Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture

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Abstract—Walking is only possible within immersive virtual environments that fit inside the boundaries of the user's physical workspace. To reduce the severity of the restrictions imposed by limited physical area, we introduce "impossible spaces," a new design mechanic for virtual environments that wish to maximize the size of the virtual environment that can be explored with natural locomotion. Such environments make use of self-overlapping architectural layouts, effectively compressing comparatively large interior environments into smaller physical areas. We conducted two formal user studies to explore the perception and experience of impossible spaces. In the first experiment, we showed that reasonably small virtual rooms may overlap by as much as 56% before users begin to detect that they are in an impossible space, and that the larger virtual rooms that expanded to maximally fill our available 9.14m x 9.14m workspace may overlap by up to 31%. Our results also demonstrate that users perceive distances to objects in adjacent overlapping rooms as if the overall space was uncompressed, even at overlap levels that were overtly noticeable. In our second experiment, we combined several well-known redirection techniques to string together a chain of impossible spaces in an expansive outdoor scene. We then conducted an exploratory analysis of users' verbal feedback during exploration, which indicated that impossible spaces provide an even more powerful illusion when users are naive to the manipulation.

Index Terms—Virtual environments, perception, spatial illusions, redirection.

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1 INTRODUCTION

Immersive virtual environments can provide compelling experiences that transport users to a synthetic world, making them momentarily forget the real space they physically occupy. Sensorimotor actions are an important component of this phenomenon - if the user cannot naturally move around and engage with virtual content as if it were real, then illusion of being in another place may break [17]. However, supporting natural locomotion remains a practical challenge for virtual reality applications that require travel through expansive virtual environments larger than the size of the physical room, such as urban scenes commonly desired for immersive training simulators. To overcome these physical space restrictions, a number of *redirection* techniques have been proposed to manipulate the user to follow a virtual path that diverges from their physical movements. These techniques are designed to preserve the feeling of moving naturally through a stable virtual world while simultaneously keeping the user physically constrained within the boundaries of the real workspace. While numerous redirection studies thus far have demonstrated compelling and promising results, these techniques are still somewhat limited in their practical applicability, and can benefit from the introduction of new approaches to augment their combined utility.

In this paper, we describe a novel virtual environment design mechanic for compressing a larger architectural layout into a smaller physical area, which we refer to as *impossible spaces*. These environments are designed with self-overlapping architecture, for example, a building with multiple rooms that are "bigger on the inside." Such illusions have been represented in popular fictional works, such as the time machine in the television show *Doctor Who*. While these spatial illusions are not physically realizable, virtual reality technology provides the unique opportunity to experience phenomena that would otherwise be inaccessible to human beings in the real world. When combined with existing redirection techniques, impossible spaces can substantially augment the effective walking area, allowing potentially vast synthetic worlds to be explored using natural body movement within reasonably-sized physically workspaces.

Two formal user studies were conducted to investigate impossible spaces. In the first experiment, we adapted an approach from psychophysics to estimate the perceptual detection thresholds for overlap in adjacent rooms that partially occupied the same area, and evaluated participants' perceptions of distance within the impossible space. In the second experiment, we combined impossible spaces with several existing redirection techniques to facilitate travel between multiple buildings in an expansive outdoor scene. We then performed an exploratory qualitative analysis of participants' verbal feedback while exploring the virtual environment. In general, the results from these experiments demonstrate that impossible spaces provide powerful illusions that are often not perceived by users, and have minimal negative impact on the experience even when users do notice them.

2 PREVIOUS WORK

The benefits of supporting natural body movement have been extensively studied in head-mounted display virtual environments. For example, walking through an environment has been shown to result in higher self-reported sense of presence than walking-in-place and joystick-based locomotion [24]. In particular, numerous studies have compared walking to virtual locomotion techniques commonly implemented with joysticks and gamepads. Walking has shown to provide superior performance on search tasks [16], more efficient travel involving fewer collisions with virtual geometry [22], and benefits for spatial orientation [5]. Studies have also demonstrated cognitive benefits for natural walking in areas such as attention [21] and higher mental processes [30]. Additionally, the travel paths taken during walking-in-place and virtual locomotions do not correlate well with the motions elicited when walking naturally [25].

Despite the well-known advantages of walking in virtual environments, virtual travel techniques are often employed instead by VR

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practitioners because a direct mapping of physical walking motions to virtual movements makes it impossible to reach any area of the virtual environment that falls outside the boundaries of the workspace. To overcome such limitations, a number of redirection techniques have been proposed to guide the user along a virtual path that diverges from their real world movements. The ultimate goal of such techniques is to prevent users from exiting the tracking area, thereby effectively compressing a larger virtual environment into a smaller physical space. Approaches to redirection can be broadly divided into two categories: (1) manipulation of perceived self-motion and (2) manipulation of the spatial qualities of the virtual scene.

2.1 Manipulation of Self-Motion

Self-motion manipulation techniques work by slowly and continuously amplifying or diminishing a component of the user's motion in the virtual environment. These approaches work in practice because vision tends to dominate over vestibular and proprioceptive sensation when these cues conflict, so long as the magnitude of the conflict is within tolerable limits [1]. Self-motion manipulation techniques can be generally divided into three categories: (1) translation gains, (2) rotation gains, and (3) curvature gains.

Translation gain techniques measure the change in tracked head position, and scale the translations to move over smaller or greater distances in the virtual world [26]. The "Seven League Boots" approach extended this method by estimating the user's intended direction of travel and scaling only the motion aligned with that direction, thereby avoiding any exaggeration of the oscillatory head sway associated with natural walking motion [8]. Psychophysical studies have shown that distances can be downscaled by 14% or upscaled by 26% without being noticeable to the user [19].

Rotation gain techniques measure the change in tracked head orientation, and scale the virtual rotation to guide the user's path towards a target location, usually away from the boundaries of the workspace [15]. These manipulations can be applied under different conditions, such as during head turns while the user is standing still [9] or during body turns as the user navigates around obstacles [3]. Studies of these techniques have shown that users can be physically turned approximately 49% more or 20% less than the perceived virtual rotation without noticing [19]. Researchers have also developed a psychophysically-calibrated controller that optimizes rotation gains based on human sensitivity to visual-proprioceptive conflicts during walking [6].

Curvature gain techniques work by adding offsets to real world movements. There are two cases where curvature gains can be applied - either when users move straight on a path while the virtual rotation is manipulated, or when they engage in head turns while the virtual translation is manipulated [19]. In either case, the user will unknowingly compensate for the offset, walking along a circular arc. Studies have shown that a walking arc with a radius of at least 22m is necessary for curvature gains to be imperceptible to the user [19]. Noting that the effectiveness of curvature gains changes based on walking speed, a redirection controller that dynamically adjusts gains based on the user's velocity has been recently proposed in the literature [11].

In addition to be applying continuous redirection while the user moves around, it may also be advantageous to interrupt the user and "reset" their location with rotation gains [27]. Resetting techniques are often used as a failsafe to prevent the user from exiting the physical workspace, and have been combined with other redirection approaches such as translation gains [29]. To mitigate the potential breaks in presence caused by such interventions, researchers have studied the use of distractors to elicit the head turns necessary to reorient the user, and showed that they were preferred over visual or audio instructions [12]. Studies have shown that when combined with distractors, redirected walking techniques allow users to perform no worse on pointing and sketch map tests than natural walking without redirection [13], and are significantly better in supporting navigation and wayfinding than walking-in-place and joystick locomotion interfaces [14].

Finally, visual illusions that influence optic flow fields during walking has also been proposed to influence self-motion perception, and it has been suggested that they could be used to potentially compensate for the underestimation of travel distances in virtual environments [4].

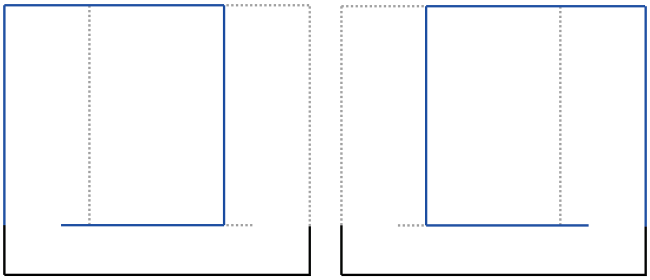

(a) State 1 (b) State 2

Fig. 1. An example of an impossible virtual environment consisting of a building with two adjacent rooms that spatially overlap. To ensure that the user's view is visually consistent, the environment shifts between two states, with only a single room visible at any one time. The net result is a larger overall building that can be explored in a smaller physical workspace.

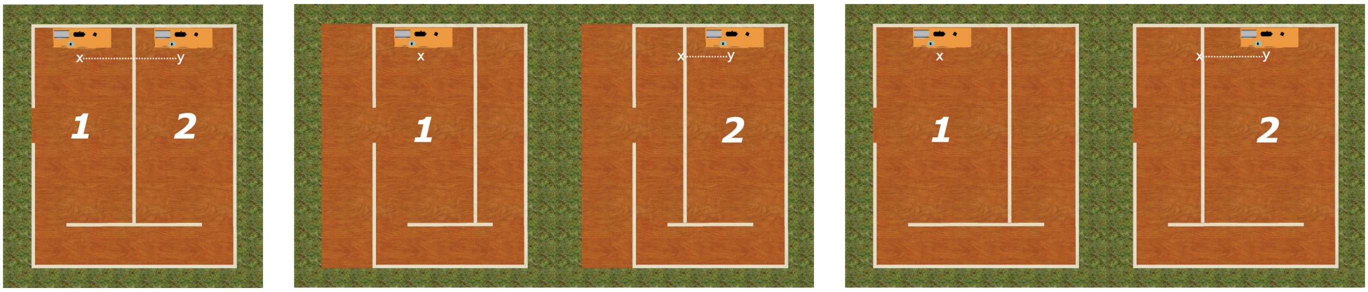
2.2 Manipulation of Virtual Scene

While self-motion manipulation techniques have been extensively studied, virtual scene manipulation is a relatively new class of techniques with similar goals but drastically different implementations. One proposed method of leveraging virtual scene content has been the use of virtual portals that instantaneously transport the user from one location to another [2] [18]. Perhaps the most similar to impossible spaces is recent work that explored the use of change blindness illusions that instantaneously shift between discrete architectural states to reorient the user in physical space [20]. While their results were highly promising from a perceptual perspective, with very few participants able to notice the manipulation, the technique only worked in a fairly constrained scenario, and it remains unclear whether such illusions are generalizable enough to be practically useful. However, their results suggested that spatial manipulations may be strikingly powerful, and that participants' perceptions of space in virtual environments may be far more malleable than previously realized. This finding is a strong motivator for our current research, and thus impossible spaces represent an attempt to leverage spatial manipulation in a way that will be more practical than previous work.

The idea of impossible environments has been previously explored in the context of studying the mental representation of an environment during navigation. Researchers found that environments with severe violations of Euclidean geometry or planar topology did not seem to interfere with navigation of a 2D projected virtual environment using a joystick, nor did participants appear to be aware of the spatial manipulations [31]. These results suggest that impossible spaces may be promising, but previous work has not addressed the application of these illusions towards augmenting the effective walking space in an immersive virtual environment. Given that previous studies have shown that walking in a virtual environment provides superior spatial orientation and knowledge acquisition (e.g. [5] [16]), it remains unclear whether impossible spaces will prove just as effective in this context. Furthermore, to the best of our knowledge, no previous studies have made an attempt to quantify the magnitude of "impossibility" that may be achieved before the illusion becomes noticeable to the user. Thus, we attempt to address these questions, and others, in our experiments.

3 IMPOSSIBLE SPACES

Impossible virtual environments contain geometry that violates the rules of Euclidean space, and therefore cannot exist physically in reality. While there are many potential ways in which virtual content may transgress physical laws, for the purposes of maximizing effective walking space, we focus on one specific type of Euclidean violation:

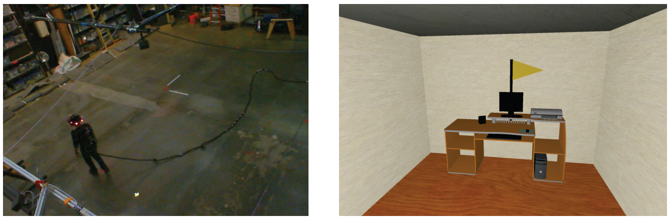


(a) 0% Overlap (b) Fixed Room - 50% Overlap (c) Expanding Room - 50% Overlap

Fig. 2. (a) An overhead view of the 9mx9m environment tested in Experiment 1 with 0% overlapping rooms. The user entered the building, activated the computer monitor in room 1, then proceeded to room 2. During the distance estimation task, participants stood on location Y and walked "blindfolded" along the dotted line to the target (location X). (b) In the fixed room size condition, the adjoining hallway was shortened, causing the rooms to partially overlap in space. (c) In the expanding room condition, the rooms were arranged to maximally fill the available tracking space, and the overlap level was increased by moving the shared wall into the space formerly occupied by the adjacent room.

self-overlapping architecture. Figure 1 shows an example of a simple virtual building consisting of two adjacent rooms connected by an adjoining hallway. These two rooms are too large to exist together simultaneously within the confines of the physical tracking space. However, by arranging the rooms so that they spatially overlap, it becomes possible to "compress" the building to fit within a smaller physical area. This requires the environment to switch between two discrete architectural states depending on the user's location, so that only one room is visible at a time. In order to ensure that the user's point of view in the virtual environment remains visually consistent, it is necessary to have a transition area where the rooms can be switched out without being visible. In our example, we perform the switch when the user is halfway down a connecting hallway between the two rooms. The net result is that the user can naturally walk through the entire virtual building even though the total size is larger than the physical workspace.

Similar to many other techniques for enabling natural walking through large-scale virtual environments, the versatility of impossible spaces is primarily limited by the size of the available physical workspace. With a sufficiently expansive tracking area, it is quite possible that more complicated building layouts could be defined, with three or more rooms that overlap in a more sophisticated spatial arrangement. However, for workspaces the size of a medium-to-large room, which are now practically feasible using wide-area tracking technology, our example employing two virtual rooms and a connecting hallway provides a simple design mechanic that would be appropriate for use in many virtual environment settings, such as indoor office buildings. Additionally, impossible spaces may also be combined with more traditional approaches to redirection, such as rotation or curvature gains, thus further augmenting the utility of natural walking (see Section 5).



(a) (b)

Fig. 3. (a) A user exploring a virtual building while wearing the head-mounted display. (b) A screenshot of the user's view in the virtual world.

4 EXPERIMENT 1: PERCEIVING IMPOSSIBLE SPACES

Impossible spaces represent a departure from most previous redirection approaches that manipulate the users' perceived self-motion. To the best of our knowledge, spatial manipulation of self-overlapping architecture has not been evaluated before in the context of enlarging the effective walking space in HMD-based virtual environments. Therefore, we conducted a formal user study to probe the degree to which users perceive impossible spaces at different levels of self-overlap. To this end, we adapted an approach commonly used in psychophysical studies to estimate detection thresholds for perceptual phenomena. Additionally, we also asked participants to estimate the distances to targets in adjacent overlapping rooms, in order to shed light on their perceptions of scale in the compressed space.

4.1 Test Environment

The experiment task required participants to explore a series of virtual buildings while wearing a head-mounted display. Some of these buildings were possible in the real world, consisting of two adjacent non-overlapping rooms connected by a hallway (see Figure 2.a). In other cases, the building was an impossible space, with rooms that partially overlapped in space (see Figure 2.b). In each virtual building, participants were asked to approach a desk in each room, which would activate a computer monitor. They were told to pay attention to the location of a yellow flag, which was placed on the desk in the first room of the building (see Figure 3). After turning on the monitor in the second room, they were asked to perform two tasks:

- **Impossible Space Perception Task:** Participants were instructed to perform a *two-alternative forced-choice* (2AFC) task by responding verbally with the choices "possible" or "impossible." They were then asked to indicate confidence in their answer by saying "not confident," "somewhat confident," or "confident."

- **Distance Estimation Task:** Participants were asked to turn towards the direction of the flag in the first room, indicated by a directional marker in the virtual world, and imagine where they thought the flag was. The head-mounted display then went black, and they were asked to walk in a straight line and stop when they had reached the flag.

4.2 Participants

A total of 19 people participated in the study (12 male, 7 female), with a mean age of 36.26 (*SD* = 12.56). When participants were asked to rate their experience playing 3D video games, nine participants indicated that they were inexperienced, five were a little experienced, and the remaining five were very experienced. They were recruited from craigslist online classifieds and university email lists, and were offered $20 for participating. They were required to be over the age of 18, able to walk without assistance, able to communicate in spoken and written English, and have normal or corrected-to-normal vision. We excluded people who were pregnant, had a history of epilepsy or seizures, or were sick with an illness transmitted by contact.

4.3 Study Design

The study used a within-subjects design with two independent variables, corresponding to the amount of spatial overlap and the dimensions of each room. We tested six overlap levels measured in percentage of the square footage of an individual room: 0% (no overlap), 15%, 30%, 45%, 60%, and 75%. For manipulating the room dimensions within our 9.14m x 9.14m tracking area, we tested the following two conditions:

- **Fixed Room:** The dimensions of each room were fixed at 3.66m by 7.32m, which is approximately one-third of the square footage of the tracking area (see Figure 2.b). This corresponds to one potential usage scenario for impossible spaces, in which a number of smaller rooms are arranged throughout the space in an impossible way, resulting in a larger overall building layout.
- **Expanding Room:** The rooms were positioned as far away from each other as possible to maximally fill the available tracking space, and then expanded by moving the shared wall towards the adjacent room until the desired level of overlap was reached (see Figure 2.c). This corresponds the another usage scenario for impossible spaces, which would seek to represent the largest rooms possible within the physical constraints of the system.

We hypothesized that although the expanding room condition presents the most utility for compressing large environments into small workspaces, the fixed room condition would be less noticeable to users, especially at higher overlap levels when the individual room dimensions were approaching the full size of the tracking area. It is important to note that participants were able to see the workspace prior to being immersed, so they were aware of how large the physical workspace was in reality. Additionally, we also hypothesized that when performing the distance estimation task in a spatially compressed environment, participants would walk farther than the actual distance to the flag, as if the rooms were side-by-side without any overlap.

Each of the six overlap levels were tested for both room dimension conditions, resulting in 12 room combinations. This process was repeated twice for each participant, for a total of 24 virtual buildings to explore across two sessions, separated by a brief break. Within each room dimension condition, the six overlap levels were presented in pseudorandom order. The order of presentation for the room dimension condition was counterbalanced across the experiment.

4.4 Equipment

Participants explored the virtual environment using a Fakespace Wide 5 head-mounted display. This display provides a total field-of-view of 150 degrees horizontal and 88 degrees vertical, and uses a variable resolution with higher pixel density in the central region and lower resolution in the periphery. The interpupilary distance was set to the population average of 6.5cm. Tracking was accomplished using a PhaseSpace Impulse Motion Capture System with 52 high-resolution cameras mounted throughout a 9.14m x 9.14m area. Seven active LED markers were rigidly attached to the display, allowing participant head movements to be captured by the system. In addition to the display, participants wore a backpack weighing approximately ten pounds to hold the display control box and other necessary hardware.

To provide an immersive experience, we attached a lightweight, opaque Lycra fabric around the edges of the display optics, which fell against the participants faces and eliminated peripheral visual cues from the real world. Additionally, participants wore Pioneer SE-DJ5000 sound-isolating headphones, which issued text-to-speech audio instructions and also looped brown noise (approx. 6 dB rolloff per octave, 44kHz sampling rate) at comfortable levels observed to effectively obstruct conversation, noise from cable drag, and other ambient sounds present in our lab. The experiment was run on a dual Intel Core i7 2.93 GHz PC running Windows Vista with a total of eight cores, 6GB of RAM, and an NVIDIA GTX 570 graphics card. Each eye was rendered at 60 frames per second using the Unity3D Pro game engine. Tracker data was received by the engine using a VRPN plugin [23].

4.5 Methods

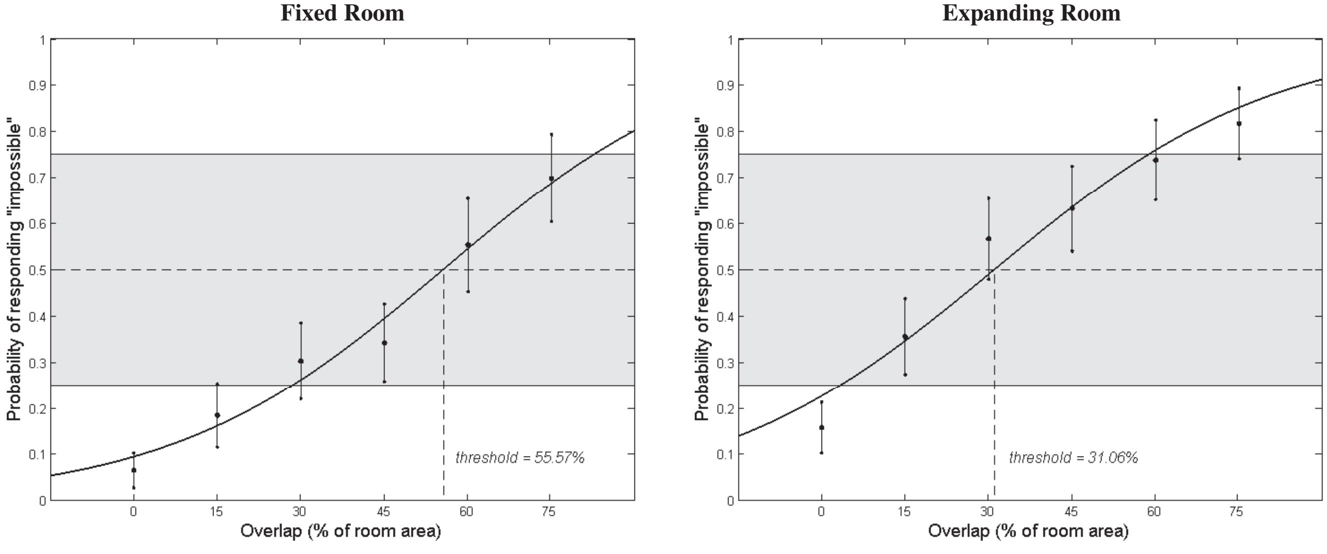
The study took approximately one hour to complete. Participants were initially given an opportunity to read the informed consent form and ask questions about the study. After consent was obtained, participants completed the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [10]. Next, participants were led to the experiment area, and the equipment and task was explained to them. To ensure that they understood the difference between impossible and possible spaces, we used visual illustrations to demonstrate the concept of spatially overlapping rooms, and participants were verbally interviewed to confirm their understanding of the task. When participants were ready, they were equipped with the head-mounted display, backpack, and headphones, and then were told to complete a practice trial, where the experimenter walked them through example tasks step-by-step. After completing the practice, participants then completed the experiment tasks for all 24 virtual buildings, with a 3-5 minute break halfway through to alleviate fatigue and reduce the chances of simulator sickness. During the experiment, participants' verbal responses on the impossible space perception task were recorded on a chart by the experimenter.

Immediately after the virtual reality session was concluded, participants completed the SSQ post-test so we could compare the changes in reported symptoms after being immersed in the virtual environment. Next, participants were asked to complete a feedback questionnaire, where they were given several free response qualitative questions to gather feedback about the experience, such as "When you were inside a virtual environment that was impossible in the real world, how did this make you feel?" and "Was there anything that contributed to or took away from your experience of the virtual world? If so, please describe them." After responding to these questions, they also completed a demographic and video game experience questionnaire. The experiment was then concluded, and participants were debriefed and given a final opportunity for comments or questions.

Our analyses use methods adapted from perceptual detection studies typically used in the field of psychophysics. For each overlap level, we calculated the pooled probability that subjects were responded "impossible" when asked to judge the space they were experiencing. From this data, we calculated separate psychometric curves for the detection of impossible spaces in the fixed room and expanding room conditions. In psychophysical detection studies, the overlap level at which this curve reaches a probability of 0.5 is typically defined as the *absolute detection threshold*. For this experiment, the threshold defines the level for which participants are equally likely to judge the space as possible or impossible. For overlap levels greater than the detection threshold, participants begin to reliably detect the presence of an impossible space. Conversely, for overlap levels that are lower than the threshold, participants are able to detect the impossible space with poorer likelihood than selecting randomly.

To evaluate the difference between the fixed and expanding room conditions, as well as learning effects, we combined participant judgments and confidence responses and recoded them to form a 1-6 scale (1= confident possible, 2 = somewhat confident possible, 3 = not confident possible, 4 = not confident impossible, 5 = somewhat confident impossible, 6 = confident impossible). It should be noted that because of the nature of the 2AFC task, it was not possible to include a neutral value in this scale. For each of the two VR sessions, we then averaged these values over the different overlap levels to form an overall combined response/confidence score for each room type. We excluded the 0% overlap condition when calculating these scores, because we specifically wanted to evaluate participant perceptions of the impossible spaces, not the possible ones.

To analyze results of the distance estimation task, we divided each participant's walked distance by the actual real world distance to the target in each trial. This percentage calculation represents the degree to which they overestimated or underestimated the actual target distance based on the level of overlap between rooms.



(a) (b)

Fig. 4. Detection results and standard errors for impossible spaces tested in Experiment 1. Rooms in the environment were (a) fixed at 3.66m x 7.32m or (b) expanded to maximally fill the available 9.14m x 9.14m physical workspace. The *x*-axis shows the different overlap levels, represented as percentages of the area of individual rooms. The *y*-axis represents the probability that participants judged the space as impossible. The intersecting dotted lines indicate the *absolute detection threshold*, the overlap level for which participants on average responded with the accuracy of random chance.

4.6 Results

Unless otherwise noted, all tests cited in this paper used a significance value of $\alpha = .05$.

Impossible Space Perception

Figure 4 shows pooled response probabilities and standard error across all participants. The *x*-axis shows the different overlap levels, and the *y*-axis refers to the probability of responding "impossible" when asked to judge the virtual space they were in. The solid line is the fitted psychometric function of the form $f(x) = \frac{1}{1+e^{a*x+b}}$ with real numbers a and b. The absolute detection thresholds were calculated at 55.57% overlap for the fixed room condition and 31.06% in the expanding room.

The combined response/confidence scores were treated with a 2x2 repeated measures analysis of variance (ANOVA) testing the within-subjects effects of room type (fixed or expanding) and session number (first or second session). The results revealed a significant interaction effect, $F(1,18) = 7.13, p = .02, \eta_p^2 = .28$. The main effect for room type was significant, $F(1,18) = 16.20, p < .01, \eta_p^2 = .47$, indicating that overall participants were able to more confidently identify the impossible spaces in the expanding room condition (M = 4.14, SD = 1.68) compared to the fixed room condition (M = 3.25, SD = 1.27). The main effect for session number was not significant, $p = .06$. To evaluate the interaction effect, post-hoc paired samples t-tests were conducted with Bonferroni-adjusted $\alpha = .025$ to correct for compounded error in multiple comparisons. Subjects experienced a learning effect in the expanding room condition, as they were able to more confidently identify impossible spaces in the second session (M = 4.58, SD = 1.54) compared to the first session (M = 3.69, SD = 1.74), $t(18) = 2.52, p = .021$. In the fixed room condition, however, subject performance did not significantly improve from the first session (M = 3.18, SD = 1.27) to the second (M = 3.31, SD = 1.29) and, $p = .57$.

Distance Estimation

Figure 5 shows the walked distances represented as percentages of the actual physical distance to the target, plotted in relation to the different room overlap levels. The horizontal gray dotted line represents the distance we would expect participants to walk if they were moving to the actual spot at which they experienced the target in physical space, which would indicate that they were aware of the spatial compression. The red dotted line represents the distance we would predict if participants were walking as if they were in an environment where the rooms were non-overlapping, which is estimated by the equation $f(x) = \frac{1}{1-x}$, where x represents the percentage level of overlap in decimal format. For example, in the case of 50% overlap, the predicted non-overlapping walk distance would be 200% of the actual target distance. The graph shows that the average walk distances followed the profile of the predicted curve in all tested conditions, even for overlap levels greater than the detection threshold. An overall trend analysis testing overlap level with quadratic polynomial contrasts was significant, $F(1,18) = 91.17, p < .01$, indicating that the trend exhibits quadratic growth. In general, participants appeared to slightly overestimate the distance at lower overlap levels, as the predicted curve falls at or just below the lower bound for the 95% confidence interval in almost all cases. At the highest overlap level of 75%, participants walked 372% of the actual distance in the fixed room condition and 420% in the expanding room condition, and the predicted value of 400% falls squarely within the 95% confidence intervals for both fixed (316.69-428.08) and expanding rooms (364.70-475.19).

To test for the effects of room type and learning over time, we pooled the walk distance percentages across all overlap levels that were impossible (i.e., excluding 0% overlap). A 2x2 repeated measures ANOVA was performed, testing the within-subjects effects of room type (fixed or expanding) and session number (first or second). The analysis revealed a significant main effect for room type, $F(1,18) = 5.42, p = .03, \eta_p^2 = .60$, indicating that participants overestimated distances a greater amount in the expanding room condition (M = 247.25%, SD = 58.21%) compared to when the room sizes were fixed (M = 225.40%, SD = 60.16%). The main effect for session number was not significant, $p = .15$, nor was the interaction effect, $p = .53$.

Simulator Sickness

One participant indicated that he used strong prescription glasses, and that looking through the display with them on made him feel nauseous. We excluded this participant from the simulator sickness analysis to avoid biasing the mean. Participants experienced a small increase in self-reported simulator sickness from before the experiment (M = 2.70, SD = 5.10) compared to afterwards (M = 12.05, SD = 12.86),

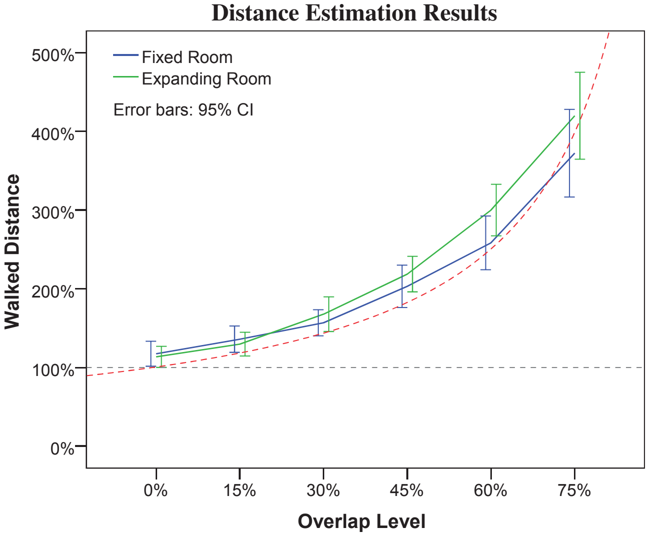


Fig. 5. Results for the distance estimation task in Experiment 1. The *x*-axis shows the different overlap levels, represented as percentages of the area of individual rooms. The *y*-axis represents the walked distance calculated as a percentage of the actual real world distance to the target.

confirmed by a paired samples *t*-test, $t(17) = 3.01$, $p < .01$. This is not surprising considering that participants were immersed for a long amount of time (approximately 40 minutes), and spent the majority of this period actively moving around.

4.7 Discussion

To analyze participants' perceptions of the impossible spaces, we employed a psychophysical approach common in perceptual detection studies. It should be noted that this methodology is typically used for low level sensory stimuli. For example, a similar approach was employed in previous virtual reality studies to discriminate between the rotation and scale gains used by redirected walking techniques [19]. While our experiment tested a higher level perception of space, we believe such a procedure is still useful in this context, and that our results are rather striking. Indeed, our initial expectation was that 75% overlap was a reasonable upper limit for spatial compression, and we were startled by how much overlap was achieved before participants could reliably notice. We believe we tested the feasible upper limit for the expanding room condition, since the detection curve reaches the higher levels and the slope begins to taper off, as would be expected in psychometric curves. However, in the fixed room condition, the detection curve is lower at 75% overlap and the slope is still increasing, indicating that we probably could have pushed the space compression to a higher level of overlap.

Based on our observations, we speculate that individual rooms seem like "islands" - as long as the view seems locally consistent, users are less likely to notice inconsistencies in the global model. However, larger rooms that maximally fill the space are more likely to alert users that the environment does not make sense. These observations are corroborated by many of the qualitative survey responses we received from participants, such as "There was a moment of confusion during the overtly impossible environments, but in practice the new room I entered seemed believable once I entered it." We observed that certain participants would employ clever strategies to determine whether the space was possible, such as walking around the perimeter of each room and counting their steps to measure the dimensions. Other participants would stand in a doorway and shift their head back and forth from the room to the hallway, comparing the lengths visually. As one participant noted, "It wasn't disorienting unless the rooms were both very large and the hallway was very short, then it seemed a little strange." Overall, participants tended to describe the obviously impossible spaces with terms such as "strange" or "weird," but we did not receive any overtly negative comments that would strongly discourage future use.

The distance estimation results also suggest a very compelling illusion. It is interesting that participants continued to overestimate the distances the way we would expect even when the overlap levels were above the detection threshold. In other words, even when participants could identify the space as impossible, this did not seem to be reflected in their judgment of distance within the space. We believe that participants were using the locally consistent visual information from the room they were in to measure the rest of the space. It is interesting that participants experienced a learning effect in the expanding room condition, becoming able to more confidently identify impossible spaces in the second session. Though we did not observe this in the fixed room condition, it is always possible that their performance might improve given a larger amount of repeated exposure to such environments. Additionally, we also observed distances were slightly overestimated in the 0% overlap condition, which is the opposite result from previous studies that have shown distance underestimation in immersive virtual environments. However, since the blind walking was performed based on targets that were not visible immediately prior to the beginning the test, we speculate that participants were relying more on their spatial memory and body-based cues than visual information. Thus, our results are not directly comparable to previous distance estimation findings.

We designed the test environment using a basic scenario (two rooms connected by a hallway) that could be versatile for use in more complicated architectural layouts, such as a virtual office building. However, spatial design is a complex topic, and different types of architecture may introduce visual cues that could make impossible spaces more or less obvious to the user. Ultimately, though, our results are highly promising, and we believe that impossible spaces will be a useful design mechanic for virtual reality practitioners that seek to provide immersive walkthroughs of virtual environments, assuming that preserving exact spatial relationship is not required by the application domain. Additionally, the results from this experiment are likely conservative since participants had been primed with knowledge of how impossible spaces work, and were consciously trying to detect the presence of overlapping rooms. In an actual usage scenario, the users' experiences of impossible spaces would likely be quite different if they were naive to the manipulation. This is one of the questions we sought to investigate in Experiment 2.

5 EXPERIMENT 2: EXPERIENCING IMPOSSIBLE SPACES

In Experiment 1, impossible spaces proved much more effective than we initially expected, and so they seem to have excellent utility. As such, we wanted to test how they would work in practice - in a single cohesive environment that participants would explore for longer and more engaging periods of time. In general, studies of redirection techniques in the previous literature have focused primarily on whether participants can detect manipulations when they are happening to them (e.g. [19] [20]), or have evaluated other quantitative metrics such as task performance and spatial knowledge acquisition (e.g. [14] [29]). While such formal quantitative experiments are valuable, it is difficult to draw detailed conclusions about participants' experiences. Such feedback is often gathered through open-ended questionnaires or interviews "tacked on" after the experiment session. Thus, for Experiment 2, we employed several well-known redirection techniques to string together a chain of impossible spaces and chose to evaluate this experience with non-primed users in a qualitative study.

5.1 Participants

A total of 17 people participated in the study (ten male, seven female), with a mean age of 36.00 (*SD* = 13.53). Ten participants were inexperienced with 3D games, two were a little experienced, and five were either experienced or very experienced. They were recruited from craigslist online classifieds and university email lists, and were offered $20 for participating. We used the same inclusion and exclusion criteria as Experiment 1.

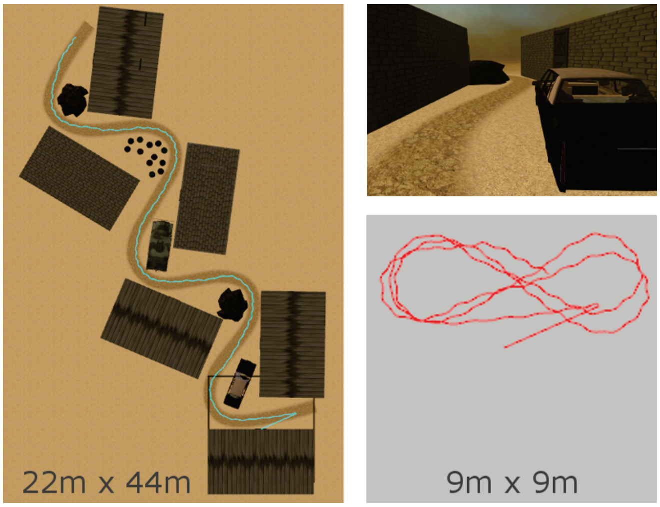


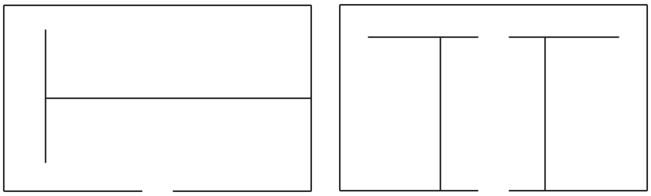
Fig. 6. (left) Users followed an "S" curve through an expansive outdoor desert environment with six explorable buildings. (bottom right) Users were redirected around the curves, resulting in a "Figure Eight" pattern in the real world. (upper right) A screenshot of the user's view of the virtual scene.

Three of the people that signed up had previously participated in Experiment 1 approximately one month prior, and had been heavily primed with prior experience and knowledge about how impossible spaces work. We did not want to exclude them from the study, since it is still very interesting to assess their reactions to the environment. Therefore, we were careful to evaluate them separately from participants that were naive to the manipulations.

5.2 Test Environment

The virtual environment was designed as an expansive desert village with six buildings spread out across a total area of approximately 22m by 44m (see Figure 6). Participants were asked to search through every building in the virtual world for stashes of weapons that were hidden in containers such as barrels. To facilitate exploration of and movement between multiple buildings, we divided the real world space in half, forming two distinct zones: an area for redirecting the user in the outdoor environment and an area for exploring the interior of buildings. We then employed a redirection controller using curvature and translation gains to string together buildings that contained impossible spaces. While walking around curves in a virtual path through the outdoor environment, curvature gains were applied dynamically to keep participants within the outdoor zone. This path was designed as an "S" curve, resulting in a real world path that formed a "Figure Eight" pattern. Curves such as this are an ideal place to apply redirection, as gains will be less perceivable during body turns [3], and it has the practical advantage of easy cable management. After completing the curve, the distance to the next building door was calculated, and translation gains were dynamically applied to align the building precisely within the indoor zone, thus ensuring the optimal use of available physical space. This design mechanic is fairly versatile; it allows users to walk down the path for a potentially infinite distance, allowing but not requiring them to explore interior buildings along the way. It would also be possible to enable the redirection in reverse, allowing users to backtrack to the beginning of the environment, though for the purposes of the experiment we did not implement this functionality.

Impossible space techniques were used to make each building larger on the inside, implemented using the "Expanding Room" method described in Section 4.3. We selected expanding rooms because we wanted to evaluate the impossible spaces that were most detectable in Experiment 1 to see if participants would be able to detect them without consciously looking. The six buildings were evenly divided between two-room and three-room designs, both of which also included a hallway for transitioning between rooms (see Figure 7). Within each floor plan design, the virtual buildings were modeled with either 25%, 50%, or 75% overlap in area. The buildings were placed along the outdoor path in ascending order starting with the lowest overlap levels.



(a) Two Room Floor Plan (b) Three Room Floor Plan

Fig. 7. Conceptual diagrams of the buildings used in Experiment 2. For each floor plan, three buildings were generated with the adjacent rooms overlapping by 25%, 50%, and 75%.

In our pilot testing, we found that users would sometimes "shortcut" curves by walking in diagonal lines across them, which is not an optimal case for applying curvature gains. To prevent this behavior, we placed obstacles such as vehicles and debris on the inside corner of the turn, thereby ensuring that participants walked around the full contour of the curve. Since curvature and translation gains were dynamic, they varied depending on the participant's specific motions. On average, curvature gains were employed at speeds of 22.52 degrees per meter and translations were scaled upwards by 33.27% of the actual movement distance. These values are intentionally above the perceptual detection thresholds found by [19], since we wanted to specifically evaluate redirection under more practically applicable conditions than previous studies that attempted to keep them completely unnoticeable. This was motivated by recent panel and workshop discussions by researchers in the field, where it was suggested that it may not matter if participants notice that they are being redirected, so long as severe negative side effects can be avoided.

5.3 Study Design

In this experiment, we sought to more thoroughly understand participants' experiences and impressions while exploring impossible spaces and being redirected using curvature and translation gains. We gathered information about participants' experiences using an experimental design similar to "think aloud" experiments commonly performed in the field of human-computer interaction. However, rather than ask participants to narrate the actions they were performing, we instructed them to describe out loud what they were experiencing, noticing, and feeling as they walked through a virtual environment. They were specifically asked to pay special attention to describing anything that they felt was unnatural or implausible about their experience. We were especially interested in these phenomena due to recent theoretical literature on the nature of presence, which describes the importance of plausibility for maintaining the illusion of being immersed in a virtual environment [17]. This approach has several notable advantage over post-questionnaires and interviews. First, it allows participants' impressions to be captured immediately as they occur, rather than afterwards when details may have faded from memory. Additionally, through video and audio recordings, we can analyze participant verbal behavior to observe details about their experience that they may not think are important to share or may not be consciously aware of.

We were interested gathering data about participants' qualitative experiences when exploring impossible spaces and being redirected by the curvature and translation gains. In addition to observing whether participants noticed the various manipulations as they occurred, we were also hoping to shed light on other questions that have been less commonly explored by prior work, such as: (1) when participants are manipulated without them noticing, does this introduce any negative side effects? (e.g. balance issues, disorientation); (2) do participants have verbal exclamations that indicate a reaction they may not be able to consciously articulate? (e.g. "whoa!"); and (3) when participants do notice manipulations, does this knowledge negatively impact their experience?

5.4 Methods

The study took approximately 45 minutes to complete. Participants first read and signed the consent form, then completed the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [10]. Next, participants were led to the experiment area, and the equipment and task was explained to them. We used the same VR equipment and software as Experiment 1 (see Section 4.4). To capture the participants' physical movements, we recorded the entire VR session using a ceiling-mounted Microsoft Lifecam Cinema 720p webcam. The participant's view was also projected on a screen that was visible to the webcam, which provided context when reviewing the recordings. Audio was captured using a Sennheiser EW 100 G2 wireless microphone system.

To motivate exploration of the environment, participants were instructed to search every building they came across for stashes of weapons that were hidden in containers spread out across the virtual world. During this time, they were instructed to describe out loud what they were noticing, thinking, and feeling, while paying special attention to describing anything that that they felt was unnatural or implausible about their experience. The actual exploration of the environment took approximately 15 minutes from start to finish. When they had finished searching the final building, the VR session was concluded after they walked back outside. Immediately afterwards, they completed the SSQ post-test, followed by a qualitative feedback questionnaire. This included the following qualitiative open-ended questions that were designed to draw out impressions that might not have come out during the VR session:

- At any point during your experience, did you notice anything strange or unnatural that negatively impacted your experience? If so, please explain what you noticed and how it made you feel.
- At any point during your experience did you feel lost or turned around? If so, please describe how you felt and when you felt it.
- You explored a very large virtual environment. However, the walking area you were actually in was much smaller. How do you think that happened? If you're not sure, then please say so.
- When you were walking around curves in the road, the virtual world would slowly rotate around you so that you would not walk outside of the edges of the physical workspace. Did you notice this? If so, how did it make you feel?
- When you were inside the buildings, the space that the rooms took up would overlap each other. This allowed us to fit a larger virtual building in a smaller physical space. Did you notice this? If so, how did it make you feel?
- Was there anything that contributed to or took away from your experience ofthe virtual world? If so, please describe them.

Lastly, they completed a demographic and video game experience questionnaire, after which they were debriefed and given a final opportunity for comments or questions.

To analyze participant verbal behavior, the video recordings were annotated using ELAN, a software tool commonly used in language and multimodal interaction studies [28]. We developed the following annotation scheme to code participant utterances, concentrating on vocalizations that were pertinent to the tested manipulations or possible side-effects:

- *Impossibility:* comments relating to the fact that virtual environment was too large to fit within the physical space (e.g. "this room is bigger than it should be")
- *Rotation:* comments about to perceived rotation speed (e.g. "I'm turning too quickly")
- *Translation:* comments about perceived movement speed (e.g. "I'm moving too fast")
- *Physiological:* comments about negative physiological effects (e.g. "I feel off balance" or "I'm dizzy")
- *Cognitive:* comments about negative cognitive effects (e.g. "I'm confused" or "I feel lost")
- *Exclamations:* non-specific negative verbalizations (e.g. "whoa" or "huh?")

The points in time at which participants entered an impossible space or underwent curvature or translation gains were also annotated in the video file. Finally, the completed annotation files were reviewed, and the utterances that occurred during or directly after each manipulation were counted and analyzed. In linguistic analysis, Cohen's κ is commonly calculated using several raters to validate the reliability of complex annotation schemes. However, the scheme we used in this experiment was very simple, and the utterances were fairly obvious, requiring little subjective judgment. Furthermore, coded utterances in our data set were sparse. As a result, calculating κ was not necessary.

5.5 Results

Impossible Spaces

Out of the 14 participants that were not primed with prior knowledge, we observed that 12 of them explored the buildings without appearing to notice the impossible spaces. This was confirmed on the feedback questionnaire, where all 12 participants wrote after the manipulation was disclosed to them that they did not notice the manipulation. Only two of the unprimed participants made vocalizations indicating that they were able to detect the overlapping rooms. One participant stated immediately upon exploring the 25% overlapped space, "It doesn't make sense. This room is too big considering that one was over there." This participant was a clear outlier in our experiment, and was the only person to put on the display and immediately realize that the virtual environment was too large to fit in the physical room, noting that "It seems kind of weird that this [curve] is making a right when I noticed that that part was closed off." The other participant that noticed expressed less confidence, musing upon entering the second room, " I would have thought I was in the same room," but did not appear to question the space further. Both of these participants indicated that they were experienced with 3D video games on the demographic questionnaire, which may have trained them to be more sensitive to spatial relationships in synthetic environments. All three of the people that had participated in Experiment 1 also verbally noted the impossible spaces at the higher overlap levels (one at 50%, and the other two at 75%). However, this is not suprising, considering that they had previously experienced similar spatial illusions, and were likely expecting them.

Interestingly, the participant vocalizations about impossible spaces seemed observational in nature, and we did not observe any overtly negative assessments during the explorations. In fact, one participant even expressed indifference, saying, "It seems like this wall is where it shouldn't be, but whatever." Two participants did comment that some of the buildings seemed like a maze, but these vocalizations were expressed in the corridors, not the overlapping rooms. Several participants commented that the corridors were disorienting because they were too narrow. On the feedback questionnaire, the previously noted outlier expressed disappointment about the overlapping rooms, writing, "I did not like it. It would have been nice to really have been in a large space." This was the only negative comment we received about the impossible spaces. In general, we conclude that in most cases it does not appear to matter much if participants notice self-overlapping architecture, as we did not directly observe any negative side-effects or behavior stemming from those realizations. Indeed, as one of the participants noted on the feedback questionnaire, "I did notice this, but it didn't bother me."

Curvature and Translation Gains

Very few participants offered an articulated description of what they were experiencing during the curvature and translation gains. Only one participant overtly mentioned rotation, stating "when making those turns it feels a little too quick sometimes." During the translation gains, this participant also commented, "when I'm walking it feels like a roller coaster." One other participant offered a similar comparison during translation gains, comparing the experience to walking on a treadmill.

While at first it may seem reasonable to conclude that most participants did not notice when the curvature or translation gains were applied, analysis of their non-specific verbal exclamations indicates that some of them did perceive the manipulation on some level, though perhaps not consciously. We observed a number of negative exclamations such as "whoa," "yikes," and "oops" that occurred during or immediately after redirection. This occurred more frequently during the curvature gains (12 utterances, 7 participants) than translation gains (5 utterances, 5 participants). Additionally, participants also made several negative physiological statements during these manipulations, such as "I feel a little bit dizzy" and "I feel a little off balance here." Again, this occurred more commonly during around curves (6 utterances, 5 participants) than during translations (3 occurrences, 2 participants).

On the feedback questionnaire, six participants indicated that they did not notice the rotations at all after the manipulation was fully disclosed to them. The remaining participants all mentioned to some degree that the curves felt strange, or made them feel off balance. For example, one participant wrote, "I felt unbalanced when the road curved. I didn't specifically notice the rotation, but it definitely made me feel uncertain physically." However, one participant indicated that while initially awkward, it was possible to adjust to it over time. This was corroborated by our informal observations during the experiment - participants appeared to grow more confident towards the end of the experiment, maintaining their balance through the turns with less difficulty.

Simulator Sickness

Participants experienced an increase in self-reported simulator sickness from before the experiment (M = 3.30, SD = 5.27) compared to afterwards (M = 21.12, SD = 16.67), confirmed by a paired samples t-test, $t(16) = 4.81$, $p < .01$. This was a greater increase than Experiment 1, even though in the previous experiment participants spent more than double the amount of time immersed and explored many more impossible buildings. While there were many differences between the environments, we believe that this increase is a practical cost of increasing the redirection thresholds, particularly the curvature gains. However, the magnitude of the increase was only in the slight to moderate range, as we did not observe any symptoms that were rated as "severe" by any of our participants.

5.6 Discussion

Our major finding is that most participants did not notice the impossible building layouts, nor did we observe any negative consequences or behavior stemming from the application of these spatial illusions. These results are compelling, especially since four out of six buildings used overlap levels well above the absolute detection threshold of 31% that was previously determined for the expanding room method. We suggest that this was likely due to the fact that users were unaware that impossible spaces were being used, and so were not actively looking for them. This is supported by the observation that the three people who participated in both studies, and were therefore primed with prior knowledge and expectations, noted the presence of overlapping rooms in the second experiment. Since impossible spaces cannot exist in the real world, we speculate that humans have no pragmatic reason to have developed a sensitivity to such illusions. We further suggest that users seem to maintain a local world model that they do not appear to question unless they are presented with immediate visual information that does not make sense in the moment. Therefore, we speculate that to a large extent, users will accept and adapt to what they see in virtual environments, so long as it does not seem overtly wrong and does not induce significant physiological side effects. Recent work in visual perception has also reached similar conclusions, though in a different context than our experiments [7]. This finding has substantial practical implications for virtual reality designers that are not bound by the physical constraints of the real world.

It is worth noting that users were allowed to freely explore all interior buildings in any way they wished. In other words, the impossible space technique makes no assumptions and imposes no limitations on the user's route or motions in the environment. This is not the case with many existing approaches to redirection, including the previously developed spatial manipulations that leveraged change blindness illusions [20]. Thus, impossible spaces are a versatile solution for spatially compressing architectural virtual environments, and we believe they are generalizable to many different interior space layouts. However, this work focuses on the perception and experience of impossible spaces, and so the development of guidelines for their design and practical deployment are beyond the scope of this paper, and thus represents an open area for future research.

Even though the curvature gains employed in this experiment are likely pushing the limits of what should be considered for practical use, the "Figure Eight" redirection controller seemed to work well in facilitating travel between multiple buildings. Future implementations of this design mechanic may be further optimized to reduce the curvature and translation gains required to link the explorable features in an environment, such as by orienting the path diagonally through the physical space. With more tolerable gains, we believe that this metaphor will be useful for exploring urban environments that combine outdoor and indoor scenes, such as those desirable in immersive training simulators.

Not surprisingly, the vast majority of participant utterances revolved around the content of the virtual world. Many participants were quite vocal about things in the environment that seemed wrong to them, such as textures that appeared unnatural, objects that seemed out of place, and lighting that looked unrealistic. Nevertheless, we observed many positive comments about the immersive qualities of the environment, such as "The more I walk through this, the more I'm starting to believe it." Interestingly, one participant noted that we had turned off the air conditioner to reduce ambient noise, and afterwards commented on the fact that the room got warmer, stating, "I know that the air was off for noise reduction reasons, but I think it added to the total effect, like you really did walk a few miles in the desert." To further improve the believability of the environment, several participants suggested adding visual representations of their hands and feet so that they could physically interact with virtual objects.

6 CONCLUSION AND FUTURE WORK

In this paper, we presented a design mechanic that leverages the illusion perceived when exploring architecture that is "bigger on the inside." Motivated by the observation that users' spatial perceptions of virtual environments appear to be malleable, the impossible space metaphor can be used to compress relatively larger virtual spaces into smaller physical areas that are more practical to explore through natural body motion. In the first experiment, we showed that reasonably small virtual rooms may overlap by as much as 56% before users begin to detect them when actively trying, and that the larger virtual rooms that expanded to maximally fill our available 9.14m x 9.14m workspace may overlap by up to 31%. However, our qualitative experiment suggests that impossible spaces may offer an even more compelling illusion when users are naive to the manipulation. Additionally, even when users could reliably detect that they were in an impossible space, their distance judgments to targets in the adjacent overlapping space did not appear to be compressed.

Although we tested a specific scenario for impossible spaces, there are potentially many other ways in which self-overlapping environments may be leveraged in virtual environments. Thus, exploring and formalizing the design of impossible virtual environments is an important area of future work. We also plan to further explore the practical use of impossible spaces in conjuction with other types of redirection techniques. Additionally, the impact of these environments on spatial knowledge acquisition has not been tested formally, and thus remains an open question. However, the manipulation as described in this paper does not fundamentally alter the route structure of the virtual environment, and so we do not believe that it will negatively impact the process of building a mental map of the space. Furthermore, the illusion does not impose any assumptions on the route or motions that the user must take through the environment, which is a notable limitation of many previously developed redirection techniques. Thus, impossible spaces represent a promising new approach for augmenting the effective walking space in immersive virtual environments.

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REFERENCES

[1] A. Berthoz. *The Brain's Sense of Movement*. Harvard University Press, Cambridge, MA, 2000.

[2] G. Bruder, F. Steinicke, K. Hinrichs, and M. Lappe. Arch-Explore: A Natural User Interface for Immersive Architectural Walkthroughs. In *IEEE Symposium on 3D User Interfaces*, pages 145–152, 2009.

[3] G. Bruder, F. Steinicke, K. Hinrichs, and M. Lappe. Reorientation During Body Turns. In *Joint Virtual Reality Conference of EGVE - ICAT - EuroVR*, pages 145–152, 2009.

[4] G. Bruder, F. Steinicke, and P. Wieland. Self-Motion Illusions in Immersive Virtual Reality Environments. In *IEEE Virtual Reality*, pages 39–46, 2011.

[5] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis. Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration. *Presence: Teleoperators and Virtual Environments*, 7(2):168–178, Apr. 1998.

[6] D. Engel, C. Curio, L. Tcheang, B. J. Mohler, and H. H. Bülthoff. A psychophysically calibrated controller for navigating through large environments in a limited free-walking space. In *ACM Virtual Reality Software and Technology*, pages 157–164, New York, New York, USA, 2008. ACM Press.

[7] A. Glennerster, L. Tcheang, S. J. Gilson, A. W. Fitzgibbon, and A. J. Parker. Humans ignore motion and stereo cues in favor of a fictional stable world. *Current Biology*, 16(4):428–432, Mar. 2006.

[8] V. Interrante, B. Ries, and L. Anderson. Seven League Boots: A New Metaphor for Augmented Locomotion through Moderately Large Scale Immersive Virtual Environments. In *IEEE Symposium on 3D User Interfaces*, pages 167–170. Ieee, 2007.

[9] J. Jerald, T. C. Peck, F. Steinicke, and M. C. Whitton. Sensitivity to scene motion for phases of head yaws. In *Symposium on Applied Perception in Graphics and Visualization*, pages 155–162, New York, New York, USA, 2008. ACM Press.

[10] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *International Journal of Aviation Psychology*, 3(3):203–220, 1993.

[11] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. H. Bülthoff, and B. J. Mohler. Velocity-Dependent Dynamic Curvature Gain for Redirected Walking. In *IEEE Virtual Reality*, pages 151–158, 2011.

[12] T. C. Peck, H. Fuchs, and M. C. Whitton. Evaluation of reorientation techniques and distractors for walking in large virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 15(3):383–94, 2009.

[13] T. C. Peck, H. Fuchs, and M. C. Whitton. Improved Redirection with Distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments. In *IEEE Virtual Reality*, pages 35–38. Ieee, Mar. 2010.

[14] T. C. Peck, H. Fuchs, and M. C. Whitton. An Evaluation of Navigational Ability Comparing Redirected Free Exploration with Distractors to Walking-in-Place and Joystick Locomotion Interfaces. In *IEEE Virtual Reality*, pages 55–62, 2011.

[15] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected Walking. In *Eurographics (Short Presentation)*, 2001.

[16] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction*, 16(1):1–18, Apr. 2009.

[17] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 364(1535):3549–3457, Dec. 2009.

[18] F. Steinicke, G. Bruder, K. Hinrichs, A. Steed, and A. L. Gerlach. Does a Gradual Transition to the Virtual World increase Presence ? In *IEEE Virtual Reality*, pages 203–210, 2009.

[19] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2010.

[20] E. A. Suma, S. Clark, S. L. Finkelstein, Z. Wartell, D. M. Krum, and M. Bolas. Leveraging Change Blindness for Redirection in Virtual Environments. In *IEEE Virtual Reality*, pages 159–166, 2011.

[21] E. A. Suma, S. L. Finkelstein, S. Clark, P. Goolkasian, and L. F. Hodges. Effects of travel technique and gender on a divided attention task in a virtual environment. In *IEEE Symposium on 3D User Interfaces*, pages 27–34. Ieee, Mar. 2010.

[22] E. A. Suma, S. L. Finkelstein, M. Reid, S. V Babu, A. C. Ulinski, and L. F. Hodges. Evaluation of the cognitive effects of travel technique in complex real and virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 16(4):690–702, 2010.

[23] R. M. Taylor, T. C. Hudson, A. Seeger, H. Weber, J. Juliano, and A. T. Helser. VRPN: a device-independent, network-transparent VR peripheral system. In *ACM Virtual Reality Software and Technology*, pages 55–61, 2001.

[24] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks. Walking $>$ walking-in-place $>$ flying, in virtual environments. In *ACM Conference on Computer Graphics and Interactive Techniques (SIGGRAPH)*, pages 359–364, New York, New York, USA, 1999. ACM Press.

[25] M. C. Whitton, J. V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. J. Poulton, B. McLeod, and F. P. Brooks. Comparing VE locomotion interfaces. In *IEEE Virtual Reality*, pages 123–130. Ieee, 2005.

[26] B. Williams, G. Narasimham, T. P. McNamara, T. H. Carr, J. J. Rieser, and B. Bodenheimer. Updating orientation in large virtual environments using scaled translational gain. In *Symposium on Applied Perception in Graphics and Visualization*, volume 1, pages 21–28, New York, New York, USA, 2006. ACM Press.

[27] B. Williams, G. Narasimham, B. Rump, T. P. McNamara, T. H. Carr, J. Rieser, and B. Bodenheimer. Exploring large virtual environments with an HMD when physical space is limited. In *Symposium on Applied Perception in Graphics and Visualization*, volume 1, pages 41–48, New York, New York, USA, 2007. ACM Press.

[28] P. Wittenburg, H. Brugman, A. Russel, A. Klassmann, and H. Sloetjes. ELAN: a Professional Framework for Multimodality Research. In *International Conference on Language Resources and Evaluation*, pages 1556–1559, 2006.

[29] X. Xie, Q. Lin, H. Wu, G. Narasimham, T. P. McNamara, T. H. Carr, J. Rieser, and B. Bodenheimer. A System for Exploring Large Virtual Environments That Combines Scaled Translational Gain and Interventions. In *Symposium on Applied Perception in Graphics and Visualization*, volume 1, pages 65–72, 2010.

[30] C. A. Zanbaka, B. C. Lok, S. V. Babu, A. C. Ulinski, and L. F. Hodges. Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. *IEEE Transactions on Visualization and Computer Graphics*, 11(6):694–705, 2005.

[31] C. Zetzsche, J. Wolter, C. Galbraith, and K. Schill. Representation of space: image-like or sensorimotor? *Spatial Vision*, 22(5):409–424, Jan. 2009.