intuitive means to traverse and interact with VEs, locomotion systems enhance the sense of presence and empower individuals to fully immerse themselves in these VEs. From walking-in place (Wendt et al., 2010) and on treadmills (Iwata, 1999) to point-and-teleport methods, joystick navigation, and real walking approaches, a wide range of locomotion techniques have emerged, catering to diverse user preferences and optimizing the overall VR encounter. Among these techniques, teleportation remains one of the most commonly used. It can be achieved in various ways, allowing the user to either translate or to both translate and rotate. Additionally, teleportation can be employed with or without the user's knowledge. For example, the user might be transported by a bird to a new location or moved to another section of the corridor that appears identical to their current position, without realizing it. In such cases, while the immediate surroundings remain the same, everything beyond the user's current field of vision is different. This method would constitute seamless teleportation.

Real walking, as a locomotion technique, stands out for its potential to enhance presence and immersion in the VE (Usoh et al., 1999; Cherni et al., 2020) and provides a more simple, straightforward and natural user experience compared to other locomotion techniques. It allows users to physically move within the virtual space, providing a high level of control precision and minimizing the occurrence of motion sickness. However, real walking has one significant drawback, since it requires a considerable amount of physical space, making it impractical for small tracking areas commonly found in home-based VR setups. Here, redirection techniques come into place that allow using smaller physical environments for navigating large VEs.

Redirection Techniques: take advantage of human perceptual limitations and enable users to navigate large VEs while keeping them within the bounds of their tracking space. These techniques can be ap-

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plied either to the user or to the VE. For example, (Langbehn et al., 2020) seamlessly integrated redirection into a game, where the world was turned around the players while they were concentrating on a task, i.e. making whipped cream. Various redirection techniques exist, and efforts have been made to classify them. In the taxonomy proposed by (Suma et al., 2012a), redirection techniques are separated based on their geometric flexibility versus the likelihood that they will be noticed by the users. Redirection techniques are divided into repositioning and reorientation. Repositioning techniques modify the mapping from points in the real world to the virtual world to condense a larger VE into a compact physical environment. Reorientation techniques rotate the user's heading away from the boundaries of the physical space. Concerning the noticeability, the taxonomy distinguishes between subtle and overt methods. Finally, redirection techniques can be implemented in a discrete or continuous manner. Discrete techniques are applied instantaneously, while continuous techniques are applied over time. Another taxonomy was presented by (Vasylevska and Kaufmann, 2017a) where they distinguish 4 categories of algorithms "Basic Reorientation", "Rendering Manipulation", "Sense Manipulation", and "Scene Manipulation".

Redirection of a user can be achieved by techniques that modify the VE. Such techniques rely on impossible spaces that defy conventional logic but also challenge Newton's laws of motion and the fundamental principles of geometry. An example of such spaces are overlapping architecture (OA) is a technique that optimizes tracking space utilization by overlapping spaces. One example are overlapping neighboring rooms where the goal is to create the illusion that these rooms occupy separate areas while, in reality, they share the same physical space. The overlap occurs when the user traverses a corridor and the wall separating the two rooms shifts. The maximum allowable overlap before users perceive it was explored by (Suma et al., 2012b). Additionally, "Change Blindness" (Suma et al., 2011) refers to the technique of altering the position of objects within a space when the user is not noticing it. This allows for the manipulation of the space and enables the reuse of the physical area for various segments of the VE.

Prior studies investigating the detection of redirection thresholds (Suma et al., 2012b; Vasylevska and Kaufmann, 2015; Steinicke et al., 2010) have primarily involved non-naive participants who were already familiar with the concept of the redirection applied. Moreover, existing research papers that analyze the detection of impossible spaces by the users have predominantly used a specific implementation involving two overlapping rooms. However, there is a lack of research exploring alternative methods relying on seamless teleportation to generate such spatial implausibilities. Lastly, the studies that have incorporated portals and teleportation (Koltai et al., 2020; Lochner and Gain, 2021) to create spacial implausibility have not examined how users perceive these spaces, particularly in terms of perception or detection.

In this work, we focus on the perception and cognitive map in a new type of spatial implausibilities where the users skips certain parts of the VE. As shown in Figure 1, omitting specific segments of a corridor enables spatial manipulation, thereby reorienting the VE. This technique allows moving portions of the VE previously outside the physical space boundary into it. This is in contrast to previous implementations of portals which allowed reusing the same physical space for different segments of the VE. This is highlighted in Figure 1 by showing that the small room shown by the small rectangle could have been colliding with an obstacle but after the reorientation the room could be explored. The contributions of this paper are as follows:

- Presentation of a new type of subtle reorientation technique relying on corridors and teleportation,
- Investigation of the perception of the users of such a technique based on various levels of implausibility and different layouts.

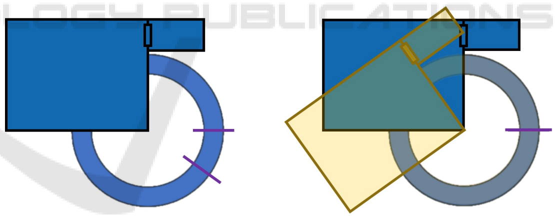


Figure 1: Illustration of spatial manipulation using portals, by teleporting the user in the corridor between the two rectangles (left image) the environment changes orientation as seen in yellow (right image).

2 RELATED WORK

2.1 Perception for Scene Manipulation Techniques

A well-known concept of generating spatial implausibilities is named "impossible spaces", which was introduced by (Suma et al., 2012b). Here the threshold metric was the overlap between neighboring rooms. The study concluded that reasonably small virtual rooms could overlap by up to 56% before users detected it. Moreover, based on a qualitative experiment it was observed that participants who are naive to the manipulation of impossible spaces tend to experience a more compelling illusion. Other researchers took that same spatial compression approach and did further research on the influence of path complexity in overlapping space detection (Vasylevska and Kaufmann, 2015). The research gap they addressed was the lack of knowledge on the effect of different virtual architectural layouts on the perception of such overlapping spaces. There findings suggest that path complexity is a variable that has to be taken into consideration when trying to optimize spatial compression. In a later study by (Vasylevska and Kaufmann, 2017b), they explored the influence of layout properties on the perception of impossible spatial arrangements. Their study aimed to analyze various parameters associated with the path connecting two overlapping rooms. These parameters encompassed the "number of turns, relative door positions, sequences of clockwise and counterclockwise turns, as well as symmetry and asymmetry". Among other results, they found that the absence of landmarks made it harder for participants to orient themselves in space. This in turn is more beneficial for spatial compression. A more recent study (Epplée and Langbehn, 2022) examined the effects of using a minimap during exploration of a VE featuring impossible spaces. (Ciumedean et al., 2021), on the other hand, tested the effects of different layouts in impossible spaces: "open rooms", where rooms are not separated by walls but only by small objects to prevent direct crossing from one room to another without using the corridor; "open corridors", characterized by partial walls that allow the user to view the outside space; and "total inclusion", the standard condition. The focus was on how these layouts impact the detection threshold.

2.2 Teleportation as a Locomotion Technique

Various studies (Freitag et al., 2014; Langbehn et al., 2018) compared the use of teleportation as a locomotion technique in navigating virtual environments. Another work by (Langbehn et al., 2018) compared teleportation with redirected walking techniques, focusing on cognitive map building, cybersickness, and user preferences. In their studies, teleportation is initiated through deliberate user action, as opposed to being seamlessly integrated. Other research (Bruder et al., 2009) has explored combining teleportation with techniques like portals and redirected walking enhancing the exploration in large virtual environments. Teleportation can be implemented in two distinct ways: partial concordance, where it is used solely for translational movements, and full discordance, where it is employed for both rotation and translation. The effects of these methods have been investigated on spatial updating and piloting (Kelly et al., 2020). Furthermore, a detailed literature review is provided in (Prithul et al., 2021), comparing teleportation techniques with alternative locomotion methods. This review also encompasses a discussion of various approaches to implementing teleportation.

2.3 Spatial Implausibility Using Seamless Teleportation

Another interesting way of implementing spatial implausibility is by changing the user's position through instantaneous and seamless teleportation. The work by (Koltai et al., 2020) presented a method for creating scaleable overlapping architecture in VR by "procedurally generating tile-based mazes that seamlessly teleport the user using portals". To implement this unnoticeable teleportation, they used portals on specific locations in the virtual maze. These portals consisted of a rendered plane on which the corresponding part of the next maze element was displayed. When the users crossed the portal threshold they were teleported to the maze element that was displayed on the portal itself. Like this, the users could not notice the teleportation and an illusion of continuity was created. Similarly, (Overdijk, 2023) utilized the same method, combining it with the game's narrative to guide the user, enabling continuous walking in the virtual world. In the same fashion, portals were introduced by (Lochner and Gain, 2021). They analyzed different locomotion techniques in impossible spaces, and used portals and teleportation. In their work, they used pairs of portals to travel between different subspaces of the VE. The portal pairs all had the same local position and orientation so that the user's rotation would not need to be altered when teleporting. Only the users' position had to be translated to the corresponding subspace. Through this, they were able to compress several virtual rooms into the space of one for their experiments.

The aforementioned studies primarily concentrated on users' perception of implausible spaces while navigating spaces featuring impossible geometries and change blindness. In contrast, other research has focused on teleportation as the primary locomotion technique. However, only a few of these have seamlessly integrated teleportation. These instances primarily utilized teleportation to overlap virtual spaces rather than to manipulate them. Seamless teleportation could enable the alteration of the VE's

(a) Circular Corridor. (b) Hexagonal Corridor.

Figure 2: Illustration of the two closed-loop corridor layouts.

orientation in relation to the physical space. This gap in research has motivated the current work, where we explore combination of teleportation and corridors and the noticeability of implausible spaces. This research will explore how different corridor shapes, specifically circular and angular with corners, affect the user's cognitive map. Additionally, it will examine the user's perception of seamless teleportation, particularly how skipping certain portions of the corridors influences this perception.

3 IMPLEMENTATION

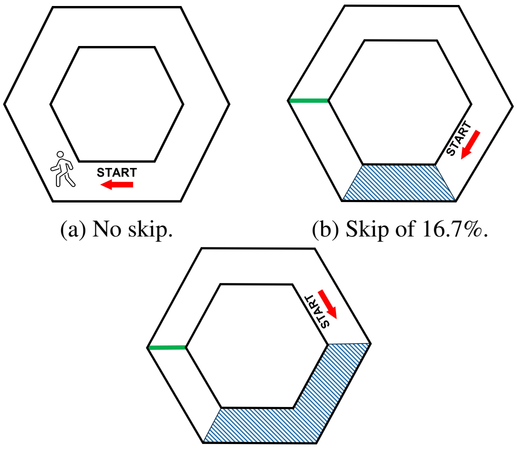
Since we want to investigate how users would detect the implausibility of the space relying on teleportation, we decided to use two closed-loop corridors in which participants could walk. One corridor had a circular shape, and the other a hexagonal one. The corridors each consisted of a white inner and outer wall with grey ground and ceiling. The decision to intentionally omit textures in the scenes was made in order to avoid visible landmarks, minimize distractions, and thereby reduce the number of variables that needed to be taken into account. The size of the corridors was chosen to fill the available physical tracking space (7m $\times$ 9m) with a height of 2.5m. This leads the corridors to have a width of 1.1m. We also added a start sign together with a red arrow, positioned on the inner wall, as a reference point for the users and to indicate the direction the participant would need to walk. The sign is also the cue for the user that he is back to the initial position. Figure 2 shows the corridors with the ceiling removed.

3.1 Seamless Teleportation Design

To create an implausible space within the corridors, we implemented portals in conjunction with teleportation. The idea was to seamlessly teleport the users walking in the corridors from one point in the corridor to another point in the corridor. This has the effect that users skip a section of the corridor and therefore reach the starting position faster, which would not be possible in a real-world scenario. The objective of this approach is to make users believe that they are walking along the entire corridor while, in reality, they are skipping a certain section of it. If the users do not notice this illusion, then the implausibility of the space is successfully unnoticed and the orientation of the physical space is changed. We included three levels of teleportation for each corridor shape which would later represent different experiment conditions. The first condition is the Zero condition where the users are not teleported at all while walking along the corridor. We represent these conditions as C0 and H0, where C represents the circular corridor, H represents the hexagonal corridor and 0 represents that no sections have been skipped in the corridor. The following conditions use the same terminology. In conditions C1 and H1 a sixth of the corridor is skipped and in conditions C2 and H2 a third of the corridor is skipped.

To ensure seamless teleportation, we employed instantaneous repositioning of the user. We implemented a collision plane located at the end of the first section of the corridor. When the user walks through this plane, it triggers the repositioning of the player. The corridor the user is teleported to was already rotated to a specific degree around its z-axis. The advantage of using a pre-rotated corridor as the destination instead of teleporting the player within the same corridor lies in the fact that we only need to translate the player's position, without requiring a change in rotation. Implementing a rotation change of the player would be considerably more challenging. Consequently, this means that in conditions C1 and H1 the corridor where the user is teleporting to is rotated by $60°$ and for conditions C2 and H2 it is rotated by $120°$, illustrated in Figure 3.

Portals are generally 2D planes on top of which the VE is rendered. They are usually placed on walls or corridor endings where the architectural overlap of the VE would happen. Consequently, by walking through the portals, together with teleportation, a seamless transition from one VE to another is created. Users perceive this as exploring a new VE, yet they are reusing a space of the physical tracking space. We used stencil buffers to create portals which render parts of a VE that we want to see while hiding the parts that we do not want to see. The stencil buffer is a dedicated buffer within the shader that can decide if a pixel of an object is drawn or not. To decide which pixels are to be drawn and which are not, we can assign certain reference values to objects using the stencil buffer. By doing a so-called "stencil



(a) No skip. (b) Skip of 16.7%. (c) Skip of 33.3%.

Figure 3: Implausible space implementation for the hexagonal corridors. The green bars indicate the position of the portals. The patterned sections specify the possible spatial compression achieved by each condition. The same principles apply to the circular corridors.

test" the stencil buffer then compares the values of two objects. If the values coincide the pixels of the object can be chosen to be drawn, if not the pixels are discarded. This technique helps us create seamless transitions between different VEs. To implement the stencil buffer portal we first need to create two separate VEs within the same scene in Unity. One is the VE where our user will be starting and the other is the VE where he will be teleported to.

3.2 Hardware and Software

The VE was developed using the Unity engine, and the Meta Quest 2 was used as the headmounted display (HMD) for presenting the VE during the user study. The HMD utilizes an LCD panel with a resolution of 1832 × 1920 per eye at a frame rate of up to 120Hz, featuring a horizontal field of view (FOV) of around 104° and a vertical FOV of 98.2°. To prevent participants from peeking through the gap between their nose and the HMD we installed a little paper flap. The reason was that we wanted to prevent the users to be able to orient themselves on the tracking space. The VE was streamed from a PC through SteamVR, the PC had a GeForce RTX3090 graphics card paired with a 10^{th} generation Intel Core i9 CPU.

To develop our VE and to conduct our user study, we utilized the Unity game engine (editor version 2019.3.19f1) together with the SteamVR plug-in, which enables us to make VR applications which can be directly run on the PC and also streamed to other HMD, like in our case. Since Unity is limited in its ability to create custom shapes and 3D objects we utilized the Unity package called ProBuilder. This package is a 3D modelling and design tool which allows users to create simple geometries[1].

4 USER STUDY PROCEDURE

Prior to developing our user study, it was necessary for us to determine the hypotheses we aimed to validate. This allowed us to design our user study in accordance with these hypotheses. We decided on the following hypotheses:

- Hypothesis 1: Implausible space detection increases if more sections of a closed-loop corridor are skipped,
- Hypothesis 2: Implausible space detection is higher for closed-loop corridors with sharply curved paths compared to smooth curved paths.

Our first hypothesis is straightforward since it is natural to expect users to notice the implausible space if the changes are more drastic. In our second hypothesis, we assume that sharp corners can be used as landmarks (Vasylevska and Kaufmann, 2017b) to help the users to orient themselves in space and thus help them understand the spatial impossibility induced by the teleportation.

Participants for both studies were recruited from the university community. The sole criterion for participation was the ability to walk, ensuring a broad and accessible participant pool. Prior to commencing the experiments, we refrained from disclosing the objective of the user studies in order to prevent participants from actively seeking hints about the redirection technique. Each participant was required to provide their informed consent by signing a form. Subsequently, the user began by completing questionnaires on demographics and the Simulator Sickness Questionnaire (SSQ). They were then introduced to the hardware in the SteamVR room, where they could walk around and familiarize themselves with the system. The user study procedure is shown in Figure 4.

The study then commenced, and the VE featuring the corridors was launched. The participants started at the start position in the corridor and were then told to walk along it until they reach the start position again shown by the start sign. Following each corridor experience, participants were presented with a simple transition scene consisting of a wooden floor and sky. They were instructed to follow a floating hand on the screen, controlled by the experimenter, until instructed to stop. This procedure was conducted while

[1] https://unity.com/features/probuilder, accessed on 02.07.2023

the participant wore the head-mounted display. The dual purpose of this approach was to disrupt the participant's spatial orientation within the tracking environment and prevent them from seeing their final position in the physical space. Additionally, it facilitated repositioning the participant to the starting point for each corridor iteration. This procedure was consistently repeated for each corridor. Each participant had in total two series of walking. In each series, the participant had to walk through three different corridor conditions of the same corridor shape. Half of the participants started with the circular corridors and half of them started with the hexagonal corridors. After each series, the participant had to execute a drawing task where he had to draw the virtual environment where he walked. In the walking series, the sequence of skip levels within the corridors was predetermined in a counterbalanced order to ensure that each condition occurred uniquely. Consequently, some users might first experience a 33% skip, while others could begin with no skip or a 16% skip. The purpose behind this was to prevent learning effects and to be able to analyze different corridor conditions.

After the study, the true purpose of the user study was revealed, and we proceeded to explain the participants how the corridors operated and provided an explanation of the potential of spatial implausibility techniques. Subsequently, users were requested to provide informal feedback regarding their impressions of the manipulation.

4.1 Drawing Task

In the drawing task, participants had to draw the floor plans of the three corridors they have just walked along. Additionally, they had to indicate on each corridor drawing the "START" position and to try drawing the corridors to scale. Drawing to scale meant that if they perceived certain corridors to be smaller or larger than others, they had to indicate it by drawing larger or smaller corridors or alternatively describe it with words. It is important to state that participants were only told about the drawing task after walking the corridor to prevent participants from focusing unnaturally much on the corridor layout. The implementation of a counterbalanced user study, where participants were equally exposed to commencing with either the hexagonal or the circular condition, contributed to neutralizing potential biases of the results. Participants were instructed to draw the corridor floor plans into boxes by the order they walked them. The boxes contained a grid to help the participants with their drawings and to make it easier to draw them to scale. To extract meaningful data from the drawings of the participants, we evaluated the drawings by two measures and compared them to the actual condition they were supposed to represent.

In order to assess whether participants detected the implausibility of the spaces, we searched for corridors that were either not closed or had additional start or stop points drawn. Drawing an non-closed corridor indicated that the users were aware that they have not walked a full round. The same holds true for drawing two separate start signs since changing the starting sign to a different section in the corridor would have the same effect as teleporting the player. Examples of non-closed-loop corridor drawings and double start positions can be seen in Figure 5. The other measure we evaluated was if the participant drew the corridors within a series in different sizes or shapes (SoS), compared to each other. Our reason was that if they did so, they have not detected the implausible space but they still detected a change going from corridor to corridor. Drawings, where only one change in SoS occurred, were also counted as a detection. If no change in SoS was detected, we counted it as no detection.

5 RESULTS

From the 25 participants enrolled in our user study, 16 (64%) were male, while 9 (36%) were female. The age distribution spanned from 16 to 30 years, with an average age of 21.76 ± 2.69 years. The participants consisted of 20 students and 5 non-students. More than half of the participants (52%) reported having between zero and five hours of previous VR experience. Six participants had no experience, 3 participants had between 20 and 100 hours of experience, 2 participants had between 5 and 20 hours of experience, and 1 participant had over 100 hours of experience. The mean SSQ total difference prior and after the user study was 1.65 ± 9.58. Analysis of the SSQ responses, administered both before and after the user study, indicated no significant variance among participants. Consequently, no participant required exclusion from the study.

5.1 Drawing Task Results

From all participants, four did neither detect the implausibility of the space space nor a change in the SoS of the corridors. Two participants noticed both, the implausible space and a change in SoS. The rest of the participants detected at least either of those.

The overall results from the user study regarding the detection of the implausibility of the space are de-

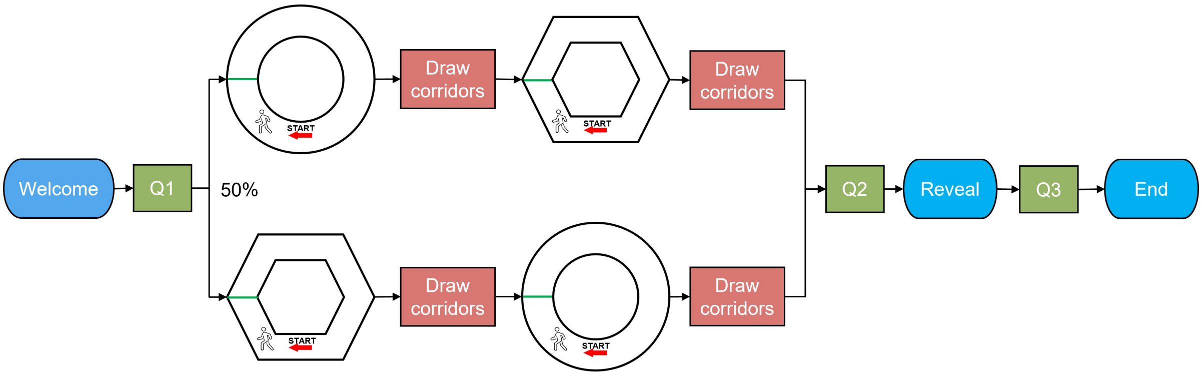
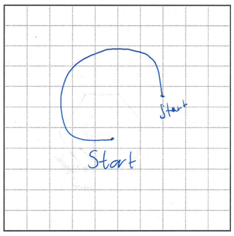
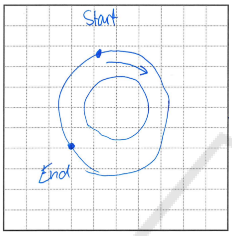


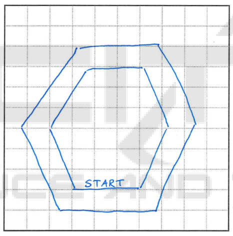
Figure 4: Procedure of the user study testing detection thresholds for a novel type of impossible spaces. Green boxes indicate questionnaires for participants, and red boxes denote drawing tasks.



(a) Non-closed corridor.



(b) Multiple start positions.



(c) No detection.

Figure 5: Drawings (a) and (b) count as detection of the teleportation, while (c) counts as no detection.

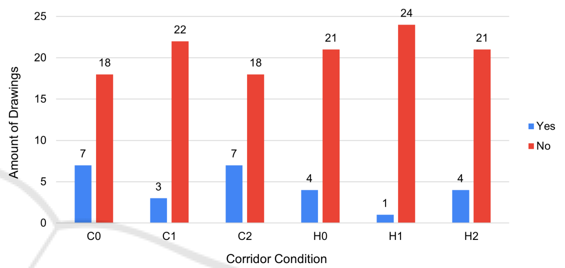


Figure 6: Column chart representing the detection of the space manipulation for each condition. "Yes" represents the corridor drawings where an implausible space was detected and "No" represents the drawings it was not detected. For each corridor condition, n=25 drawings were analyzed.

picted in Figure 6. This chart shows the detection rates for each condition (C0, C1, C2, H0, H1, and H2). The blue columns depict which percentage of the participants detected the space implausibility, and the red columns represent the percentage that did not notice this. The main assumption is that if the user doesn't perceive the implausible space, they believe that they reached the same physical space location after each navigation task in the corridor.

Hypothesis 1 investigated whether the implausible space detection increases if larger sections of the corridors are skipped. In the comparison of detection rates, a pattern was noted: in conditions C1 and H1, participants detected the implausible space 3 and 1 times, respectively. In contrast, for conditions C2 and H2, these numbers increased to 7 and 4 detections, respectively. However, the application of McNemar's test did not yield statistically significant evidence ($p = 0.25$ and 0.125, respectively) to justify the rejection of the null hypothesis which indicates no difference in detection of implausibility in terms of the degree of skip. Thus the hypothesis that increasing the level of implausibility would make the user more prone to notice the seamless teleportation effect cannot be accepted.

Hypothesis 2 investigated whether corridor layouts influence a user's ability to detect seamless teleportation and alters their cognitive map of the space. To examine this, we employed McNemar's test for repeated measures to assess differences in detection between the conditions C0,H0; H1,C1; and C2,H2. However, the analysis faced a limitation due to the low number of participants who successfully detected teleportation or a distortion in the spatial layout. Consequently, the p-values obtained (0.375, 0.25, 0.625) for all three comparisons were significantly high. This outcome negates the necessity for applying a Bonferroni correction, as the p-values inherently indicate a lack of statistical significance in the difference between the corridor layouts. This finding does not align with the previously presented research, affirming the potential influence of corner landmarks in aiding user's navigation and layout identification.

Participants faced challenges in discerning the condition without a skip. This is evidenced by 7 out of the 25 participants identifying an implausible space in the C0 condition and four in the H0 condition, in contrast to 3 and 1 participant in the C1 and H1 conditions, respectively. This initial observation underscores the success of the seamless teleportation effect. This finding was not expected before the realisation of the study. Out of the 11 implausible space detections in the zero conditions, 9 of them (82%) started with either a one-section skip (C1 or H1) or a two-section skip (C2 or H2). This leads us to believe that those participants might have taken the first corridor as a reference and compared the other two corridors to it.

5.2 Change in Size and Shape Detection

Since 21 (84%) participants out of 25 did not notice the spatial manipulation by itself but instead noticed a change in SoS, we also examined this for all patterns. For both, the hexagon- and the circular-shaped corridors, 17 participants detected a change in the size or shape of the environment while 8 did not. This was expected since they could compare the trials with each other. However, this supports the previous finding that corners did not help in better perceiving the teleportation. However, it should be noted here that such a detection in the hexagonal shape means the user perceives less turns or corners thus changing the layout he draw from a hexagonal to a square or pentagon despite the fact that all the angles at the corner are still equal to 120°. While for the circular corridors, the change in size refers to perceiving the same layout a full circle which is smaller thus the cognitive map would be the same.

To check for the sequence effect on the detection, we combined the skips into two categories like C0 to C1 as "1 Section Different" and larger changes like from C0 to C2 as "2 Sections Different". There was a total of 61 "1 Section Different" corridor changes and 39 "2 Sections Different" corridor changes. This difference can be explained by the higher chance of having "1 Section Different" corridor changes since there are simply more possible combinations. There is only a small difference in the detection ratios between "1 Section Different" (49% detected) and "2 Sections Different" (54% detected).

The primary implication of this study is that the proposed scene manipulation does not cause sickness or discomfort in users, unlike other similar methods such as redirected walking. Since users had difficulties identifying when the manipulation occurred, this highlights the effectiveness of the implementation, suggesting that such scene manipulations are unlikely to cause discomfort. Another key finding is the potential to preserve the overall cognitive map layout of the environment, despite distortions caused by teleportation. This was particularly evident as most users still perceived a circle, even though parts of it were skipped. In contrast, in the hexagon experiments, the change was perceived as fewer turns, altering the hexagon into a pentagon or square, implying a change in shape. Therefore, these insights enable us to determine where this method should be applied, based on the need to maintain an accurate cognitive map.

6 LIMITATIONS

Our user study includes two separate rounds of walking, where after each round the participant had to perform the drawing task. Because of this sequential approach, the participants might have experienced a learning effect since in the second walking round most anticipated that there will be another drawing task. Due to the limited number of participants, this could not be avoided. From of the 75 corridor drawings in each round, we see that in the first round of the walking series 12 drawings were attributed to a correct spatial manipulation detection (16%). In the second round, it was 21 drawings (28%). This is an increase of 12% in the second round. By doing the McNemar's exact test, we get a one-tailed p-value of p=0.057 which is very close to being a significant difference and might indicate a correlation. This supports that future studies using the drawing method should focus on having one condition per user to avoid the learning effect. Another limitations of the drawing task is that users stated in the informal feedback that participants had to remember three corridor paths at once. During our study, some participants reported not being sure in which sequence the corridor conditions appeared. By decreasing the number of corridors a participant has to walk this problem could probably be mitigated.

7 CONCLUSION

In this work, we created a new architectural layout which implemented spatial manipulation using portals and teleportation. Our architectural layout consisted of closed-loop circular and hexagonal corridors, in which users skipped up to 33% of the path through teleportation. To collect the necessary data, we developed a user study where the main task was for the participants to walk through corridors with different levels of space manipulation and then draw the floor plan of these virtual corridors. Overall, the detection of the correct spatial manipulation was relatively low, between 4% and 28% depending on the corridor condition. Participants could also not significantly tell apart the three levels of space manipulation. This means that our implementation of spatial manipulation shows a valid approach to manipulating the space without the users knowing what exact manipulation was done. We also did not find any evidence proving that there is a significant difference in detection for hexagonal corridors compared to circular ones. Because we noticed that the participants perceived the corridors to be of different SoS, we additionally analyzed this aspect. We categorized any detection of change in SoS separately from the detection of the implausible space. A total of 21 (84%) out of 25 participants did notice an SoS change going from corridor to corridor. This is an indicator that the spatial manipulation was felt to a certain degree, but the participants did not correctly specify which kind of manipulation.

7.1 Future Work

Future studies will include a larger number of participants and assign each a single drawing task to mitigate learning effects. Furthermore, investigating a variety of polygon shapes could provide insights into how different angles influence the perception of impossible spaces. Practical applications of these impossible spaces also require further exploration. Lastly, efforts can be made to quantify detection in more intricate corridor designs, such as those with left and right turns, prior to teleporting the user.

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