Towards Efficient Spatial Compression in Self-Overlapping Virtual Environments

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ABSTRACT

Space available for any virtual reality experience is often strictly limited and abridges the virtual world to a size of a room. To extend the amount of virtual space accessible by walking within the same real workspace the methods of spatial compression were proposed. Scene manipulation with a controlled spatial overlap has been shown to be an efficient method. However, in order to apply space compression effectively for a dynamic, scalable and robust 3D user interface, it is important to study how the human perceives different layouts with overlapping spaces.

In this paper, we explore the influence of the properties of the layout used on human spatial perception in a physically impossible spatial arrangement. Our first reported study focuses on the following parameters of the path within a simple self-overlapping layout: number of turns, relative door positions, sequences of counter- and clockwise turns, symmetry and asymmetry of the path used. In addition, in the second study we explore the effect of path smoothing by substituting the right-angled corridors by smooth curves. Our studies show that usage of the smooth curved corridors is more beneficial for spatial compression than the conventional right-angled approach.

Keywords: Spatial perception; spatial manipulation; spatial compression; redirected walking; user study; virtual reality.

Index Terms: H.5.2 [Information interfaces and presentation]: User Interfaces—Theory and methods; H.5.1 [Information interfaces and presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities.

1 INTRODUCTION AND OVERVIEW

Virtual reality (VR) provides unlimited possibilities for creative imagination. The majority of existing VR applications and many existing hardware solutions focus on a seated setup. Simultaneously, both developers and users strive to get the most natural, immersive and realistic experience possible.

For instance, one of the fundamental interaction tasks within virtual environments (VE) is navigation [1]. In the real world, navigation is most commonly achieved through the natural body motions associated with walking. From a user's perspective walking is simple and intuitive, but its implementation varies a lot depending on the used approach. To increase the fidelity of the VR setups various prototypes of interface devices and locomotion metaphors have been developed to support walking in VEs [2]. Unlike the other solutions for locomotion in VR real walking has been shown to have a positive impact on user's sense of presence [3], spatial updating [4], search task performance [5], attention [6], and higher mental processes [7]. However, supporting this natural method of locomotion in large-scale VEs remains a significant challenge due to space and cost limitations.

To address the problem of fitting natural free locomotion in VEs within available real workspace a number of techniques for spatial compression were developed. We distinguish methods that manipulate users' senses (e.g. redirected walking [2]) from methods that manipulate the 3D scene itself.

A class of techniques known as redirected walking [2] belongs to the methods that employ senses manipulation. They build upon the principle that the brain considers the visual cues as more accurate and therefore more important for orientation than other senses of the human body. However, since humans are still sensitive to these methods, the amount of applied manipulation that stays unnoticed for the user is limited [8].

It is also possible to manipulate the visual cues to cause the desired user behaviour. Sun et al. demonstrates the technique of rendering based wrapping a VE to fit into an arbitrary real world workspace [11].

Virtual scene manipulations have a large potential to increase the compression factor for VEs without unnatural senses manipulations. The core approach is to enable sharing of the same real workspace between different parts of VEs by relocating some elements of VE depending on users' actions. A number of promising approaches for spatial manipulation have been suggested, such as change blindness effects [12], a self-overlapping architecture known as "impossible spaces" [13], and dynamic procedural generation of self-overlapping layouts called "flexible spaces" [14]. They demonstrate that spatial overlap can be efficiently used in cases where learning the spatial arrangement is not required and show its benefits for effective workspace usage.

Both types of manipulation techniques might even be comprised with haptic feedback like in [9], where a wall simulation supports unlimited walking along a corridor with turns. The TurkDeck project demonstrated how a haptic feedback could be provided for an arbitrary VE like flexible spaces [10].

At the same time, the spatial perception in VEs that use scene manipulations for space compression is heavily underexplored. The reported studies tested the feasibility of compression with this approach. However, the questions on how exactly humans perceive self-overlapping architecture and what properties of such VEs lead to the most natural and efficient spatial compression remain open. Our paper aims to fill this gap. We present two user studies that explore in details the influence of spatial architecture on spatial perception in self-overlapping VEs. Our main contribution is:
- analysis of spatial distortions caused by the path properties;
- comparison of the right-angled and curved corridors;
- insights on the intentional distortion of spatial perception for self-overlapping spaces;
- a new interactive evaluation method for self-overlapping spaces that allows users to interactively reconstruct their understanding of the VE they experienced. Our method allows checking the assumptions made in previous research such as if there is a distance between the overlapping rooms or whether the cognitive map of a VE is actually deformed.

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Hereby we extend the knowledge about the users' experience of "impossible spaces" [13] and "flexible spaces" [14]. Our findings will help to further improve the efficiency of spatial compression.

1.1 Scene Manipulation Techniques

Scene manipulation for space compression in VEs is a relatively new concept. The first attempt was done by Suma et al. in [12] and [15]. They modified the direction of the user's movement within multiple rooms connected with a corridor by changing the position of the door in a room during task performance. The interesting outcome of the study was that many participants were able to draw a consistent map of the VE. This method majorly relied on the control over the attention of a user. Without the task-forced shifts in direction of attention, the introduced changes would have been easy to notice.

The "impossible spaces" study [13] questioned how much overlap it is possible to introduce in a simple real-world-like spatial layout. Two ways of a spatial overlap implementation were explored. In the "fixed room" layout the rooms of constant size were moved closer to each other to increase the spatial overlap. As a result, the length of the connecting corridor was decreasing while the amount of overlap grew. The maximum unnoticeable overlap for two rooms in this layout was approximately 50%. The "expanding room" layout fixed the area occupied by two rooms. The rooms were increasing in size when the wall between them was moved towards the center of the other room, thus creating a spatial overlap and keeping the corridor length constant. In this condition, users were likely to notice an overlap of over 30%. This study results showed that scene manipulations might produce a large distance overestimation between the overlapping spaces in VEs in a blind walking task.

In [16] the dependency between the path complexity and the blind distance estimation between two targets has been researched, in a scenario similar to the "expanding room" of "impossible spaces" with three types of corridors. It has been shown, that the introduction of additional length and corners to the path decreases the probability of the overlap detection and increases the estimated distance between targeted virtual tables. Distance overestimation in physically impossible spaces turned out to be up to two times more than the actual distance in the simple layouts and up to three times in layouts with more complex corridors. However, previously researchers have demonstrated that distances in general [17], [18], [19] and the distances one has traveled [20] are underestimated in VEs in comparison to the real world. These findings partially contradict the observed overestimation. In [16] authors also reported an interesting observation of the room displacement reported by the users. Users were insisting on taking a diagonal path to the targeted objects while the rooms of the same size and targets were aligned along one of the axes and the connecting corridors were symmetric.

Both studies mentioned above used blind walking as a distance estimation method. Blind walking requires a user to walk to the previously seen target without visual feedback. This approach has been shown to be most accurate, reliable, and a commonly accepted metric for distance estimation [21]. However, the original blind walking required participants to walk to the target in direct line of sight immediately after viewing. These conditions could not be fulfilled in spatially overlapping VE as it excludes the possibility of a direct line of sight and also includes the need to travel from one point to another to complete the observation phase. Therefore, the drawn assumptions about the spatial perception and cognition of the space cannot be conclusive and there is a need for another measure for spatial manipulation techniques.

Ultimately, the benefit of a scene manipulation approach is that unlike redirected walking it excludes the conflict between the visual and other human senses. However, real-world-like spatial structure cannot always be maintained with scene manipulation methods. Nevertheless, a better understanding of human perception will definitely help to find an optimal trade-off between these valuable parameters in each given case.

2 Study 1

In this study, we tried to identify the correlations between the layout arrangements and spatial perception. We hypothesize that the spatial perception in self-overlapping VEs might be influenced by the following layout properties:

- the number of corners in the connecting corridor;
- the sequence of corners in the connecting corridor;
- the positions of the corridor endpoints (doors) relative to the overlap zone;
- the symmetry and asymmetry of the path.

2.1 Design

As our target application area is spatial compression, we focus on paths that do not lead too far away from the targeted end point. Also, it has been reported that a path length difference of 10m did not produce any significant effect [16]. Therefore we excluded the length of the corridor from consideration. However, as the travel time should be comparable within each set of layouts, we kept the length of the paths to 8,5m. Only for the layouts were aimed at different positions of the doors (endpoints) the corridors' length reached 10,5m due to the spatial geometry.

Aiming for a realistic room size we chose identical rooms sized 3m × 4m (12m^2). The overlap was implemented along the shorter wall side (X axis). Using the overlap perception results reported in [13] and [16] we estimated that the borderline for overlap is perceived at approximately 50% of shared space, meaning each room shares half of its area with the other room (see Figure 1a). Therefore, we fixed the amount of overlap for all layouts at a level of 50%. Consequently, the total area occupied by two rooms was equal to 4.5m × 4m (18m^2).

According to the criteria mentioned above, we developed several sets of spatial layouts in order to look at each specific parameter of the path, while the others are controlled. As the overlap zone is an area of our interest for the layouts set the endpoints' positions were chosen to be furthermost from it, directly in it and on a diagonal to it. The layouts used are shown in Figure 1. An example of 3D models of the layouts used is shown in Figure 2a.

The layout sets were organized as follows:

- a number of turns: U-, J- and short C-shaped layouts with 2, 3 and 4 corner corridors respectively (Figure 1b-d);
- different endpoints' positions: C-, O- and L-shaped corridors with opposite, in and diagonally positioned doors relative to the overlap zone (Figure 1e-g);
- turn directions: short C-, G-, P-, and S-shaped corridors with the same turn directions, change of direction near the end, one-time change of direction in the middle, and a complete change of direction in the middle respectively (Figure 1h-j);
- asymmetry and walking direction: contains all the layouts that are not symmetrical, meaning J-, L-, G-, and P-shaped layouts (Figure 1c,g-i).

For this user study, we chose a within-group study design. Participants experienced all the layouts in a counterbalanced pseudo-random order. In order to prevent the patterns of movements in space, the layouts were randomly rotated by 0, 90 or 180 degrees as well as spread throughout the available tracking space.

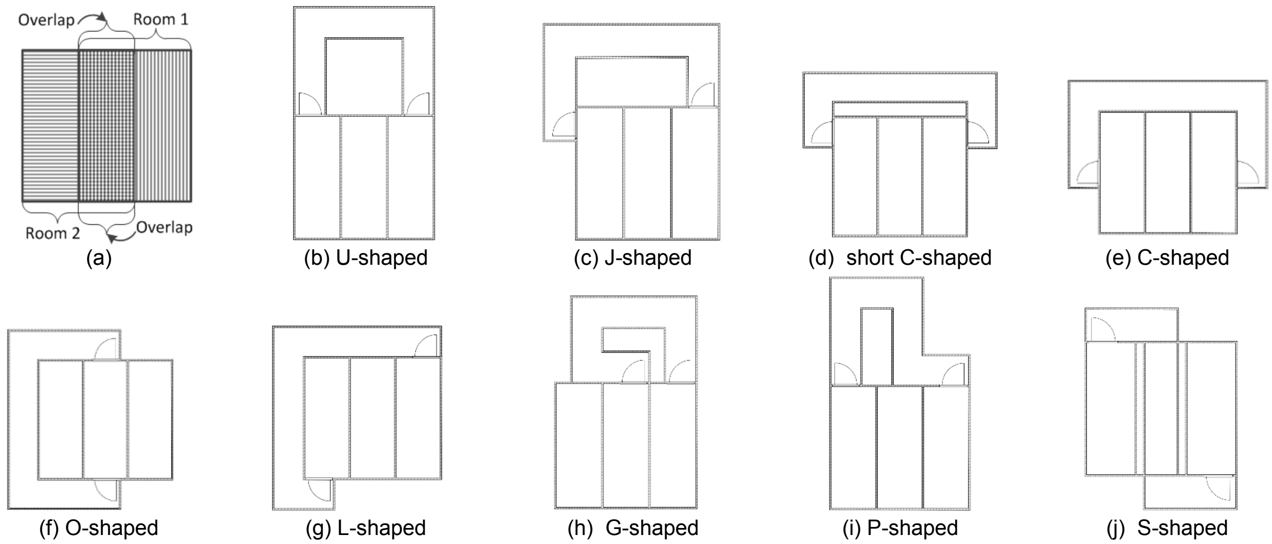

Figure 1 – Study 1 design: (a) - two rooms aligned and overlapping along X axis that share 50% of each other's space. Layouts with different corridors: (b)-(d) - Layouts with corridors that contain 2, 3 and 4 corners respectively. (e)-(g) - Layouts with different doors positions relative to the central overlap zone. (h)-(j) - Layouts with turns in different directions.

The spatial abilities were evaluated using a questionnaire similar to [22], that was modified to be more relevant for the indoor environments and our particular use-case (see Section 3.3.3).
To measure the spatial perception we also introduced a new interactive and direct measure that allows visual recreating of the spatial arrangement according to participants' perception. In our measuring technique after a participant walked from one virtual room to another room through a virtual corridor once, we switch to the semi-transparent rendering of rooms without a corridor. The participant stays in the room which she entered last and sees the first room at a random position outside. Then, maintaining the first person perspective, she visually reconstructs the rooms' relative positions by modifying the position of the first room.

2.2 Technical Setup

The environment was implemented using the Unity 3D game engine. For tests, we used Oculus Rift DK2 head-mounted display with 100° nominal field of view and resolution 960 x 1080 per eye. The participants' global head position was estimated using the tracking system with ID markers [23] and IDS camera uEye UI-3251LE with a 190° fish-eye lens. Overall 156 markers were mounted within the 12m x 9m workspace and the tracking provided millimeter accuracy.
Participants wore a backpack with a laptop that weighed about 3.5 kg. The laptop performed both tracking and rendering of the 3D environment using dual NVIDIA GeForce GTX 880M and an Intel Core i7 CPU, making the entire setup fully wearable and wireless. In addition, participants were equipped with a wireless 360 Xbox hand-held controller for the task performance. A fully equipped participant in the workspace is shown in Figure 2c.

2.3 Procedure

The total time of the study was approximately 35 minutes. At the beginning of the study participants signed the informed consent and filled the Kennedy simulator sickness questionnaire to indicate how they were feeling prior to the experiment [24].

2.3.1 Preparation Phase

The objective of the study required full awareness and understanding of the extended possibilities of spatial layout

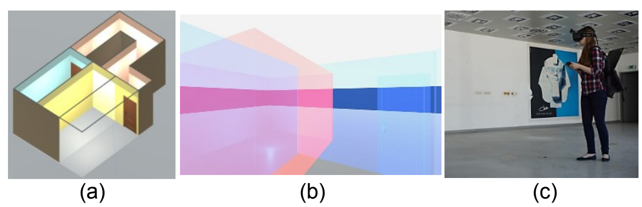

Figure 2 – Experimental environment (a) - A 3D model of a P-shaped layout used in user the study. (b) – Participant's view during task performance in transparent mode. (c) – Participant walking in a real workspace.

arrangement in the virtual world. Therefore, along with the study instructions we suggested the possibility of four main types of spatial arrangement: two adjacent rooms with a partially or fully shared wall, overlap along a single wall, overlap along a diagonal that connects the centres of the arbitrarily placed rooms, and arbitrary placement of the rooms with some distance between them. We stressed that any layout arrangement could be used in any of the sets, but it was the participants' task and challenge to decide for each case, what was the arrangement of the rooms relative to each other. For that, they were instructed to visually reconstruct from a first person perspective the rooms' positions relative to each other starting from a randomly modified semi-transparent scene. We used examples to make sure that the task was understood correctly. In addition, to stimulate the participants' attention participants were informed that each set of two rooms and a corridor will be somewhat different from the rest.

Participants were notified that they can take breaks or discontinue the experiment at any moment. They were also encouraged to share their observations and impressions during the experiment by talking aloud. During the instruction process the participants were able to see the workspace before the exposure to the VE; thereby, they were aware of the dimensions of the physical space.

Next, participants were fitted with a head-mounted display (HMD), a backpack with equipment, and an Xbox controller for task performance.

During the entire experiment, the experimenter was walking next to the participants to ensure their safety and to prevent the participants from using the experimenter's position or direction of her voice as a spatial reference point.

2.3.2 Task Phase

As soon as the preparation phase was completed, participants were instructed to locate a green platform in the environment and to step on it to start the experiment. After that, the participants saw themselves within a virtual room of the first set. As instructed before, they had to carefully explore the room and when ready proceed to the corridor through the door, keeping their task in mind. After reaching the end of the corridor participants entered the second room. They were instructed to look around carefully and activate the transparent mode at will by pressing a button on the Xbox controller.

The task was to locate the original position of the first room from the current position in the second room. Therefore, in transparent mode (see Figure 2b), the room entered last becomes semi-transparent blue. This room also maintains a semi-transparent door that identifies the direction that a participant came from as an aid for spatial orientation.

At the same time, another room was rendered as semi-transparent red. This room had to be moved with the Xbox controller to the position of the original first room. The door of that room is not rendered, neither is the corridor rendered. This red room was randomly displaced on both coordinate axes from the original first room position. However, it was roughly placed on the correct side, relative to the blue room. The reason for this is that our pilot try-outs showed that placing the red room to the opposite side caused longer search times of the red room, major confusion and a loss of spatial orientation with the resulting inability to perform the aforementioned task.

Using the joystick of the Xbox controller the participants were asked to move the red room from its random position to its original position in the layout they explored. The forward direction of the joystick was aligned with the forward direction of the HMD.

The participants were allowed to walk within the blue room but were warned not to cross its boundaries. Additionally, participants were asked to perform the task within a one-minute time limit to stimulate a perception based judgment rather than a logical one, as well as prevent an increase of confusion over time.

Upon completion of the task, they were asked to press another button and then locate another green platform to activate the next layout as in the beginning.

2.3.3 Final Phase

After completion of the task phase for all the layouts, the participants filled a final questionnaire which started with the simulator sickness questionnaire and general questions regarding participants' age, gender, game and 3D game or virtual reality experience. Also, the questionnaire included questions about the strategy used to identify the spatial arrangements if anything had a positive or negative impact on their virtual experience. Additionally, we asked a modified set of questions from [22] regarding their spatial abilities that contained the following questions:

1. I can easily find my path with a map.
2. After seeing a path only once, I can easily find and walk the same way again.
3. I often cannot tell how far an object within a room is.
4. I am good at following directions when navigating through a city.
5. At home, I can easily walk with closed eyes.
6. I can easily estimate the distance from me to any known location in the city.
7. I'm good at providing directions to locations in the city.
8. After seeing a path just once, I have troubles walking back.

The answers were given on a 7-point Likert scale formulated as "strongly disagree" up to "strongly agree" and coded from 1 to 7 so that a higher score indicated better spatial abilities.

2.4 Participants

24 participants (11 female and 13 male, aged 18-49, M = 30, SD = 8.99) participated in the study. 17 participants had no prior experience with 3D VEs and only 4 identified themselves as experienced users.

The participants were recruited at Facebook's local English-speaking groups on a volunteer basis. They were required to be over 18 years old, with normal or corrected to normal vision, to not suffer from severe motion sickness, epilepsy, contact-transmitted diseases and be able to walk normally with a backpack weighing approximately 3.5 kg.

2.5 Results

All the calculations are done in local coordinates of each layout. The distance between the rooms were calculated as a length of a vector that connects their centers (originally equal to 1.5m). Taking into account that the layouts are explored in different directions, but the rooms are symmetrically arranged along the X axis, we transformed the data to obtain a uniform and comparable representation of results. We recalculated the obtained X values to get the deviation of the position of a room moved by the user from its correct initial position. In addition, the sign of the X values was modified so that the positive value signified a decrease of the overlap. A negative X value signified the increase of the overlap, up to 100% overlap in case of X = -1.5 and positioning of the room to the wrong side for values below -1.5.

Distance data were evaluated using repeated-measures ANOVA. The resulting estimated distances are shown in Figure 3.

Given that the majority of the obtained results violate the assumptions of normality according to the Kolmogorov-Smirnov normality test, for the X and Y coordinates data analysis we used assumption-free non-parametric tests such as Friedman's ANOVA and Wilcoxon signed-rank test with significance level 0.05. The

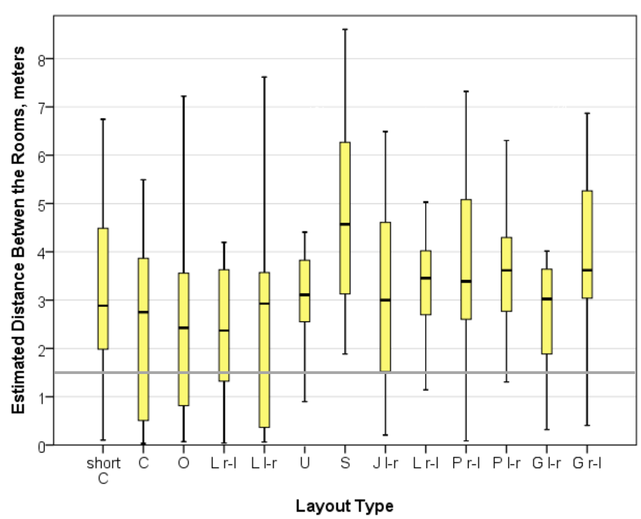

Figure 3 – Distances estimated for each type of right-angled layout. Indices "l-r" and "r-l" for asymmetric corridors show the walking direction "from left to right" and "from right to left". The actual distance between the centers of the rooms is 1.5 meters (bold grey line).

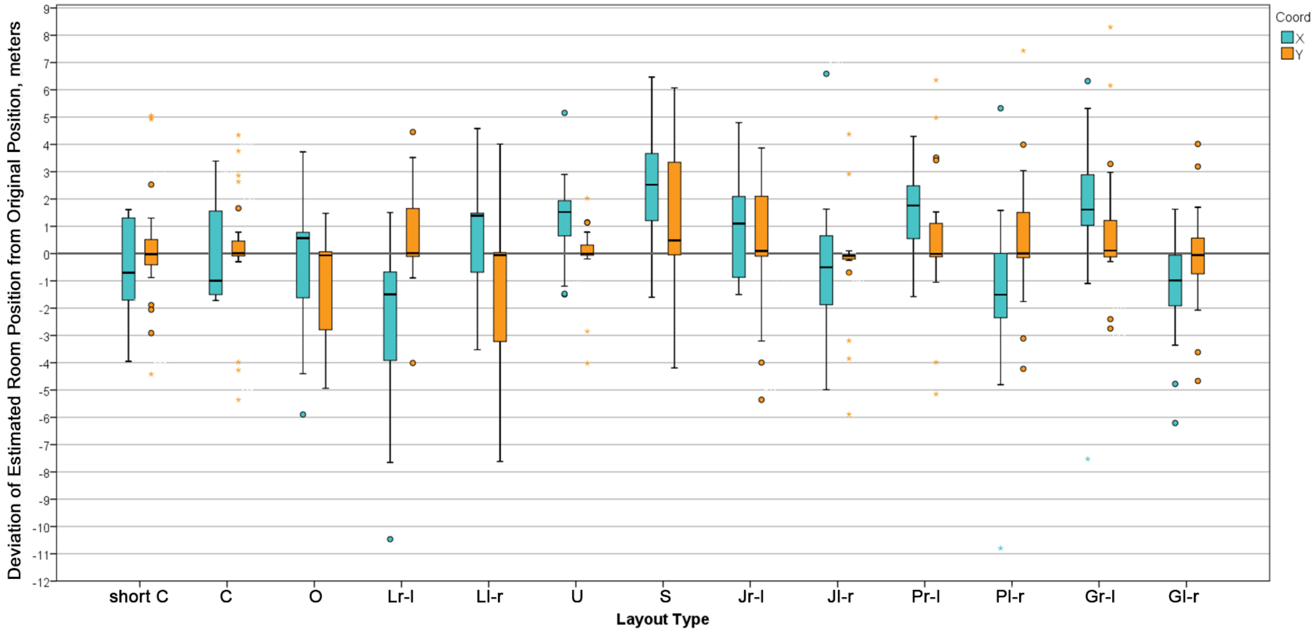

Figure 4 – Deviation boxplot of the estimated position from the correct position of the red room along X and Y axes for each type of layout. For asymmetric corridors indices "l-r" and "r-l" depict the walking direction "from left to right" and "from right to left" accordingly.

deviation of the room position estimated from the original position along X and Y axes for each layout is shown in Figure 4.

For the quantitative measure of the strength of a phenomenon, we rely on the effect size that does not depend on measurements scales. We used Pearson's correlation coefficient (r) for effect size estimation and Cohen's benchmark for interpretation ($r \approx 0.1$ – small, $r \approx 0.3$ – medium, and $r \approx 0.5$ – large effect).

2.5.1 Simulator Sickness

Kennedy simulator sickness questionnaire [24] results were coded as 4-point Likert scale where "None" of presence a symptom was coded as 0 and 3 points indicated a "Severe" case of a symptom. The combined difference over all questions in pre- and post-exposure scores showed minor aftereffects M = 2.5, SD = 2.77. From 24 participants 8 did not observe any change in their state and 9 participants reported a minor increase in symptoms up to 3 points in total.

2.5.2 Spatial Abilities and Strategies

The results of 8 questions of the spatial abilities self-report were rated from 1 to 7, where 7 signified the best and 1 stood for the worst spatial ability. The summarized results showed that our participants had the spatial abilities slightly above average M = 4.95, SD = 0.77 on the same scale.

Strategies: among the participants, 5 did not use any strategies, 5 more attempted to count steps, 12 relied on their spatial memory, and 2 were using other strategies such as imagining a bird's eye view of the scene.

2.5.3 Number of Turns

Friedman's ANOVA showed that overall the distributions between the U-, J-, and short C-shaped layouts were not significantly different along the X axis $\chi^2_F(2) = 4.75$, $p = 0.093$, and along the Y axis $\chi^2_F(2) = 4.083$, $p = 0.13$. The follow-up comparisons were done with Wilcoxon signed-rank tests (see Table 1).

The distance between the virtual rooms in different layouts was not significantly different. The contrasts between the different layouts turned out to be not significant as well.

Table 1. Pairwise comparisons for number of turns set

Layout pairs		T	p	r
U-shaped vs J-shaped	X	99	0.145	-0.21
	Y	*82*	*0.052*	*-0.28*
J-shaped vs sh. C-shaped	X	139	0.753	-0.05
	Y	202	0.137	0.21
sh. C-shaped vs U-shaped	X	**220**	**0.046**	**0.29**
	Y	148	0.954	-0.01

2.5.4 Positions of Endpoints

According to Friedman's ANOVA the overall distribution of results between the C-, O-, and L-shaped layouts differed significantly along the X coordinates $\chi^2_F(2) = 12$, $p = 0.002$, and not significantly along the Y coordinates $\chi^2_F(2) = 2.25$, $p = 0.325$. Follow up tests were used to further explore the obtained data (see Table 2).

At the same time the estimated distances between the virtual rooms were not significantly different. Similarly, all the contrasts between the different layouts were not significant.

Table 2. Pairwise comparisons for layouts set with different positions of endpoints

Layout pairs		T	p	r
C-shaped vs O-shaped	X	188	0.278	0.16
	Y	*88*	*0.076*	*-0.26*
O-shaped vs L-shaped	X	**28**	**< 0.001**	**-0.5**
	Y	**231**	**0.021**	**0.33**
L-shaped vs C-shaped	X	**241**	**0.009**	**0.38**
	Y	131	0.587	-0.078

2.5.5 Asymmetric Path and Walking Direction

We also examined the asymmetrical paths layouts whether the results are changing depending on the direction in which the path is taken. For this, we performed a pairwise comparison for each layout with the Wilcoxon signed-rank test. The results are presented in Table 3.

Repeated measures ANOVA showed a significant effect of the layout type on the distances between the rooms F(3,69) = 4.327, p = 0.007, but no overall effect of the walking direction. The two-tailed t-tests showed no significant difference in distances caused by walking direction in any of the layouts, but there was a trend for the G-shaped corridor (t = 1.96, p = 0.06, r = 0.38).

Table 3. Comparison of clockwise (left to right) and counter clockwise (right to left) locomotion in asymmetric layouts

Layouts		T	p	r
L-shaped	X	**287**	**< 0.001**	**0.56**
	Y	**78**	**0.04**	**-0.3**
J-shaped	X	**233**	**0.018**	**-0.34**
	Y	198	0.17	-0.2
P-shaped	X	**28**	**< 0.001**	**-0.5**
	Y	136	0.689	0.06
G-shaped	X	**285**	**< 0.001**	**-0.56**
	Y	183	0.346	0.14

2.5.6 Turn Directions

Friedman's ANOVA showed that in general the distributions of the resulting values for the short C-, G-, S-, and P-shaped layouts were significantly different along the X axis ($\chi^2_F(3) = 11.55$, p = 0.009), and did not differ much along the Y axis ($\chi^2_F(3) = 3.75$, p = 0.29). Results of the pairwise comparisons are shown in Table 4. Given the significance of movement directions, the asymmetric layouts' data are taken for both directions of movement.

The change of turn directions significantly influenced the distance estimated by participants, F(3,69) = 4.575, p = 0.006. The planned contrasts indicated a significant difference between the distances estimated in layouts with G- and S-shaped corridors F(1,23) = 14.228, p = 0.001. For the rest the contrasts were not significant.

Table 4. Pairwise comparison for turn direction set depending on walking direction in asymmetric layouts

		Left to right			Right to left		
Layout pairs		T	p	r	T	p	r
sh.C-shaped vs G-shaped	X	180	0.391	0.12	**239**	**0.011**	**0.37**
	Y	140	0.775	-0.04	175	0.475	0.1
G-shaped vs S-shaped	X	**235**	**0.015**	**0.35**	*213*	*0.072*	*0.26*
	Y	**228**	**0.026**	**0.32**	188	0.278	0.16
S-shaped vs P-shaped	X	*84*	*0.59*	*-0.27*	96	0.123	-0.22
	Y	97	0.13	-0.22	107	0.219	-0.18
P-shaped vs sh.C-shaped	X	100	0.153	-0.2	**76**	**0.034**	**-0.31**
	Y	141	0.797	-0.03	143	0.841	-0.03

2.6 Discussion

The results obtained from the set of layouts, where a number of the corners in the corridor varied from 2 to 4, suggest that the difference in perception requires a difference of at least two turns to produce a significant effect. An overall effect showed to be present along the X axis, while the effect of the Y coordinates lacked power.

The set of layouts focusing on the positions of the corridors' endpoints showed that this parameter might be potentially used to manipulate the spatial perception. Against our expectations the placement of doors that were aligned with the center of the overlap zone, and orthogonal to each other, did not produce a large enough effect. Simultaneously, the doors placed in the furthermost diagonal positions made a significant difference but were also associated with the asymmetrical corridor. Due to geometrical limitations of space and the correctness of interactive rendering of VEs, the modification of the endpoints' position will most likely be used in conjunction with other parameters discussed below.

We also have to mention that the majority of the door positions in the experiment were gravitating to the rooms' corners in order to maintain control over the endpoints. It also caused the layout with a C-shaped corridor (see Figure 1d) to stand out among the rest of the layouts, as its doors were placed in the middle of the longer wall and opposite to the overlap zone.

The set considering the importance of the sequence of turns showed a significant overall effect along the X axis and a trend along the Y axis. The C-shaped layout was used here as a baseline for a comparison. The results suggest that inner twists of the path are producing the most powerful effect. Changing the turn direction near the door (G-shaped corridor) resulted in beneficial significant differences only in comparison to the loop-like C-shaped corridor and only when the change of direction was in the end of walkthrough, possibly by breaking a loop pattern. However, for the P-shaped corridor the twist was more efficient closer to the beginning of the walk through. Here the layout resulted in a realistic room arrangement even with a small distance between them while in the opposite direction it caused an increase of the overlap.

A complete switch of the corridor direction produced by the layout with an S-shaped corridor was even more effective and extended the gap up to 1m. This could be partially explained by its presence within the overlap zone, thereby creating a hard to imagine triple overlap in a single scene. Moreover, only a two participants noticed the irregularity of the spatial dimensions in this case. That suggests that it is possible to superimpose a corridor and room near to room's edges.

The path asymmetry turned out to be the most efficient approach. It produced significant differences in all the asymmetrical corridors. Interestingly, all the layouts produced a significantly larger effect along the X axis. The results were positive in the direction from right to left and mostly negative in the opposite direction for all layouts, except for the one with an L-shaped corridor with an opposite result. Moreover, in the direction from right to left the results for the L-shaped layout suggest an overlap created by manipulating the Y coordinate instead of X. Taking a closer look at the asymmetrical layouts we were able to spot a pattern that correlates with the definition of path complexity from [16]. There, complexity was defined as a combination of path length and number of corners. In our case, there are parts of the paths where two corners are connected with a rather short path. Only the L-shaped corridor had two corners so close to each other that they could be perceived as a single turn. These results suggest that corner distribution in the beginning of the path exploration has a decisive influence on a not naïve user's attitude, and might cause her to be significantly more suspicious of the presence of overlap in the layout, than if the corners are close to each other. Therefore, the complexity definition could be extended with a component that describes the path from the perspective of corner distribution along its length.

One of the limitations of the current study was that the symmetrical layouts were not explored in both directions in order to minimize the effect of repetition of the familiar layout. Therefore, it is not possible to judge whether the overall turn direction plays a role.

The resulting distances obtained during the task performance are in accordance with the previous findings – the distances are systematically overestimated in average by 100%, which is similar to observations in [16]. Here an S-shaped layout clearly stands out with a median of the distance of about 4.5m. At the same time, the distances estimated for the endpoints set are slightly lower than the rest, while the corridors themselves are 2m longer than the others. This could be explained by the fact that only in these layouts the corridors follow the rooms' perimeters, thus they are closer to the real life experience.

Finally, results of this study that were significant mostly along the X axis showed that in right-angled layouts an X-aligned overlap

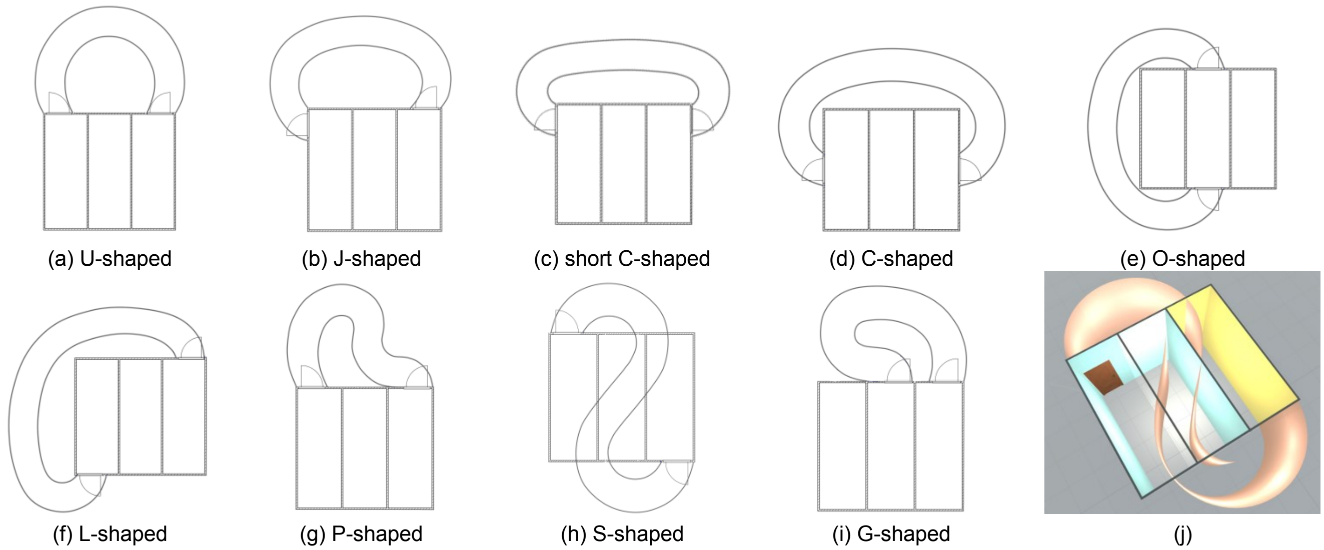

Figure 5 - Study 2 setup: two rooms that share 50% of each other's space are connected by differently curved corridors. (a)-(c) - Layouts with corridors that contain 2, 3 and 4 full 90° rotations respectively. (d)-(f) - Layouts with different door positions relative to the central overlap zone. (g)-(i) - Layouts with turns in different directions. (j) - A 3D model of an S-shaped layout used in the user study.

zone is noticeably perceived by people. Although, the perception is not always correct and might sometimes be bundled with a notion of a mirrored arrangement of rooms. Simultaneously, the diagonal distortion of relatively small scale layouts observed in [16] was also confirmed in our study with the use of a different measure. And although the deviation medians along the Y axis were gravitating towards zero, the results also show that in several cases the majority of participants assumed a displacement of the room along the Y axis. This is particularly visible in cases of O-, L- and S-shaped layouts (see Figure 4).

3 Study 2

As all the previous studies of space compression methods and impossible spaces, in particular, rely on a reality-like architecture of the indoor VEs, the question about the influence of shapes on spatial perception is not yet fully answered. By using only right angles VR designers might be limiting themselves. According to [25] spatial geometry, namely, corners might be used as landmarks for spatial orientation and task performance.

Of course, use of rounded corners that might deviate from right angle could be potentially beneficial for unnoticeable distortion of the spatial cognition. However, there is still an opportunity to determine an angle empirically and use still visible corners as landmarks. Therefore, we suggest to replace the customary sharp angled geometry by rounded shapes. Consequently, in our second study, we explore the most extreme case of change of the corridor shape – corridors that consist of smooth curves only.

3.1 Design

Our objective in the design of this study was to maximally round the corners and smoothen the differences between the corners and straight segments of the path, thus eliminating the possibility to use features of spatial geometry as landmarks.

In order to obtain a better understanding of the influence of the curved path on the perception, we decided to check whether the conclusions made before hold in this new geometry. Therefore, we modified the layouts used in the first study by hand so that the corridors consisted only of curves. For a valid comparison, we preserved the rectangular rooms with the same positions relative to each other as well as doors' positions in each layout.

In this study, the transition from simple right-angled corridors to the curved corridors modified the paths in a number of ways. The introduction of curves made it difficult to maintain the length of corridors uniform, as it was in the previous study. To achieve a smooth curve of a corridor and avoid obvious violations of the spatial geometry some corridors were augmented with additional curvature. That in turn, could provoke additional rotation for the user, which is an unavoidable property of the curved geometry.

The study was carried out with the same technical setup and followed the same procedure described in the first study. The resulting layouts are shown in Figure 5.

The geometrical limitations, as well as the requirement for elimination of the straight parts of the path, caused changes in path lengths by a few meters, depending on the specific layout. According to previous research, this modification should have a minimal impact.

3.2 Participants

26 participants, 10 females and 16 men, aged from 18 to 52 ($M = 28.6$, $SD = 8.35$) took part in the experiment. Only 4 participants identified themselves as very experienced with 3D applications, 9 had minor exposure and 12 had no experience at all.

The participants were recruited at Facebook's local English-speaking groups on a volunteer basis and had to fulfill the same health requirements as before. None of them participated in the first study.

3.3 Results

Distance data were evaluated using repeated measures ANOVA. The cumulative distance boxplot is shown in Figure 6.

Similar to the previous experiment the obtained coordinates' results violate the assumptions of normality according to the Kolmogorov-Smirnov normality test. Therefore, in our analysis, we used assumption-free non-parametric tests such as Friedman's ANOVA and Wilcoxon signed-rank test for the X and Y coordinates data. The coordinates' data are shown in Figure 7.

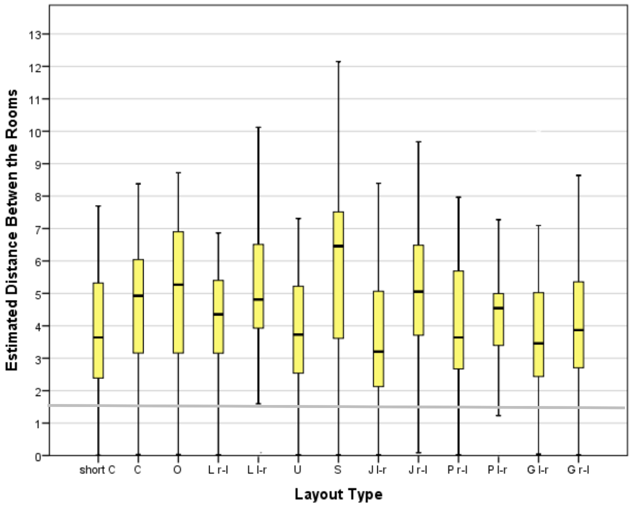

Figure 6 – Distances estimated for each type of curved layout. Indices “l-r” and “r-l” for asymmetric corridors show walking direction “from left to right” and “from right to left”. The actual distance between the rooms is equal to 1.5 meters. (bold grey line).

3.3.1 Spatial Abilities and Strategies Used

The questionnaire on spatial orientation abilities showed a similar result to the previous study: slightly above the middle line M = 5.21, SD = 0.89 on a scale from 1 to 7, where 7 is the best score.

Strategies: out of 26 participants 3 did not use any strategy, only 2 participants persisted with counting steps (3 more participants attempted it in the beginning, but quickly switched to another or no strategy), 14 relied on spatial memory and 7 used other methods to orient in the VE. An interesting strategy was in trying to make only 90° rotations, which sometimes resulted in sideways locomotion. Another unique strategy applied inventive self-motivation that transformed the task to a quest of remembering where a chocolate shop was with imaginable chocolate crumbs left along the way.

3.3.2 Simulator Sickness

Kennedy simulator sickness results for each of 16 symptoms were coded as 4-points Likert scale from 0 for the answer “None” to 3 for “Severe”. The combined difference score of pre- and post-questionnaire showed minor effects of the VR exposure M = 1.15, SD = 2.6. In fact, only 3 participants reported an increase of simulator sickness symptoms by more than 2 points after the exposure, 8 did not feel any changes in their state and 4 participants reported even a decrease of symptoms up to 3 points in total.

3.3.3 Amount of Rotation

Friedman’s ANOVA showed that overall the distributions between the U-, J-, and short C-shaped layouts were significantly different along X axis $\chi^2_F(2) = 20.846$, $p < 0.001$, and not significantly different along the Y axis $\chi^2_F(2) = 3$, $p = 0.223$. The results of follow-up comparisons are presented in Table 5.

Table 5. Pairwise comparisons for number of turns set

Layout pairs		T	p	r
U-shaped vs J-shaped	X	**22**	**< 0.001**	**-0.54**
	Y	179	0.929	0.1
J-shaped vs sh. C-shaped	X	204	0.469	0.1
	Y	*246*	*0.073*	*0.25*
sh. C-shaped vs U-shaped	X	**300**	**0.002**	**0.44**
	Y	101	0.58	-0.26

Repeated measures ANOVA did not detect any significant layout effect on the estimated distance, nor did the planned contrasts.

3.3.4 Positions of Endpoints

According to Friedman’s ANOVA, the overall distribution of results between the C-, O-, and L-shaped layouts differed significantly in both X coordinates $\chi^2_F(2) = 13.154$, $p = 0.001$, and Y coordinates $\chi^2_F(2) = 21$, $p < 0.001$. The follow up findings are shown in Table 6.

The mean distances in the corresponding layouts $M_C = 4.61$, $SD_C = 2.14$, $M_O = 5$, $SD_O = 2.55$, $M_L = 4.2$, $SD_L = 2.12$. Repeated measures ANOVA did not show any significant layout effect on distances. Planned contrasts were also not significant.

Table 6. Pairwise comparisons for set of layouts with different positions of endpoints

Layout pairs		T	p	r
C-shaped vs O-shaped	X	**30**	**< 0.001**	**-0.51**
	Y	**35**	**< 0.001**	**-0.49**
O-shaped vs L-shaped	X	198	0.568	0.08
	Y	**303**	**<0.001**	**0.45**
L-shaped vs C-shaped	X	**303**	**0.001**	**0.45**
	Y	209	0.395	0.12

3.3.5 Asymmetric Path and Walking Direction

We performed the comparison of the data obtained in a different walking direction for each asymmetric layout with the Wilcoxon signed-rank test (see Table 7).

The distances varied significantly for the L-shaped layout $F(1, 25) = 4.92$, $p = 0.042$ and were significantly different for the J-shaped layout $F(1, 25) = 10.904$, $p = 0.003$. The estimated distances between the rooms with P-shaped and G-shaped corridor did not differ significantly.

Table 7. Comparison of clockwise and counter clockwise locomotion in asymmetric layouts

Layout		T	p	r
L-shaped	X	163	0.751	-0.04
	Y	**43**	**0.001**	**-0.47**
J-shaped	X	**300**	**0.002**	**0.44**
	Y	**287**	**0.005**	**0.39**
P-shaped	X	**29**	**< 0.001**	**-0.52**
	Y	230	0.166	0.19
G-shaped	X	**317**	**< 0.001**	**0.5**
	Y	140	0.367	-0.134

3.3.6 Turn Directions

Friedman’s ANOVA showed that in general the distributions of the resulting values for the short C-, G-, S-, and P-shaped layouts were significantly different along the X axis ($\chi^2_F(3) = 24.785$, $p < 0.001$), and showed only a trend for significance along the Y axis ($\chi^2_F(3) = 7.615$, $p = 0.055$). The results of further analysis are presented in Table 8.

The change of turn directions significantly influenced the distance estimated by participants, $F(3,75) = 7.695$, $p < 0.001$. The planned contrasts indicated significant difference between the distances estimated in layouts with G- and S-shaped corridors $F(1,23) = 14.228$, $p = 0.001$ and the S- and P-shaped corridors $F(1,23) = 14.228$, $p = 0.001$. There was no difference between G- and short C-shaped corridors.

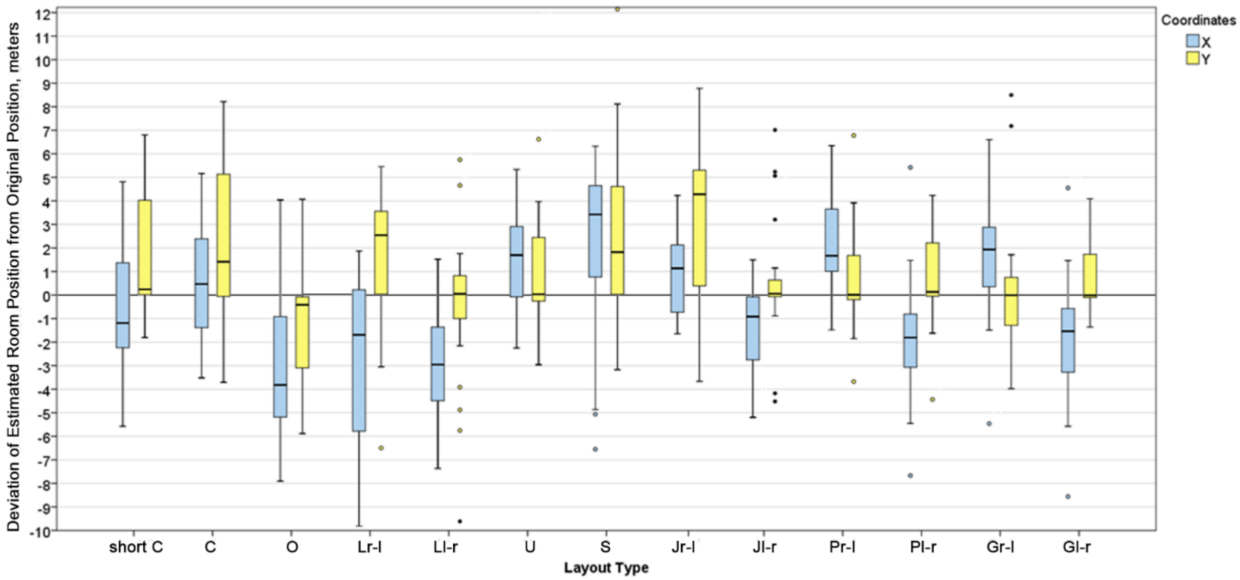

Figure 7 – Deviation boxplot of the estimated position of the moved room from its original position along X and Y axes in each type of layout. For asymmetric corridors the indices "l-r" and "r-l" depict the walking direction "from left to right" and "from right to left" accordingly.

Table 8. Pairwise comparison for turn direction set

		Left to right			Right to left		
Layout pairs		T	p	r	T	p	r
sh. C-shaped vs G-shaped	X	**96**	**0.043**	**-0.28**	**286**	**0.005**	**0.39**
	Y	**91**	**0.032**	**-0.28**	*99*	*0.052*	*-0.27*
G-shaped vs S-shaped	X	**301**	**0.001**	**0.44**	208	0.409	0.11
	Y	**277**	**0.01**	**0.36**	**275**	**0.012**	**0.35**
S-shaped vs. P-shaped	X	**53**	**0.002**	**-0.43**	160	0.694	-0.05
	Y	114	0.118	-0.22	**95**	**0.041**	**-0.28**
P-shaped vs sh. C-shaped	X	**273**	**0.013**	**0.34**	**48**	**0.001**	**-0.45**
	Y	228	0.182	0.18	**253**	**0.049**	**0.27**

3.4 Discussion

Substituting the right-angled geometry of the corridors with curves produced interesting results. Overall, participants' feedback during the study allows us to conclude that an absence of landmarks did make the orientation in space more difficult. Interestingly, in the curved setup we obtained even lower SSQ scores than in the right-angled one (M = 1.15 versus M = 2.5), when we expected an opposite result. This could be explained by the fact that participants did not look back as often as in study 1 and walked slightly slower, possibly due to the absence of landmarks.

The set of layouts focusing on the amount of rotation suggests that unlike in study 1, where we assumed that a least two corners are necessary to produce a significant difference, here we see that significance might be achieved with an additional rotation of a bit over 90 degrees. But simultaneously, the difference becomes just a trend when the corridor shapes have more in common, like in J– and C-shaped layouts.

The influence of the endpoints' positions showed a great impact in curved layouts. The O-shaped corridor with endpoints that are in the overlap zone misled the participants in a way that the adjusted room was flipped to the opposite side of its original position. The same effect was caused by the L-shaped corridor and, in addition, created an illusion that the rooms are not overlapping and arranged mostly along the Y axis when walked in a counter clockwise direction.

In terms of the turn directions, unlike the right-angled layouts, the results of curved paths produced a lot of significant differences. The S-shaped layout clearly stands out together with J-shaped layout in direction from right to left. Aside from creating an illusion of 0% overlap, both layouts also suggest a diagonal room positioning – which is ideal for space compression and minimizes the probability of perceived overlap. The S-shaped layout also suggests that rooms' nearest walls are 2m apart. That leaves free space sufficient for the slightly curved corridor (similar to the 1m distance left in the right-angled S-shaped layout). An increased distortion of the spatial perception along Y axis by the factor of four in comparison to study 1 might be an attempt to fit the overlap-free version of the S-layout into a rectangular space. Similarly, in the J-shaped layout participants placed the rooms so that the rooms touch a bit along the short walls.

Similar to the previous experiment the walking direction produced more positive results in a counter-clockwise direction (from right to left) and suggested an often increase in overlap in a clockwise direction for most of the layouts. Once again the L-shaped layout is standing out. In the right to left walking direction in this layout the results point at overlapping rooms aligned along the Y axis, instead of X. In the clockwise walking direction, the room position was flipped to the opposite side relative to the overlap and its original position. This change might be explained by the fact that unlike the right-angled layouts, the L-shaped path is detached from the rooms' walls, which might create an illusion of a spiral path, as the curvature decreases with progression. A somewhat similar doubled element that is reversed in the middle is present in the S-shaped path. This suggests that combining these two templates might lead to a reliable manipulation of spatial perception.

Finally, the distances between the rooms show a noticeable increase in average from approximately 3 meters between the rooms in right-angled layouts towards 4 meters and reaching the median of 6.5 meters for the S-shaped layout. This lets us conclude that in general, usage of the curved paths in self-overlapping indoor VEs is more efficient than common indoor right-angled paths. However, the walking direction has to be taken into consideration during the path design or generation to achieve the best user experience.

4 SUMMARY

In this paper, we presented two studies that explored the possibilities for spatial compression optimization in scene manipulation methods using different path properties. We explored the effects of two different principles in path implementation: right-angled paths, which are traditional for indoor environments and landmark-free smooth curved paths.

In both studies, we observed a tendency for path induced distortions of a small scale cognitive map from the diagonal room arrangement up to false alignment and the notion that the room was on the opposite side (with respect to the second room) from its original position. We also observed a difference in the spatial perception within the same asymmetrical layout depending on the direction that a path was taken. That is consistent with previous research on large scale cognitive maps [26], which states that human cognitive maps might often contain inconsistent angular and directional data, moreover directions between two points in space might be not reversible.

In the case of curved layouts, several participants also asked if they could to rotate the room they were adjusting. This did not happen in the right-angled layouts. This suggests that by introducing the curved paths into the flexible spaces algorithm, it might be possible to manipulate not just the placement of a room or any other object of interest, but also modify the rotation.

Overall, the curved layout introduced a lot of variance in the data, especially for the Y coordinate, which was noticeably more stable in right-angled layouts. That in turn increased the estimated distance values. In contrast, in the right-angled layouts, most of the variation in values happened along the X axis, along which the overlap was implemented. Here the distance along the X axis was questioned a lot more than along Y axis. This suggests that the overlap was perceived stronger in the right-angled layouts. Whereas in the curve-based layouts it is more difficult to say how the overlap was implemented. This promises an improvement and more optimal spatial manipulations, especially for naïve users.

In our future work, we would like to explore the effects of self-crossing paths and VEs that allow free overlap that is not limited to a single wall alignment.

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