Spatial Judgments in Impossible Spaces Preserve Important Relative Information

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ABSTRACT

In virtual reality (VR), Impossible Spaces allow rooms to overlap each other in physical space, enabling developers to better utilize the limited space available for VR systems. Prior work has explored detect thresholds for an impossible spaces, but little work has considered how impossible spaces affect users' understandings of spatial relationships within virtual environments. We present a study evaluating how impossible spaces affected participants' judgments of a room's width, and how this was impacted by whether participants considered each room individually, or within the context of the entire space. Participants' judgments of single rooms was not impacted by being in an impossible space, however judgments were significantly smaller when considering an impossible space as a whole. Even so, participants' judgments preserved the respective ratio between overlapping rooms, indicating that the relative sizes of different rooms is preserved in impossible spaces. This suggests that while absolute spatial information may be disrupted by impossible spaces, important relative information can be preserved. However, it is not yet clear how much of this effect can be attributed to lower-level perception and higher-level cognition.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; • **Computing methodologies → Virtual reality**; **Perception**.

KEYWORDS

impossible spaces, spatial information, evaluation

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1 INTRODUCTION

A perennial challenge faced by virtual reality (VR) developers is how to allow their users to explore virtual spaces that are bigger than the physical space available to users. Generally speaking, two broad classes of approaches have emerged: 1) techniques that decouple users' motion in the real and virtual world (such as teleportation [Bozgeyikli et al. 2016] or walking-in-place [Usoh et al. 1999]), and 2) techniques that leverage users' perceptual limitations to apparently expand the size of the walkable space. This later category includes techniques such as redirected walking [Nilsson et al. 2018], change blindness [Suma et al. 2011a], and impossible spaces [Suma et al. 2012].

Redirected walking subtly manipulates the rotation of a user's viewing direction to induce users to walk in curved paths in the real world, even while appearing to walk straight ahead in VR. Redirected walking may also introduce translational gains, such that one meter of space in VR may correspond to a shorter distance in the real world. Together, these techniques allow users to physically walk through virtual spaces that are larger than the corresponding physical space. Where redirected walking manipulates the users' motion, change blindness expands the space available in virtual environments by dynamically changing the environment's structural hierarchy while users are distracted (e.g. changing where a door is located, or what hallway it connects to). Impossible spaces also rely on changing the virtual environment to create larger spaces; however, rather than changing the hierarchical structure of the space, instead the dimensions of separate rooms are allowed to overlap each other in ways that are not possible in real environments.

Very little work has considered how the use of impossible spaces may affect users' spatial understanding within the virtual environments. Given that impossible spaces are radically different from real environments, it seems plausible that they could potentially distort users' sense of space within virtual environments. As such, it is important to understand how users' perceptions of spatial relationships is influenced by these techniques, and how judgments of essential spatial relationships are distorted (or preserved). In this paper, we present a study exploring how impossible spaces affect judgments of the widths of different rooms, whether this was influenced by making judgments about a single room at a time or by considering the impossible space as a whole, and how this was influenced by the relative amount rooms overlapped each other. We observed that, while impossible spaces distorted participants' absolute spatial understanding relative to the real world, important relative relationships within the virtual environment were preserved. It should be noted however that our results cannot distinguish between lower-level perceptual effects and higher-level cognitive effects. Future research employing a more direct technique, such as an action decision that is sensitive to absolute distance, is required to further explore this question.

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2 RELATED WORK

2.1 Impossible Spaces in Virtual Reality

Impossible spaces are generally created by either 1) adjusting the geometry of the environment while it is out of view of the user [Suma et al. 2012], or 2) linking separate virtual rooms together using portals that seamlessly teleport the user within the virtual environment [Neerdal et al. 2019]. Research on impossible spaces has largely focused on detection thresholds [Suma et al. 2012], the effect that the design of connecting corridors has on detection thresholds [Vasylevska and Kaufmann 2015, 2017; Vasylevska et al. 2013], and distance estimation measured via blind walking [Suma et al. 2012; Vasylevska and Kaufmann 2015].

Suma et al. used psychometric functions to determine that the detection threshold for impossible spaces was related to both the amount rooms overlapped each other and the absolute size of the room (in his experiment, detection thresholds ranged between 31.06% for larger rooms and 55.57% for smaller rooms) [Suma et al. 2012]. Vasylevska and Kaufmann used different methods, so their results are not directly comparable; they reported that participants confidence that they were in an impossible space varied based on the shape of the corridors connecting them, ranging from being very confident a space was impossible when there was a 40% overlap and rooms were connected by a short, straight corridor, to never being positively confident that rooms overlapped when rooms were connected by a C-shaped corridor [Vasylevska and Kaufmann 2015]. Vasylevska and Kaufmann's other work explored different aspects of how corridor design influenced users' understanding of impossible spaces. In general, corridors with more turns and that were asymmetric had the biggest impact on obscuring the impossiblity of a space; curved corridors without any definite landmarks increased this even further [Vasylevska and Kaufmann 2017]. Two studies have shown that distances between points in impossible spaces are overestimated relative to their actual distance; using blind walking, Suma et al. reported that participants overestimated distances, and that these estimations were very close to the distance the points would have been apart if the space had actually been possible. [Suma et al. 2012]. Vasylevska and Kaufmann found similar results, with the addition that increasing corridor complexity increased distance overestimation [Vasylevska and Kaufmann 2015]. One study has examined how impossible spaces affect the remembered location of objects within a space, as measured via pointing; Robb and Barwulor compared possible and impossible spaces with roughly the same floorplan. After exploring the spaces, participants were asked to point in the direction of objects they had seen in other rooms; participants performed substantially the same in both conditions, indicating that participants judged object locations based on relative relationships to the space, rather than on actual position in the real world [Robb and Barwulor 2019].

2.2 Spatial Knowledge in VR

While humans update their spatial knowledge using bodily translation, rotational motion, and visual information, bodily translation plays a more important role than the other two, especially during a navigational search [Ruddle and Lessels 2006]. Ruddle et al. found that participants who navigated using real-walking in an head-mounted display (HMD) performed almost as well as participants who completed the task in real life, while participants who moved using a joystick performed significantly worse; this was true regardless of if participants navigated a visually-rich or -impoverished environment [Ruddle and Lessels 2009]. Sigurdarson et al. found that physically rotating a user during a navigation task did not improve performance as compared to a purely virtual rotation; this may have been, at least in part, due to the lack of bodily motion cues associated with the physical rotation [Sigurdarson et al. 2012].

Given that bodily motion can significantly enhance spatial understanding, it is not surprising that the method of locomotion used in VR can strongly impact the development of spatial knowledge; Zanbaka et al. evaluated real-walking, joystick motion with six degrees of freedom (DOF), joystick motion with three DOF, and joystick motion on a monitor; participants who moved via real-walking demonstrated improved spatial knowledge on several measures, including sketch maps drawn after the experiment, path directness, and surveys of cognitive understanding [Zanbaka et al. 2005]. Suma et al. also found that real walking, as compared against pointing-directed motion, improved performance in a navigation task [Suma et al. 2009]. More generally, continuous locomotion methods, even those that do not involve bodily motion, typically outperform other locomotion methods: Cliburn at al. found that while teleportation did not negatively impact sketch maps, it did result in poorer recall of object locations during a navigation task [Cliburn et al. 2009]; more recently, Paris et al. examined four motion techniques commonly used in VR games, and found that continuous locomotion methods were associated with reduced error in a pointing task [Paris et al. 2019]. Discontinuous changes in rotation further impair spatial knowledge. Discordant teleportation allows users to reorient themselves while teleporting; Cherep et al. compared real walking, concordant teleportation, and discordant teleporation, and found that discordant teleportation performed worst, followed by concordant teleportation, and then real walking [Cherep et al. 2020]. Kelly et al. found that while discordant teleportation weakens performance on spatial tasks, this effect is reduced when navigating smaller spaces; however, this is due to an enhanced ability to rely on landmark-based knowledge, rather than the characteristics of the locomotion method [Kelly et al. 2020]. Real walking still outperforms other locomotion methods even when redirection is used; Peck et al. evaluated redirected real-walking, walking-in-place, and joystick motion, and found that participants who walked with redirection demonstrated greater spatial understanding and improved wayfinding and navigation [Peck et al. 2011]; this shows how bodily motion motion can improve spatial understanding even when a user's perception of motion is altered.

Several other studies have considered redirected walking's impact on spatial understanding. Suma et al. examined a similar question to our own: when a user is redirected, how do they localize the location of both real and virtual objects with respect to their current position? Suma et al. found that, when using redirected walking, participants updated their spatial model to account for the induced rotation, such that participants pointed at where an object had been visually located within the virtual space, rather than at the physical location it had originally existed at [Suma et al. 2011b]. Langhehn et al. evaluated redirected walking's impact on cognitive maps, as compared to joystick motion and teleportation, and found that participants created significantly better sketch maps after using redirected walking; additionally, locomotion method did not affect accuracy in a pointing task [Langbehn et al. 2018]. Bruder et al. considered a slightly different question, looking at whether redirected walking induces a higher cognitive load that non-redirected walking; they found that verbal memory, spatial working memory, and cognition were all affected by the presence of redirection, and that this effect scaled with the magnitude of the curvature gain applied. Suma et al. also considered the effect of change blindness on spatial understanding, and found that participants were able to draw consistent sketch maps of the virtual space, even though it changed during use; participants were also able to point back towards the physical location they started the experience in, suggesting that participants had internalized a cognitive map that was consistent with the real world, at least to some extent [Suma et al. 2011a].

2.3 Spatial Understanding and Cognitive Maps

Cognitive maps do not necessarily observe spatial constraints that are present in real space, nor are they necessarily organized similar to physical maps. Warren et. al showed that our mental representations of space are better described as labeled cognitive graphs, rather than cognitive maps or topological graphs the obey Euclidean constraints, as participants were often unaware of and were able to successfully use asymmetric wormholes (these are paths which are shorter when going one direction than when going in the other) efficiently when exploring a virtual maze [Warren et al. 2017]. Moar and Bower showed information judged from cognitive maps does not necessarily respect the Euclidean constraints imposed on angular information and judged distances [Moar and Bower 1983]: angular judgments tend to be biased towards 90 degrees, and triangular features can be reported to have more than 180 degrees; additionally, judged distances between two locations are not necessarily reversible, such that the distance from A to B can be judged to be different from the distance from B to A. Cognitive maps often rely heavily on hierarchies that group landmarks based on both spatial and non-spatial attributes [Hirtle and Jonides 1985]; this can impact judgments of distance between different pairs of landmarks, producing similar results as described by Moar and Bower. Steven and Coupe give an example of how hierarchies can produce errors in spatial judgments [Stevens and Coupe 1978]: in the United States, the state of California is west of the state of Nevada; as such, when asked what direction San Diego, California is from Reno, Nevada, participants most commonly answer that it is in a western direction. In fact San Diego is south east of Reno. In this case, participants' hierarchical organization of cities nested within states leads them astray. Other heuristics also contribute to distortions in cognitive maps, including a tendency to localize landmarks relative to other landmarks, and a tendency to rotate objects so they align with natural axes running through the space [Tversky 1981].

3 METHODS

We sought to answer three major research questions in this study:

RQ1: How accurately are people able to recall the dimensions of a single room after exploring an impossible space?

RQ2: How accurately are people able to recall the dimensions of overlapping rooms after exploring an impossible space?

RQ3: How does the amount of overlap between rooms affect width judgments in overlapping rooms?

3.1 Study Design

We employed a between-subjects repeated-measures design in this experiment. Participants completed 13 trials, where the widths of rooms A and B (and the respective overlap between rooms), was varied between trials. Participants walked between rooms through a connecting corridor; it was not possible to see both rooms at the same time. There were three conditions in the study (see Figure 1 for illustrations of the room layouts):

(1) In the **Baseline** condition the rooms were on two floors connected by an elevator. This served as our baseline condition as it would be physically possible for these rooms to occupy the same XZ coordinate, as they existed on different Y planes.
(2) In the **Impossible-Independent** condition, both rooms were on the same floor, connected by a single hallway. In this condition, participants observed each room and then reported their size judgments of each room independently on separate maps.
(3) The **Impossible-Simultaneous** condition was the same as the Impossible-Independent, except that participants reported their size judgments of both rooms simultaneously on the same map.

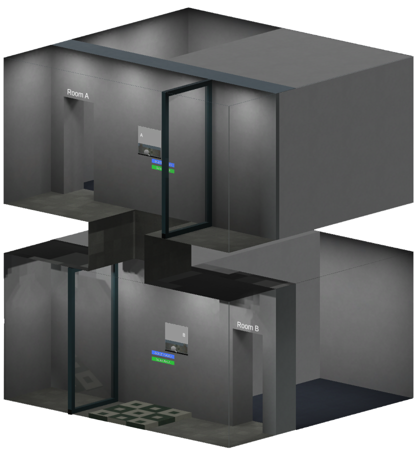
Our prior work assessed participants' understanding of spatial relationships in impossible spaces by having them point at where they believe objects had been placed [Robb and Barwulor 2019]. This work suggested that participants' memories of objects' locations were anchored to geometric relationships within the space (i.e. a object placed in an office could not occupy the same location as the hallway adjacent to the office, even when this had in fact been true due to the presence of an impossible space). As such, we used a different, map-based method in this experiment in an attempt to avoid this anchoring effect.

In all three cases, participants reported their judgments using a map of the virtual environment. Participants used a slider placed below the map to manipulate the size of each room on the map. The room visibly changed size on the map as participants moved the slider. The slider was continuous, and allowed participants to report the room as occupying anywhere between 0% and 100% of the total width of the real environment. The slider was reset to 50% at the start of each trial. The reporting of room sizes were conducted immediately after each trial. Participants did not receive feedback about their judgments.

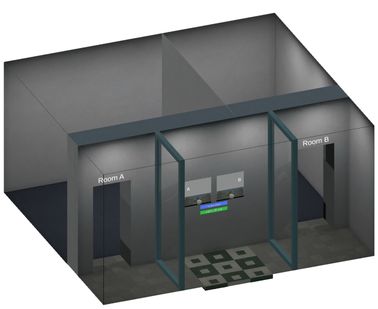
In the Baseline and Impossible-Independent conditions, participants reported the size of rooms A and B using two separate maps (see Figure 2a). Rooms were represented as a dark grey region labeled either A or B (this color was similar to the color of the carpet in the rooms). Space that (presumably) belonged to the other room was shown as a light grey, similar to the wall color. The sizes of the dark grey and light grey regions changed in sync with the position of the slider. This design encouraged participants to consider rooms one at a time while reporting room sizes. The maps were placed on separate floors in the Baseline condition, but were side-by-side in the Impossible-Independent condition. Participants in the Impossible-Independent condition would have been able to look back and forth between maps while reporting room size, however participants rarely did so.

In the Impossible-Simultaneous condition, participants reported the size of rooms A and B on one map (see Figure 2b). Room A was represented as a green room, Room B was represented as a blue room, and overlapping space between Room A and B was colored blue-green. Two sliders were used for this map, each one responsible for controlling the size of a specific room. The size of Room A changed in sync with its associated slider, and the size of Room B changed in sync with its associated slider. This design encouraged participants to consider the size of both rooms simultaneously.

The details of each trial are shown in Table 1. Room sizes ranged from 2m to 5.95m (6m was not used to prevent z-fighting graphical artifacts). The smallest amount of overlap present was 0% (one trial with 3m and 3m, and one trial with 2m and 4m), and the largest amount of overlap was 98.3% (two 5.95m rooms). Trial order was randomized for each participant; the room sizes for a given trial were randomly assigned to either Room A or B in the environment.



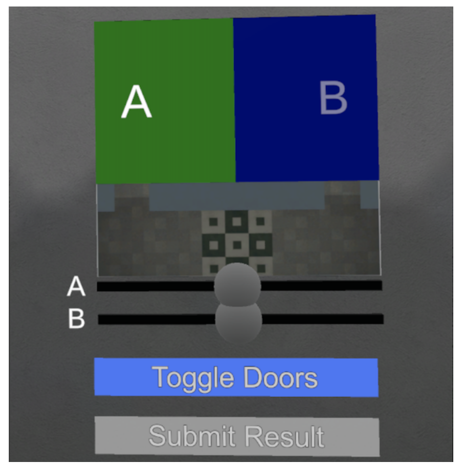
(a) Baseline condition: the two rooms were on different floors. Participants moved between floors using the elevator in the center of the hallway (currently positioned on the lower floor).



(b) Impossible conditions: the central wall moved depending on which room a participant was about to enter. The glass panels in the hallway raised and lowered to delay participants' motion between rooms by the same time delay incurred by the elevator in the possible space.

Figure 1: The (a) possible and (b) impossible spaces

(a) The above image is from the impossible-independent condition. Separate maps were also used in the baseline condition, however each map was placed separately on the floor where the associated room was located.



(b) Participants reported both rooms' sizes on the same map in the impossible-simultaneous condition.

Figure 2: The maps used in the (a) Baseline and Impossible-Independent conditions and in the (b) Impossible-Simultaneous condition

3.2 Apparatus

Participants wore a wireless HTC Vive Pro HMD during the experiment. The Lighthouse 2.0 tracking system was used to track a 4m x 6m space. The experiment was run using a computer capable of maintaining a frame rate of 90 FPS for the duration of the experiment. The virtual environment was created using the Unity game engine. The environment was divided into two regions: a 1x6m hallway connecting both rooms, and a 2.5x6m space occupied by rooms A and B. The entrance to each room was 0.5m deep, so as to prevent participants from being able to see the depth of the hallway and the room from the same vantage point. The central wall of rooms A and B was moved during each trial so as to adjust the relative size of each room. This was carefully done so as to prevent participants from ever seeing the wall move. A target was placed on a short pole located by the central wall in each room. During each task, participants had to walk up to and touch the target placed in each room prior to reporting their judgment. This was done to ensure that participants gained a sense for the size of each room.

See Figure 1a for an example of the possible space and Figure 1b for an example of the impossible space.

The elevator used to connect the two floors in the Baseline condition was placed at the center of the hallway. The elevator could be activated by pushing a button located on the wall by the elevator. Since the elevator slowed how quickly participants could move between rooms, an airlock was added at the same location for the Impossible-Independent and Impossible-Simultaneous conditions. Participants entered the airlock and toggled which side was open by pushing a button, which triggered the doors to change position. This was calibrated to take the same amount of time that the elevator took to move up and down. Both doors of the airlock were partially transparent, so as to ensure that participants could still see the full length of the hallway at all times.

3.3 Participants

We recruited thirty-six participants from a pool of psychology students. Three participants were excluded due to technical errors during their experiment. Of the thirty-three remaining participants, twenty-five (67.6%) were female and twelve (32.4%) were male. Thirty-four (91.9%) identified as White, two (5.4%) as Asian and 1 (2.7%) as Black. Participants were an average age of 18.8. Fifteen (42.4%) reported having less than one hour of experience with VR and fourteen (39.4%) reported having no experience at all.

3.4 Procedure

Participants signed an informed consent form upon arrival to the lab. They then completed a demographic pre-survey and were instructed that they would be reporting judgments on the size of a number of different rooms present in a virtual environment. Participants were not informed that impossible spaces would be present during the study. Participants were then fitted with the HMD and positioned in the center of the virtual hallway to begin the first trial.

Participants began each trial in the center of the virtual hallway. While standing there, each room was adjusted to the width specified for that trial; this was not visible to the participant. Participants then entered a room of their choice, walked to the far corner, and touched a ball placed on a rod at waist height. When touched, the ball changed color and played a sound, so as to confirm that it had been touched. Participants then returned to the hallway and reported their judgment for the room they had just entered and then repeated this process for the other room. Participants were able to adjust their judgments after visiting the second room if they desired to do so, though this was rarely observed. After they were satisfied with their reported judgments, they could begin the next trial by pressing a button on the wall in the center of the hallway. The participants' view briefly faded to black between each trial so as to help differentiate one trial from another; during this time the maps were reset so that the slider was at the 50% mark and the rooms were adjusted to the width specified for the next trial. This process continued until all trials were complete. This portion of the experiment took roughly 30 minutes to complete.

Following the trials, participants removed the HMD and completed a brief interview asking participants about their overall experience and what they believed to be the purpose of the experiment.

Table 1: The following room configurations were used in the experimental trials. The order in which trials were presented was randomized, as was which room was set to which size. The overlap % reported is how much space was occupied by both rooms for a given configuration.

Trial	Size 1	Size 2	Overlap %
1	2	4	0%
2	2	5	16.6%
3	2	5.95	32.5%
4	3	3	0%
5	3	4	16.6%
6	3	5	33.3%
7	3	5.95	49.2%
8	4	4	33.3%
9	4	5	50%
10	4	5.95	65.8%
11	5	5	66.6%
12	5	5.95	82.5%
13	5.95	5.95	98.3%

3.5 Metrics

The judged position of the central wall for rooms A and B was recorded for each trial. Judged widths were stored as a percentage of the width of the whole environment (e.g. 1.0 equates to 6m, 0.5 equates to 3m). Participants' location in the virtual environment was sampled at 30 Hz.

Several metrics were derived from the judged positions for use in our analysis: summed judged width, judged ratio, judged overlap percent, and relative error. We also calculated the true values for summed width, ratio, and overlap percent in each trial. The manner in which each metric was calculated is reported below:

(1) *Summed width* was calculated by adding the width of both rooms together.
(2) *Ratio* was calculated individually for each room in a trial; this was done by dividing a room's width by the width of the other room. Ratios under 1.0 indicate that the other room was larger, and vice versa.
(3) *Overlap percent* was also calculated individually for each room in a trial; this was done by calculating the absolute width of the overlapping region in a room and then dividing it by the width of the room in question, so as to report what percent of that room was overlapped by the other.
(4) *Relative error* was calculated by subtracting a room's judged width from the actual width, and then dividing it by the actual width. This converted the error into a percentage of the room's width. Positive error indicates that a room was judged to be smaller than its actual size, and negative error indicates that a room was judged to be larger than its actual size.

4 RESULTS

Mixed linear models were used to analyze the results of this study. Based on our research questions, each model included condition, the relevant actual width measure, and overlap percentage as fixed models. Interaction effects between condition and the other fixed effects were then evaluated and included in the final model if they were observed to significantly improve the fit of the model. Participant ID was used as a random-effect in all models. Overlap percentage and all actual width measures were centered prior to analysis; non-centered values are reported in all graphs and figures.

Outliers were removed using the IQR rule, with the threshold set to 3.0; Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. P-values were obtained by likelihood ratio tests comparing the best-fit model to the model without the effect in question [Winter 2013]. Effect sizes are reported as semi-partial marginal R^2 [Jaeger et al. 2017]. By convention, a R^2 of 0.02 represents a small effect, 0.15 represents a medium effect, and 0.35 represents a large effect [Ferguson 2016].

4.1 Size Judgments

4.1.1 Judgments of a single room's width: Condition, actual width, and actual overlap were used as fixed factors, and participant ID was used as a random factor. An interaction between condition and actual width was also included in the model. Significant main effects were observed for condition ($\chi^2(1) = 13.917, p < 0.001, R^2 = 0.078$), actual width ($\chi^2(1) = 933.86, p < 0.001, R^2 = 0.503$), and overlap ($\chi^2(1) = 10.79, p = 0.001, R^2 = 0.003$). The interaction effect between condition and actual width was also significant ($\chi^2(1) = 18.88, p < 0.001, R^2 = 0.006$). Post-hoc pairwise comparisons of condition revealed that participants in the Impossible-Simultaneous condition judged rooms to be significantly smaller than in the Baseline ($\Delta = -0.0898, p = 0.0149$) and Impossible-Independent ($\Delta = -0.115, p = 0.002$) conditions. No significant difference was observed between the Baseline and Impossible-Independent conditions ($\Delta = -0.026, p = 0.668$).

Post-hoc pairwise comparisons of the interaction revealed that width judgments increased significantly slower in the Impossible-Simultaneous condition than the Baseline ($\Delta = -0.114, p = 0.0047$) and the Impossible-Independent ($\Delta = -0.155, p < 0.001$) conditions, but there was no significant difference between the Baseline and Impossible-Independent conditions ($\Delta = -0.041, p = 0.482$).

The relationship between actual room size and judged room size can be seen in Figure 3. Participants judged rooms to be smaller in the Impossible-Simultaneous condition, and this effect was more pronounced for larger rooms than for smaller rooms. No differences were observed between the Baseline and Impossible-Independent conditions. While the effect of overlap on width judgments was significant, the effect size was small, suggesting little practical impact.

4.1.2 Judgments of summed width across both rooms: Condition, actual summed width, and overlap were used as fixed factors, and participant ID was used as a random factor. An interaction between condition and actual summed width was also included in the model. Significant main effects were observed for condition ($\chi^2(1) = 13.93, p < 0.001, R^2 = 0.122$) and actual summed width ($\chi^2(1) = 292.61, p < 0.001, R^2 = 0.098$), but not for overlap ($\chi^2(1) = 0.299, p = 0.5845$). The interaction effect between condition and actual summed width was also significant ($\chi^2(1) = 25.936, p < 0.001, R^2 = 0.007$). Post-hoc pairwise comparisons of condition revealed that participants in the Impossible-Simultaneous condition judged rooms to be significantly smaller than in the Baseline ($\Delta = -0.180, p = 0.0147$) and Impossible-Independent ($\Delta = -0.232, p = 0.002$) conditions. No significant difference was observed between the Baseline and Impossible-Independent conditions ($\Delta = -0.057, p = 0.669$).

Post-hoc pairwise comparisons of the interaction effect revealed that summed width judgments increased faster in the Impossible-Independent condition than the Baseline ($\Delta = 0.118, p = 0.0067$) and the Impossible-Simultaneous conditions ($\Delta = 0.204, p < 0.001$), but that there was no significant difference between the Baseline and Impossible-Simultaneous conditions ($\Delta = 0.086, p = 0.073$).

The relationship between the sum of participants' judgments and the actual summed width can be seen in Figure 4. The results of this analysis are similar to the results examining the width of a single room. Of note is the missing interaction effect linked with actual size. This may be attributed to the combined measurements of small and large rooms, which could cancel out the interaction effect. Of particular note is the point at which the summed judgment exceeds 1.0; this corresponds to the point at which participants began reporting an impossible space. On average, participants began reporting an impossible space at a summed width of roughly 1.175 in the Baseline condition, 1.125 in the Impossible-Independent, and roughly 1.50 in the Impossible-Simultaneous condition.

4.1.3 Ratio of width judgments: Condition, actual ratio, and overlap were used as fixed factors, and participant ID was used as a random factor. An interaction between condition and actual ratio was also included in the model. A significant main effect was not observed for condition ($\chi^2(1) = 0.387, p = 0.8238$) or for overlap ($\chi^2(1) = 0.0314, p = 0.859$), but was observed for actual ratio ($\chi^2(1) = 899.32, p < 0.001, R^2 = 0.592$). The interaction effect between condition and actual ratio was also significant ($\chi^2(1) = 8.2176, p = 0.016, R^2 = 0.002$).

Post-hoc pairwise comparisons of the interaction effect revealed that ratio judgments increased significantly faster in the Impossible-Simultaneous condition than the Baseline ($\Delta = 0.114, p = 0.0143$), but that there were no significant differences between the Impossible-Simultaneous and Impossible-Independent ($\Delta = -0.080, p = 0.121$) condition and the Baseline and Impossible-Independent condition ($\Delta = 0.031, p < 0.700$).

The relationship between actual ratio and judged ratio can be seen in Figure 5. Ratio judgments were fairly accurate when rooms were of similar size (i.e. near a ratio of 1). However, as the actual ratios grew more extreme (i.e. small rooms paired with large rooms), reported ratios were shifted towards a value of 1.0, indicating that the reported ratio was less extreme than the actual ratio. This could manifest as either small rooms being reported as bigger than they were, large rooms as smaller than they were, or a combination of both; given the results reported concerning width judgments of a single room, the shift in ratio can most likely be attributed to reporting lower widths for very large rooms. The weak interaction effect between the Impossible-Simultaneous and the Baseline condition can also be observed: the shift at extreme values towards a ratio of 1.0 was more pronounced for the Impossible-Simultaneous condition than the Baseline condition.

4.2 Error in Judgments

Condition, actual width, and overlap were used as fixed factors, and participant ID was used as a random factor. No interaction

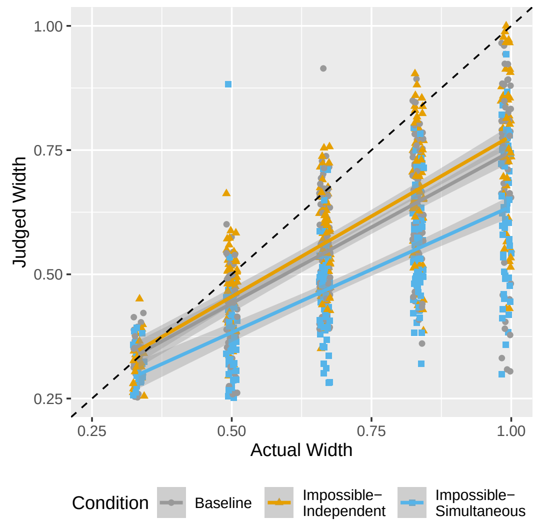


Figure 3: Judged Width vs. Actual Width: Participants made less accurate judgments as the actual width of a room increased; Judgments were also less accurate in the Impossible-Simultaneous condition.

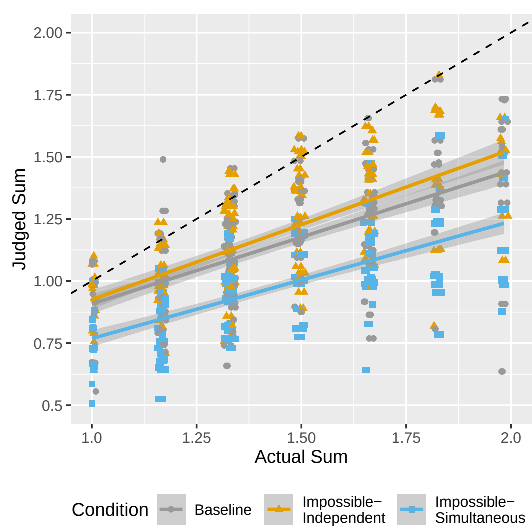


Figure 4: Summed Judged Width vs. Summed Actual Width: Participants began reporting impossible spaces when actual total width of reached 1.15 for the Baseline and Impossible-Independent conditions, and at 1.5 for the Impossible-Simultaneous condition.

effects were included in this model. Significant main effects were observed for condition ($\chi^2(1) = 15.127, p < 0.001, R^2 = 0.145$), actual width ($\chi^2(1) = 117.73, p < 0.001, R^2 = 0.070$), and for overlap ($\chi^2(1) = 9.088, p = 0.003, R^2 = 0.005$). Post-hoc pairwise comparisons of condition revealed that participants in the Impossible-Simultaneous condition made larger errors than in the

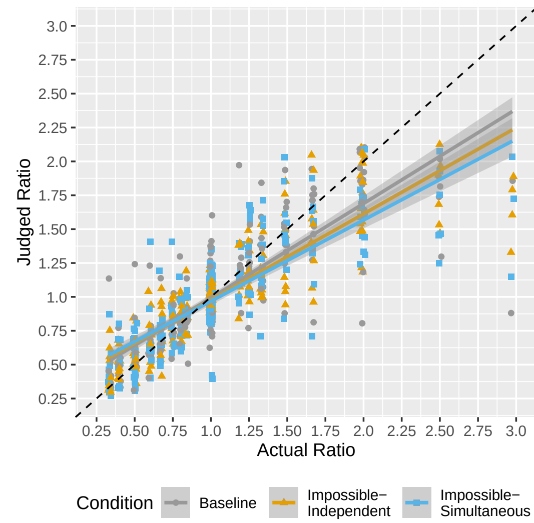


Figure 5: Judged Ratio vs. Actual Ratio: Values $<$ 1.0 indicate that the judged room was smaller than the other room, and vice versa. Participants accurately judged the ratio of rooms similar in width, but tended to report less extreme ratios when the width difference was larger. This was more extreme in the Impossible-Simultaneous condition.

Baseline ($\Delta = 0.132, p = 0.010$) and Impossible-Independent ($\Delta = 0.169, p = 0.001$) conditions. No significant difference was observed between the Baseline and Impossible-Independent conditions ($\Delta = 0.037, p = 0.658$).

The relationship between actual width and relative error can be seen in Figure 6. Relative error increased as the actual width of a room increased. Participants made larger errors in the Impossible-Simultaneous condition, however the rate with which error increased was similar to the other conditions. While the effect of overlap on ratio judgments was significant, the effect size was very small, suggesting that it had little practical impact.

4.3 Interviews with Participants

Participants were asked to report on the purpose of the study and their awareness of overlap occurring in the space. Of the thirty-three participants interviewed, only two spontaneously mentioned noticing the impossible spaces and connected them to the purpose of the study. One of these participants noted that the concept of "imaginary space… wasn't a foreign concept [to him]". Both of these participants were in the Impossible-Simultaneous condition. After informing participants about the true purpose of the study and the presence of impossible spaces, all participants did report that they had noticed that some sort of spatial overlap seemed present, especially in the trials with larger amounts of overlap.

5 DISCUSSION

Several overall patterns emerged from our analysis: first, few significant differences were observed between the Baseline and Impossible-Independent conditions; the only observed significant difference

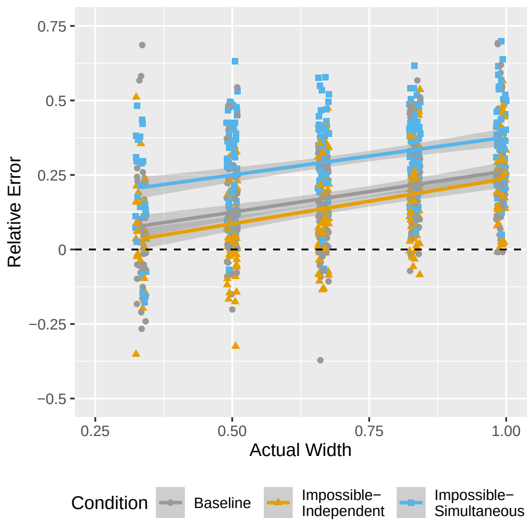


Figure 6: Relative Error vs. Actual Width: Relative error increased as rooms grew wider. More error was present in the Impossible-Simultaneous condition, but grew at essentially the same rate as the other conditions.

was in an interaction effect between condition and actual summed width, and as the effect size of this interaction was very small ($R^2 = 0.007$) this seems to be of little importance. Second, major significant differences were consistently observed between the Baseline and Impossible-Simultaneous condition. Taken together, these suggest answers to RQ1 and RQ2: impossible spaces have little impact on judgments concerning the width of a specific room, but significantly reduce width judgments of rooms within the context of the entire impossible space.

Specifically, participants in the Impossible-Simultaneous condition judged rooms to be 0.61 meters narrower than the same room in other conditions; the effect size of this change was 0.078, equivalent to a small-to-medium effect. Also notable is the difference in the point where participants began reporting an impossible space, as judged by summed width; this increased by roughly 33.3%, moving from an average of a summed width of 6.9 meters to 9 meters.

The results suggest two important refinements of these observations: first, participants judgments of the width of a space grew less accurate as the width of the space increased, and this effect grew more pronounced when judging the width of both rooms simultaneously. This can be seen in both the interaction effect between condition and actual width, and the rise in relative error as actual width increases. Second, impossible spaces had no effect on participants' judgments of the relative ratio of each rooms' sizes. While we do see a bias towards reporting less extreme ratios, this was present in all conditions. A small interaction effect was observed between condition and actual ratio, which suggested that participants were slightly more biased towards less extreme ratios in the Impossible-Simultaneous condition; however, the effect size of the interaction was extremely small ($R^2 = 0.002$), suggesting that the effect is small enough to be almost meaningless.

Finally, with regard to RQ3, while overlap was observed to have significant effects on judged width and relative error, it was not observed to have an effect on summed width judgments or ratio judgments. Additionally, the effect size for overlap's effect was extremely small for both judged width ($R^2 = 0.006$) and relative error ($R^2 = 0.005$). This suggests that while overlap may impact width judgments to a small degree, it's effect is small enough to have little impact on the outcome of users' judgments.

5.1 Limitations

It should be noted that cognitive effects may play an important role in our observations. In particular, the method of reporting differed between the Impossible-Simultaneous and the Impossible-Independent conditions. Given participants' awareness that spaces cannot overlap in real life, it may be that they under-reported perceived room widths in conditions when an overlap was present, which would then account for the difference between conditions. It is worth noting however that this effect was also observed in the lower width conditions when an impossible overlap was not present, which suggests that participants reported judgments were not only affected when confronted with an impossible space. Future research should consider employing a perceptual measure (i.e. blind walking) in order to directly assess the role perception plays in our observed findings.

6 CONCLUSION

This study found that while impossible spaces distort some spatial judgments with regard to the real world, other important relative spatial relationships are preserved; these types of relative relationships are arguably more important when acting within impossible virtual spaces. Suma et al. observed that, during redirected walking, users anchored objects with respect to the virtual world [Suma et al. 2011b]; in contrast, when experiencing a change blindness environment, users continued to anchor objects in the physical world [Suma et al. 2011a]. Our results suggest that spatial judgments made within impossible spaces are more similar to those made using redirected walking, not change blindness, as they seem to be anchored with respect to the virtual environment. This may appear surprising at first, given that impossible spaces' direct alteration of a virtual environment seems more similar to change blindness. However, impossible spaces can be thought of as applying a sort of translational gain *to the environment*, as redirected walking applies a rotational gain to the user; the scale of specific rooms is manipulated, but the overall hierarchy of the space remains unchanged; this is not necessarily true for change blindness environments, where a single door could lead to different places. Considering the strong role hierarchies play in the development of cognitive maps [Hirtle and Jonides 1985], it makes sense that reliance on this hierarchy would dominate users' judgments of an object's location. Furthermore, anchoring objects with respect to their position in the virtual world is arguably a more useful representation of position, as it supports navigation in a way that being anchored in the real world would not. Relying on the physical location is useless when multiple virtual locations can map onto the same physical spot.

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