Impossible Open Spaces: Exploring the Effects of Occlusion on the Noticeability of Self-Overlapping Virtual Environments

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Mission Impossible Spaces: Using Challenge-Based Distractors to Reduce Noticeability of Self-Overlapping Virtual Architecture

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ABSTRACT

Impossible spaces make it possible to maximize the area of virtual environments that can be explored on foot through self-overlapping virtual architecture. This paper details a study exploring how users' ability to detect overlapping virtual architecture is affected when the virtual environment includes distractors that impose additional cognitive load by challenging the users. The results indicate that such distractors both increase self-reported task load and reduce users' ability to reliably detect overlaps between adjacent virtual rooms. That is, rooms could overlap by up to 68% when distractors were presented, compared to 40% when no distractors were present.

CCS CONCEPTS

• **Human-centered computing → Virtual reality**; **Interaction techniques**.

KEYWORDS

Virtual reality, impossible spaces, distractors, redirected walking

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1 INTRODUCTION

Virtual reality (VR) allows users to travel in ways that would never be possible in physical reality. However, when the virtual environment (VE) is larger than the available tracking space, it is challenging to support the otherwise mundane act of physically walking. Suma et al. [12] proposed *impossible spaces*, which addresses this challenge by using self-overlapping architectural layouts to compress interior VEs into comparatively small tracking spaces. Even though these manipulations violate the rules of Euclidean space, they can be performed without users' knowledge, as long as the amount of overlap does not exceed the users' detection threshold. Research has shown that the shape of corridors connecting overlapping virtual rooms can affect perception of impossible spaces [14] and virtual distractions can reduce noticeablity of other forms of manipulation in VR [2, 9]. However, to the best of our knowledge, it has not been determined if virtual distractors also affect the noticeabilty of impossible spaces. In this paper, we present a study indicating that users tolerate a larger overlap between adjacent rooms, if challenge-based distractors are presented in the corridor between the rooms.

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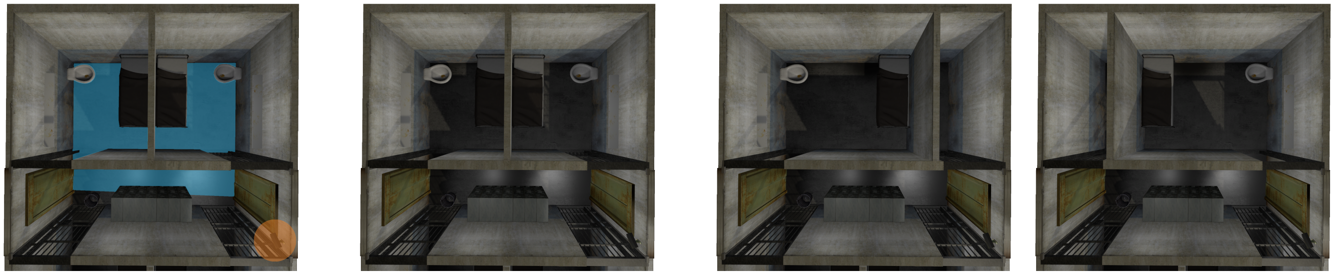
2 RELATED WORK

Redirected walking manipulates walkers' physical paths to keep them inside the tracking space; thus, making it possible to present a comparatively large VE inside that space. Redirected walking can be accomplished either by up- and downscaling users' virtual movement (*perspective manipulation*), or by reconfiguring the VE to generate self-overlapping virtual architecture (*environment manipulation*). Regardless of the type of manipulation a criterion for ideal redirected walking is imperceptibility (i.e., users should not notice that they are being redirected) [8]. Approaches to reducing the noticeability of redirected walking can be divided into at least two broad categories: *sub-threshold redirection* and *redirection masking*.

Sub-threshold redirection: Both perspective and environment manipulation can be concealed by limiting the magnitude of the manipulation. With respect to perspective manipulation, a large body of work has explored to what extent virtual movements can be scaled up and down without users noticing the manipulation. Much of this work has relied on psychophysical methods to estimate how small the magnitude of translation, rotation, curvature, and bending gains needs to be before users can only guess that they are being manipulated at chance level (e.g., [6, 10]). In their original work, Suma et al. [12] used a similar approach to determine how much two adjacent virtual rooms can overlap before users will reliably detect impossible spaces. They found that two relatively small adjacent rooms with fixed sizes (3.7m ×7.3m) may overlap by up to 56%, and larger rooms that expanded to fill the tracking space (9.1m ×9.1m) may overlap by up to 31%.

Redirection masking: Approaches belonging to this category decrease noticability by creating or awaiting opportune moments where perspective and environment manipulations can be subtly introduced. In regard to perspective manipulation, previous work



Walkable area and CCTV camera 0% overlap 50% overlap

Figure 1: Top-down views of the VE with the walkable area and CCTV camera highlighted, 0% overlap, and 50% overlap.

has show that both passive [9] and interactive [2] distractors, presented in the user's field of view, can be used to divert attention from distorted virtual rotations. Moreover, it has been shown that discrete virtual translations and rotations can be introduced during blinks [7] and saccades [13], and similar transformations can also be masked by introducing inter-stimulus images [1]. Finally, it has been proposed that narrative events or tasks can be used to create opportunities for applying translation, rotation, and curvature gains [3]. Suma et al. [11] leveraged visual change blindness to conceal environment manipulations. That is, they were able to move doors and hallways behind users' backs without it being noticed. To ensure that the users would turn their backs to the virtual doors, they were asked to perform a task requiring them to face in the opposite direction. Thus, tasks or events may be integrated into in the virtual narrative, to create opportunities where VEs can be manipulated. However, it also seems possible that distractors, imposing additional cognitive load by challenging the user, may be used to reduce the probability of users noticing impossible spaces.

3 METHODS AND MATERIALS

The aim of the study was to explore how virtual distractors affect users' ability to detect self-overlapping virtual architecture. To meet this aim, we performed a within-subjects study comparing two conditions. That is, VEs *with distractors* and VEs *without distractors*.

3.1 Participants

A total of 23 participants were recruited from the student body of Aalborg University Copenhagen. They were aged between 20 and 30 years (M=23.9, SD=2.2); 15 identified as male, 7 as female, and 1 as other; 21 had prior VR experience; and all had normal or corrected-to-normal vision and gave written informed consent.

3.2 Virtual Environment and Equipment

For each condition, the participants were exposed to six interior VEs. All six included pairs of adjacent virtual rooms connected by a corridor. The environments were either physically possible or impossible (i.e., impossible layouts involved overlapping virtual architecture). The six VEs used for each condition were identical except from six levels of overlap between the two adjacent rooms: 0% (no overlap), 15%, 30%, 45%, 60%, and 75%. Figure 1 shows VEs with 0% and 50% overlap. The overlap was not visible from inside the two rooms, and it was introduced when the participants traversed the corridor connecting the two. The VEs were displayed using a HTC Vive Pro and a pair of circumaural headphones. A single HTC Vive controller was used for interaction. The study was run on a PC with an i7-6700k processor and a Nvidia Geforce 1070 graphics card. The tracking space was approximately 3m×4m.

3.3 Scenario

We were interested in exploring the utility of distractors that can plausibly be deployed as part of a VR game or narrative experience. As a consequence, we created a scenario that supported a simple narrative and involved repeated exposure to pairs of adjacent, and potentially overlapping, virtual rooms. The participants assumed the role of a wrongly convicted prisoner and the scenario required them to escape an empty prison. The prison comprised twelve floors (six floors for each condition). Each floor included four prison cells and a corridor connecting the cells, but only two of the four cells could be accessed by the users (see Figure 1, left). To ensure that the participants did not attempt to enter inaccessible cells, the corresponding doors remained closed, whereas the doors of the accessible cells opened automatically when the participants approached them. The participants travelled between floors using elevators in each end of the corridor. However, the elevators were inaccessible and the participants simply pressed the buttons next to the elevator doors to indicate that they wanted to travel to the next floor. To ensure that the participants entered all of the accessible cells, they were tasked with finding, albeit not memorizing, a four-digit code needed to open the entrance to the prison. Each digit was painted on objects (a pillow, a box, a notepad and a plate) distributed randomly in the cells (see Figure 2, left). Only one digit was presented in a single cell, and the fourth digit was always presented in the final cell of the prison.

Figure 2: A virtual prison cell with two numbered objects (left), and a virtual corridor with the CCTV camera (right).

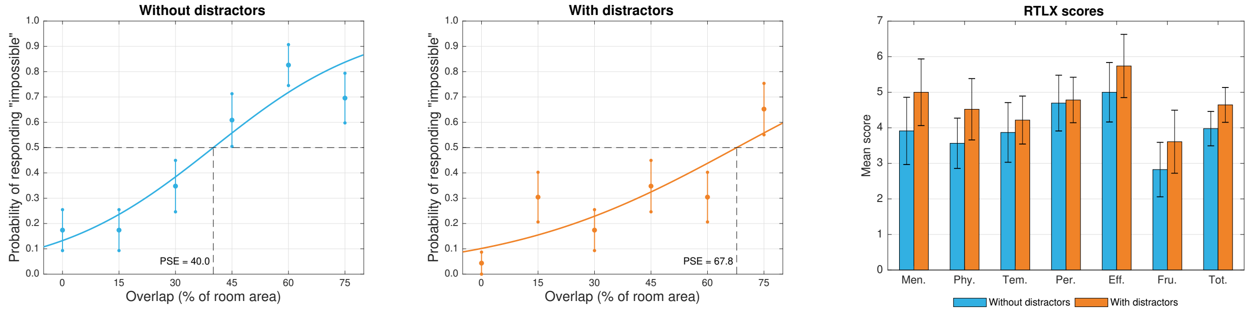


Figure 3: Left and middle: Detection results, standard errors, and fitted psychometric functions for the condition without and with distractors. The x-axes show the percentage of overlap, and the y-axes represent the probability that participants responded that the VE was ”impossible. The horizontal dotted lines show points on the curves where the participants on average responded ”impossible half of the time (i.e., random chance), and the corresponding vertical dotted line identify the point of subjective equality (PSE). Right: Mean scores of the NASA RTLX sub-scales (mental, physical, temporal, performance, effort and frustration) and mean total RTLX score for the two conditions. Error bars indicate 95% CIs.

3.4 Distractors

Because we sought to explore distractors that could be embedded in a VR game or narrative, we used diegetic distractors (i.e., distractors that are part of VE) that both presented a challenge and played a central role in the scenario. Specifically, on half of the prison's floors, the participants faced the challenge of avoiding detection from a CCTV camera placed in one end of the corridor. The camera alternately rotated leftward and rightward, and at its two extremes it was facing the inaccessible cell to its left and the accessible cell to its right. The placement of the camera is apparent from Figure 1, and Figure 2 shows the camera as seen from a user's perspective. Rotation from one extreme to the other took two seconds, and when it reached either extreme it paused for one second. Thus, the participants could only avoid by timing their walk so that it coincided with the camera facing away from the corridor. Camera movement was accompanied by a mechanical sound, indicating that it was likely to be facing down the corridor.

We believed that this challenge would introduce additional cognitive load; thus making it less likely that the participants would attend to the distance covered when moving from one cell to the next. The participants were told to avoid detection, but no penalty was imposed if they failed to avoid the camera's view. Penalties were omitted to ensure that the participants' future behavior did not change as a consequence of being detected (e.g., sounding an alarm might discourage participants from avoiding cameras on subsequent floors).

3.5 Procedure and Measures

Initially, the participants completed a questionnaire for demographic information (age, gender, and prior VR experience) and the consent form. Then they were introduced to the task and scenario. That is, they were naive to the purpose of the study, but they were informed that some VEs would include self-overlapping virtual architecture and that they had to determine which ones. Subsequently, the participants were exposed to the twelve VEs (2 conditions × 6 levels of overlap). The VEs were presented in two blocks, one corresponding to each condition, which allowed us to administer a questionnaire assessing each condition after exposure to each block of trials. Both the blocks and overlap levels were presented in randomized order. The study lasted approximately 15 minutes per participant.

To quantify the *noticeability* of self-overlapping virtual architecture, we adopted the psychophysical approach employed by Suma et al. [12] in their original work on impossible spaces. That is, our VEs involved the same six levels of overlap between virtual rooms (0%, 15%, 30%, 45%, 60%, and 75%), and after exposure to each VE, the participants performed a two-alternative forced-choice (2AFC) task, requiring them to judge whether the VE they had just visited was “possible” or “impossible.”

To gauge the *perceived task load*, we administered the NASA Raw Task Load index (RTLX) [5]. The RTLX is a common modification of the NASA task load index (TLX) [4] and includes six items asking participants rate the degree to which they experienced the following dimensions associated with task load: mental demand, physical demand, temporal demand, performance, effort, and frustration. The questionnaire included 10-point rating scales, ranging from 1 to 10, where high ratings indicated high task load. After exposure to all trials we asked the participants if the presence of the camera made the task more demanding and they were encouraged to elaborate.

4 RESULTS

Noticeability. The analysis of the data obtained from the 2AFC task was adopted from Suma et al. [12]. For each overlap level we determined the pooled probability that participants found the overlap level "impossible", and fitted separate psychometric functions for the condition with and without distractors. Figure 3 (left and middle) shows the pooled response probabilities and standard error across participants, and the fitted psychometric functions of the form $f(x) = \frac{1}{1+e^{a*x+b}}$ where a and b are real numbers. The detection thresholds associated with each psychometric function were defined as the overlap level at which the participants were equally likely to respond "possible" or "impossible" on the 2AFC task. That is, when the probability of responding "impossible" is 0.5 (chance level). As apparent from the dashed lines on Figure 3 (left and middle), the detection threshold for the condition without distractors was at a 40.0% overlap and for the condition with distractors it was at a 67.8% overlap.

Perceived task load. To compare the perceived task load, we calculated the total RTLX score for both conditions (i.e., the mean of the sub-scale ratings [4]). Figure 3 (right) summarizes the mean total RTLX scores as well as the mean scores of the sub-scales. The total RTLX scores were treated as interval data, and statistical comparison was performed using a paired-sample t-test. The total RTLX scores were normally distributed, as assessed by Shapiro-Wilk's test (p = .453). As apparent from Figure 3 (right), the scores were higher after exposure to the condition involving distractors (M=4.64, SD=1.19) compared to the condition without distractors (M=3.98, SD=1.18), a statistically significant mean difference of 0.66 (95% CI, 0.24 to 1.190), t(22) = 3.250, p = .004, d = .68. Moreover, after exposure to all conditions 20 in 23 participants explicitly stated that they found the experience more demanding when the distractors were present.

5 DISCUSSION

In this paper, we presented a study exploring if users' ability to detect overlaps between adjacent virtual rooms is impaired when distractors are presented in the corridor connecting the rooms. The results indicate that the participants were considerably less likely to detect overlaps when distractors were presented. That is, when no distractors were presented they were unable to reliably detect overlaps of up to 40%, but this threshold increased to 68% when distractors were introduced.

Furthermore, the participants reported significantly higher task load after exposure to distractors. Therefore, it seems plausible that the challenge-based distractors impinged on the participants' attentional resources and made them less likely to notice the overlapping architecture. Some participants explicitly mentioned that the presence of distractors made it harder to judge the level of overlap (e.g., *"I was so focused on avoiding it [the camera] and I was less sure about the size of the rooms"*). Nevertheless, we cannot be certain that the observed effect of distractors on noticeability can be attributed to increased task load. For example, the distractors may also have affected the participants' affective state (e.g., creating a sense of suspense or urgency), and the distractors may have increased or decreased exposure times (e.g., the participants may have moved faster or slower to avoid detection). When clarifying why they found the conditions involving distractors more demanding, some participants provided answers indicating that both the exposure time and their affective state may have been affected (e.g., *"I felt I had to hurry more"*, *"It is more time demanding when trying to avoid the camera"*, and *"It was more exciting and harder"*). Thus, future studies should explore if distractors' effect on noticability is caused by task load, other intervening variables, or a combination of these. Similarly, this points to a need for future work exploring if other types of distractors can be used to mask environmental manipulation. For example, it is relevant to explore the effects of diegetic and non-diegetic distractors and passive and interactive distractors, as has been done in relation to perspective manipulation (e.g., [2, 9]).

In their original work on impossible spaces, Suma et al. [12] found that small rooms with fixed sizes (3.7m ×7.3m) may overlap by up to 56% and larger rooms expanding to fill the tracking space (9.1m ×9.1m) may overlap by up to 31%. Our approach to impossible spaces also involved expanding the virtual rooms to fill the tracking space. However, the tracking space was considerably smaller (approx. 3m×4m), and the visual appearances and layouts of the virtual rooms differed in many respects. Hence, it is difficult to directly compare the findings. Nevertheless, it is notable that the condition devoid of distractors yielded a detection threshold of 40%, which is slightly higher than one identified by Suma et al [12]. While it is tempting to view this as an indication that smaller physical or virtual spaces may yield higher detection thresholds, it is necessary for future work to explore if this is indeed the case.

In conclusion, we feel reasonably confident that challenge-based distractors, such as the ones used in the current study, can be deployed to mask environmental manipulations and maximize the size of VEs that can be explored on foot. However, future studies are needed to determine the exact causes of the observed effect, whether the magnitude of the effect is consistent across other virtual and physical environments, and whether the effect generalizes to other types of distractors.

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