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Distance Perception and Spatial Impression in Immersive Virtual Spaces: Implications for VR and Architectural Design

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Abstract - Virtual environments immerse users in experiences that closely resemble those in physical spaces. In the process of creating a virtual environment that replicates a real-world setting, components are frequently modeled to match the actual dimensions. However, users may perceive the virtual environment differently when utilizing a head-mounted display (HMD). Consequently, this study explored the differences in spatial experience between physical space and HMD space to identify any perceptual discrepancies. Additionally, we examined flat-panel displays (DPs), which are more prevalent than HMDs for visualizing 3D models. The experiment was conducted under a personal space scenario, focusing on "perception of distance" and "evaluation of impression." Participants reported perceived distance in meters (distance perception), and rated spatial openness and object presence on a 5-point scale (impression evaluation). The results were analyzed using mean and standard deviation, along with a Holm-corrected Wilcoxon signed-rank test. The findings suggest that, irrespective of the object's position, the HMD space resulted in the shortest perceived distances and a more oppressive sensation among the three spaces. Correlation analysis revealed that perceived distance and spatial openness were evaluated independently, suggesting that the sense of oppression in VR is not solely determined by distance underestimation. However, the impression of the space did not exhibit significant differences due to the presence of the object. These results underscore the importance of considering spatial perception differences when evaluating or designing immersive virtual environments, and they may serve as useful metrics for interior arrangements, residential design, signage planning, and other applications. These findings inform the design of HMD-based visualization pipelines for immersive VR.

Keywords: Immersive virtual reality, Head-mounted display, Distance perception, Impression evaluation, View direction.

1. Introduction

Experiencing a 3D model in a virtual space has become possible in various fields. Specifically, the use of virtual spaces has been encouraged by the availability and simplicity of software for creating virtual spaces, the low cost of spatial experience devices, and advances in communication technology, among other recent developments. For example, much content exists in a wide variety of fields, such as remote surgical simulation in medicine [1], lecture rooms and blackboard displays in education [2], and shopping experience through e-commerce [3].

In recent years, high-quality, low-cost head-mounted displays (HMDs) have allowed viewers to feel as if they were in the real world. 3D models, point clouds, and photographs are displayed on HMDs, enabling an immersive spatial experience.

A virtual space is created to mimic real space and obtain the same experiences; however, a sense of discomfort has been reported [4, 5], and the perception and cognition of spatial components, such as dimensions

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and textures, may differ between real and virtual spaces [6, 7].

Therefore, this study investigates differences in perception and impression between real space and an immersive virtual space in which an HMD is used when a 3D model that mimics the dimensions and distance of a real space is created. Flat-panel displays (DPs), which are used as a general-purpose tool to visualize virtual spaces as a reference, are also considered in the analysis. In this paper, experiencing real space is referred to as “real space,” experiencing virtual space using DP is referred to as “DP space,” and experiencing virtual space by using an HMD is referred to as “HMD space.”

Previous studies of virtual space have evaluated the impression of HMD space by varying the physical quantities of the components of virtual space. For example, Llinares et al. [8] conducted a study on color temperature and memory in a classroom, and Yeom et al. [9] carried out a psychological evaluation of the view through a window, as seen from inside a room. Similarly, Jeon and Jo evaluated the impression of space by changing the audible sound environment in a city for audiovisual interactions [10]. With regard to visual perception, Ma et al. investigated comfort and performance by varying office illumination [11]. Research has also been conducted on personal space. For example, studies have been carried out on individuals’ behavior when their personal space is invaded [12], light intensity in workspaces [13], and thermal environmental systems for energy conservation [14]. Some studies have comprehensively compiled the literature on living spaces and comprehensively reviewed the comfort and adaptability of living and behavior [15].

Data for models of virtual space can be created using different approaches; for example, research is underway on a method that uses a photograph taken by a 360° camera [16] or a point cloud model that scans the space with Lidar and maintains data, such as position coordinates, color, and time [17]. Mixed reality involves methods such as real-time composition and display of 3D models in the real world [18]. Debarba et al. compared the effectiveness of such production methods [19]. Virtual spaces and models, such as building information modeling and construction information modeling, are used in all aspects of buildings, including planning, design, construction, and maintenance. Examples include computational fluid dynamic simulation for stadiums [20], simulation of human behavior [21], and on-site training [22]. Lee et al. provided additional information on this phenomenon by conducting an experiment on guidance using a system that designs optimized roles for HMD users and non-HMD users, allowing users to move through space even while walking [23]. Furthermore, Kim and Kim verified a system that uses augmented reality (AR) functions to guide the viewing route of an outdoor exhibit [24].

Other studies have revealed that components other than distance are also factors in spatial perception and investigated the perceptions of vertical projection relative to AR [25–27]. For example, Cohavi and Levy-Tzedek [28] and Han et al. [29] mentioned the possibility of cognitive training using virtual space. Han et al. also explored whether virtual content leads to health and happiness [29].

These studies have verified different components in real space or in a virtual space that mimics real space. However, they use virtual space as a substitute for real space and do not clarify the differences between the spaces. Such clarification is critical for computer graphics and vision, informing perception-aware design and evaluation of immersive visualization and rendering systems. This study makes a novel contribution to the literature by clarifying and describing differences between real space and HMD space in terms of “perceived distance” and “impression evaluation.” To examine a general-purpose personal space without limiting the purpose of room usage, a laboratory experiment was conducted with as few spatial components as possible.

This is a basic study aimed at establishing a design methodology for virtual spaces experienced through HMDs. Specifically, in this study, we envision a case in which the dimensions of spatial components in architectural and urban design are examined in an immersive virtual space; we verify whether the perceptions and impressions of real and virtual spaces are different and consider feeding perception or impressions back to each space.

First, this study examines differences in “distance” and “impression evaluation” in real space, HMD space, and DP space. Based on previous studies [30, 31], which showed that people in HMD space perceive the space as being narrower than in real space, we expected individuals to perceive distance as shorter and feel a sense of the presence of the object to be viewed. To clarify whether differences depending on the direction of the installation of objects existed, the direction of objects was varied for the study participants, and their perceptions of space were comparatively analyzed.

2. Materials and Methods

To investigate the “perception of distance” and “evaluation of impression” between real space, DP space, and HMD space, the target space, components, question items, and analysis methods were selected for an experiment conducted with 53 undergraduate and graduate students (38 male and 15 female), all majoring in architecture, aged between 18 and 23 years. Differences in responses between male and female participants are not addressed in this study, as the target space represents a general space that may be used by any person. Moreover, spaces were presented in a randomized order.

Ethical approval was waived by Ritsumeikan University. Informed consent was obtained from all participants after we explained the 12 items, elucidated the significance, purpose, and methods of the research. Participants were informed that the particulars of the research, particularly the handling of data, would be based on their voluntary consent and on the conditions and guidelines of the institution to which they belonged.

2. 1. Spatial Organization of the Experiment

For the experiment, a laboratory was built that simulated a café, office, or other setting where personal space is needed as a workspace. Specifically, one table (0.7 m long, 0.7 m wide, 0.7 m high) and two chairs (0.45 m long, 0.50 m wide, 0.45 m high) were prepared. The participants were asked to “grasp the distance” and “evaluate the impression” of a visual object in an arbitrary direction. To have the participants numerically represent the distance between a participant sitting at a table and a set of chairs, we selected a space with as few distance clues as floor or ceiling textures and pillar spacing as possible. The dimensions and layout were drawn from commercially available furniture dimensions and design reference books [32].

As a simple experimental space, two sets, each comprising a table and two chairs, were placed in a university conference room (length: 7.98 m, width: 17.66 m, height: 2.61 m); the participants were seated at one set and a dummy doll was placed at the other as an object. An experiment was then conducted to investigate personal space (Figure 1) as the set with the seated dummy doll placed at various angles on a concentric circle with a radius of 2.45 m (5 levels: 0°, 30°, 40°, 70°, and 90° from the front with the participant at the center) in random order.

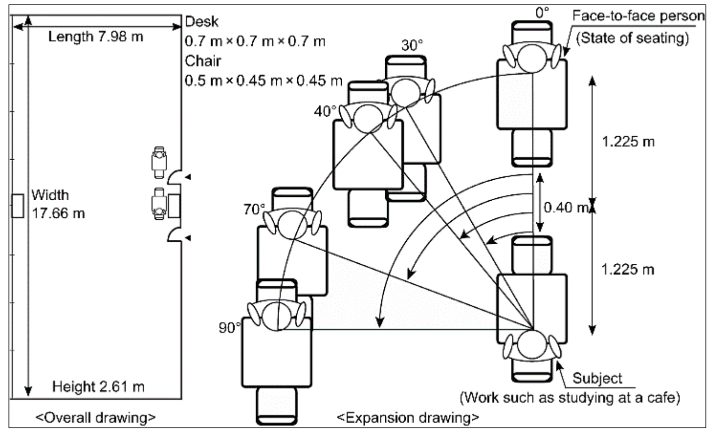

Figure 1. Plane of the experiment space. The left figure shows the entire laboratory space, and the right figure shows the positions of the participants and the objects.

2. 2. Survey Contents

Focusing on personal space in each setting, we created questions on the “perception of distance” and the “evaluation of impression” of the objects to be viewed and conducted a survey.

2. 2. 1. Distance Perception

The participants were asked to estimate the distance (in meters, up to two decimal places) from their sitting position to the installed visual object. Furthermore, participants were instructed to focus on the visual object alone without referencing the size or position of surrounding elements and to determine the distance to the dummy doll sitting at the table set.

2. 2. 2. Impression Evaluation

For the questions assessing impressions of the space, participants were asked to rate openness (1. Oppressive ⇔ 5. Open) and whether the presence of the object bothered them (1. Presence ⇔ 5. No Presence) on a 5-point scale. The participants were reminded to provide answers about their impressions of the area they could see by moving only their necks without moving their bodies from the sitting position. In addition, because of the narrow space between the eyes and the display owing to the structure of the HMD used, eyeglasses could be pushed down, altering the view; thus, people wearing eyeglasses were excluded.

2. 3. How to Create the Experience Space

The prepared experience spaces included three types: the real space described in 2.1, a DP space that mimics the real space in terms of dimensions and texture, and an HMD space.

2. 3. 1. Real Space

Except for the table set at which the participants sat and the one serving as the visual object, the interior and other spatial elements were excluded as much as possible to avoid them entering the participants' field of vision.

2. 3. 2. DP Space

The 3D model was created using modeling software (3dsMax 2017), while for rendering and display, the model was imported into a game engine (Unreal Engine 4) with texture and lighting adjusted to mimic the real space and displayed on a DP (EIZO, 27 inches, resolution 2560 × 1440). When the space was displayed, to give the participants the feeling of sitting on a chair from a first-person perspective, the camera was initially set 110 cm from the floor with a 110° field of view. In the experiment, a desk and a chair of the same height as those in the real space were prepared in front of the display, and the participants were asked to sit on the chairs and position their faces 60 cm away from the display and 20 cm from the desk; they were also instructed to adjust the height of the viewpoint in such a way that they felt as though they were sitting on a chair in the DP space. In addition, instead of pivoting, the participants could look around the space by themselves using the arrow keys "←," "↑," "↓," and "→" on the keyboard.

2. 3. 3. HMD Space

As in the DP space, modeling software and a game engine were used, and the images were displayed on an HMD (Oculus Rift, resolution: 2160 × 1200 for both eyes, 1080 × 1200 for one eye). As in the DP space, the camera was initially set at 110 cm from the floor to give the participants the feeling of sitting on a chair from a first-person perspective. In the experiment, a desk and chair were prepared at the same height as in the real space. The participants sat in front of the HMD tracking sensor and fine-tuned the chair to match their sitting height so that they felt as if they were sitting on a chair in the HMD space.

2. 4. Procedures

Each experience space differed in terms of how the space was shown and the answers were filled in (Figure 2, Figure 3). The following procedure was used for each experience space.

2. 4. 1. Real Space

First, the participants were asked to sit on a chair of a table set. They were then told that the experiment was designed as a work setting in a café or laboratory. Next, the participants read notes and questions in the survey form in Subsection 2.2, reviewed the questions,

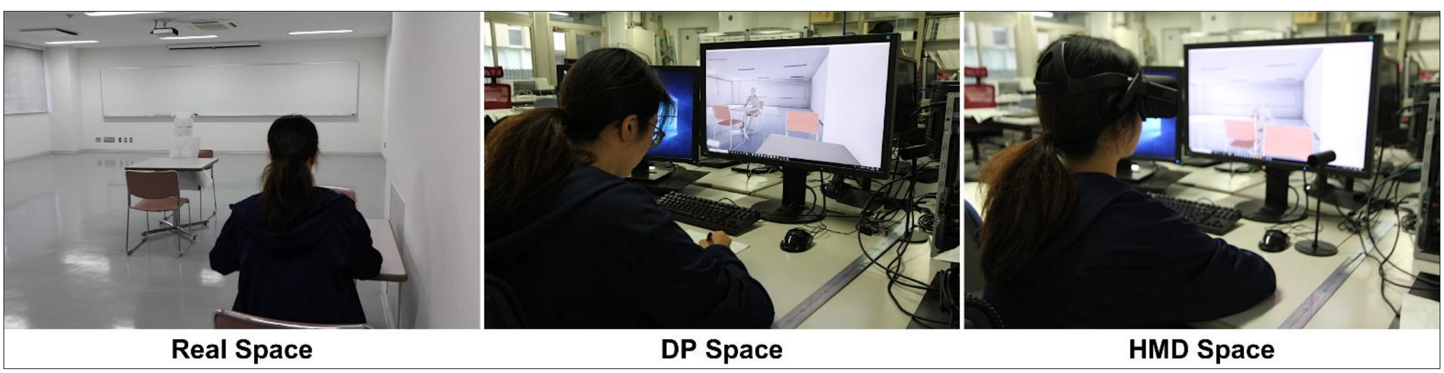

Figure 2. State of experiment. The images show the participants experiencing and responding to each space.

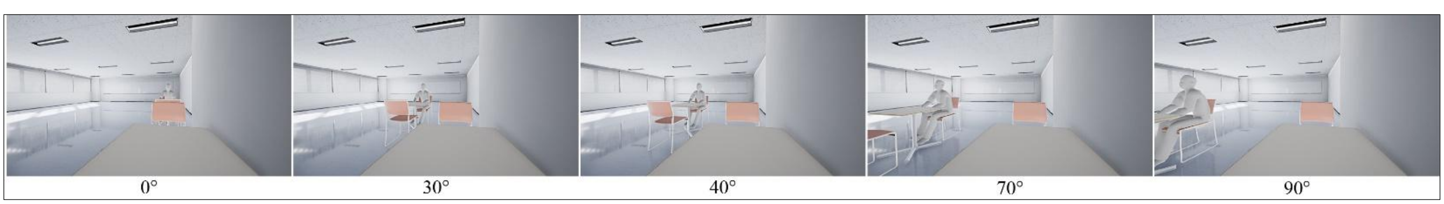

Figure 3. 3D representation of real-time rendering. Real-time rendering is used in DP space and HMD space. The images depict what the participants see when they look straight ahead while seated at each level.

and then directly filled in their answers to the questionnaire at each level. For distance perception, respondents were asked to write "how far (in meters)" they perceived from their eyes to the object.

2. 4. 2. DP Space

First, the participants were asked to sit in front of the display, and their viewpoint was adjusted. Subsequently, they were told to assume the same scenario as in the real space that the experiment was designed as a work setting in a café or laboratory. Next, the participants read the notes and questions in the survey form in Subsection 2.2., reviewed those questions, and then directly filled in their answers at each level. As the camera was set at the first-person viewpoint in the DP space, the participants were asked to specify the distance between the camera viewpoint (eye position) and the object.

2. 4. 3. HMD Space

First, the participants were asked to put on the HMD and adjust their position to match the viewpoint. Next, they were told to assume the same scenarios as in the real space—that the experiment was designed as a work setting in a café or laboratory. The participants then read the notes and questions in the survey form in Subsection 2.2, reviewed the questions, and directly filled in their answers at each level. However, the participants were not allowed to directly fill in the answer sheet while wearing the HMD, and the experimenter filled in the numerical values on the answer sheet on their behalf.

2. 5. Data Analysis

The analysis and discussion were conducted on a question-by-question basis. First, the average and standard deviation of the response values were calculated to provide an overview of the overall trend and investigate whether any variation or bias was present in the data from the survey results. Next, we used the Wilcoxon signed-rank test with Holm correction to determine whether there was a significant difference in the effect size and p-value. This was done to determine whether a difference in spatial experience existed. The experiments were one-at-a-time responses to spatial experience and installation level, and the analysis of the responses was conducted through a within-subject comparison. Furthermore, to investigate the relationship between the physical perception of distance and the psychological impression of the space,

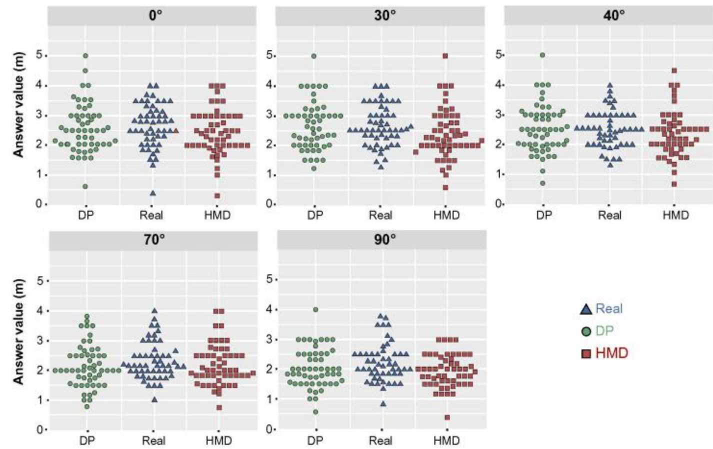

Figure 4. Answer values of angle levels by experience spaces (perception of distance). The figure is a plot of the response values when asked about the distance to the object being viewed.

Table 1. Average/standard deviation (distance perception).

		Real	DP	HMD
0°	Ave.	2.660	2.534	2.458
	SD	0.732	0.816	0.753
30°	Ave.	2.626	2.627	2.400
	SD	0.665	0.804	0.783
40°	Ave.	2.527	2.515	2.347
	SD	0.612	0.812	0.758
70°	Ave.	2.326	2.164	2.164
	SD	0.613	0.700	0.675
90°	Ave.	2.233	1.987	1.958
	SD	0.629	0.629	0.525
Average of all levels	Ave.	2.475	2.365	2.266
	SD	0.673	0.795	0.729

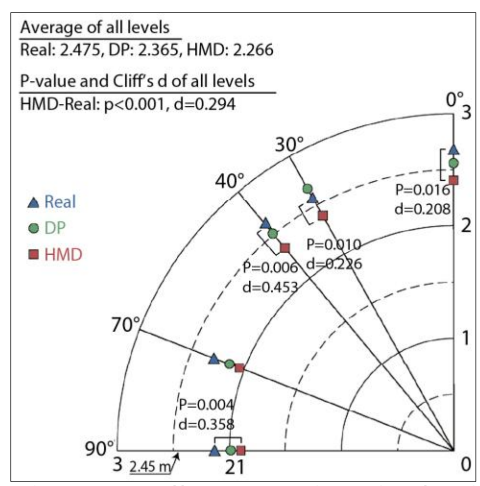

Figure 5. Average, effect size, and p-value for all levels (distance perception). The figure plots the average values for each level. In the upper left corner, the average of all levels and the effect sizes and p-values of the test results for real space and HMD space are shown.

we calculated Spearman's rank correlation coefficients between the perceived distance values and the openness ratings for each experience space.

3. Results

This section describes the results of the statistical analyses conducted for each question.

3. 1. Distance Perception

Figure 4 shows a plot of the response values for real space, DP space, and HMD space at five levels. Table 1 shows average values and standard deviations.

From Figure 4 and Table 1, average values for all levels (using all values without level distinction) were 2.475 m for real space, 2.365 m for DP space, and 2.266 m for HMD space, with HMD space having the smallest value. HMD space was perceived as the shortest distance at each level. At 30°, the values for real space and DP space were reversed, and the trend with level change in the three types of spaces was one of perceiving shorter distances as the angle increase.

Next, on examining real space and HMD space in Figure 5, we found that a multiple comparison test for all levels showed a significant difference between the two groups ($p < 0.001$, Cliff's d = 0.294). Therefore, multiple comparison tests were conducted for each level, and significant differences were found between the two groups except for 70° (0°: $p = 0.016$, Cliff's d = 0.208; 30°: $p = 0.010$, Cliff's d = 0.226; 40°: $p = 0.006$, Cliff's d = 0.453; 90°: $p = 0.004$, Cliff's d = 0.358).

Considering the above information, descriptive and inferential statistics show that the distance perceived in HMD space is significantly shorter than in real space.

3. 2. Openness of Space

Figure 6 and 7 and Table 2 present responses to the question "Do you feel openness in the space?" As for Subsection 3.1, the figures show response values, standard deviations, and results of multiple comparison tests.

Based on Figure 6 and Table 2, the average values for all levels were 3.517 for real space, 3.045 for DP space, and 3.185 for HMD space, indicating smaller response values for HMD space than for real space at each level. DP space had the smallest values at 0° and 30°, while real space had the smallest values at 40°, 70°, and 90°. The trend with changing levels of the three types of space corresponded to response values increasing as the angle increased.

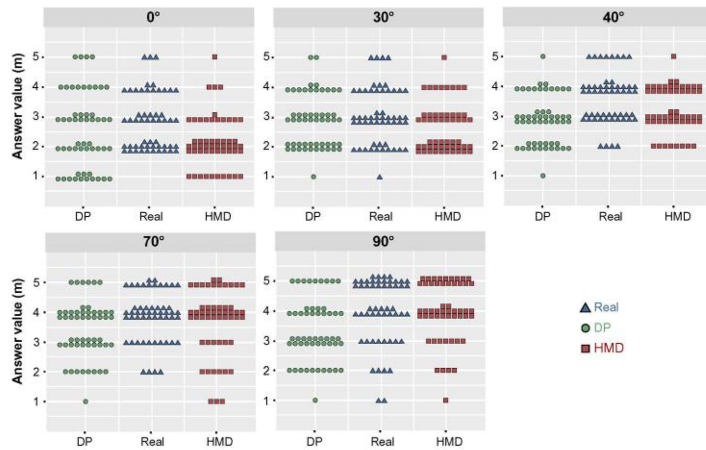

Figure 6. Answer values of angle levels by experience spaces (openness of space). The above is a plot of the response values when asked to rate the Oppressiveness/Openness to the object.

Table 2: Average/standard deviation (openness of space).

		Real	DP	HMD
0°	Ave.	2.906	2.585	2.189
	SD	0.937	1.235	0.870
30°	Ave.	3.113	2.887	2.698
	SD	0.925	0.904	0.791
40°	Ave.	3.642	2.925	3.302
	SD	0.826	0.821	0.742
70°	Ave.	3.887	3.453	3.717
	SD	0.839	0.943	1.105
90°	Ave.	4.038	3.377	4.019
	SD	1.115	1.032	0.981
Average of all levels	Ave.	3.517	3.045	3.185
	SD	1.032	1.049	1.126

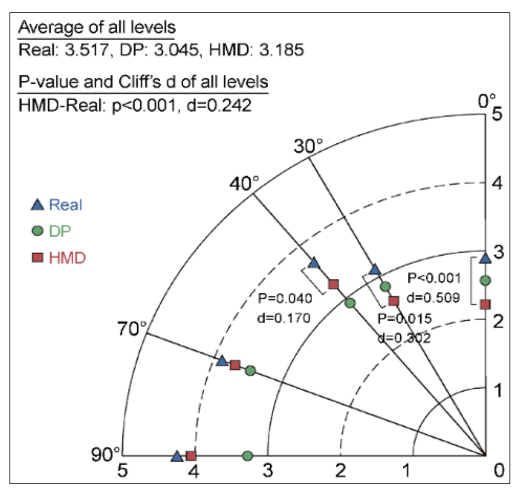

Figure 7. Average, effect size, and p-value for all levels (openness of space). The figure plots the average values for each level. In the upper left corner, the average of all levels and the effect sizes and p-values of the test results for real space and HMD space are shown.

Next, looking at real space and HMD space in Figure 7, a multiple comparison test for all levels showed a significant difference between the two groups ($p < 0.001$, Cliff's $d = 0.242$). Therefore, multiple comparison tests were conducted for each level, and significant differences were found between the two groups at the 0°, 30°, and 40° levels (0°: $p < 0.001$, Cliff's $d = 0.509$, 30°: $p = 0.015$, Cliff's $d = 0.302$, 40°: $p = 0.040$, Cliff's $d = 0.170$).

From the above information, the descriptive statistics showed that HMD space tended to be less open than real space in general, but the inferential statistics demonstrated that HMD space was less open only in the oblique direction (0 to 40°) from the front.

3. 3. Presence of the Object

Figure 8 and 9 and Table 3 present responses to the question, "Are you concerned about the presence of the object you are viewing?" As for Subsections 3.1 and 3.2, the figures show response values, standard deviations, and the results of multiple comparison tests.

Figure 8 and Table 3 show that the average values for all levels were 3.170 for real space, 2.709 for DP space, and 3.060 for HMD space, indicating that HMD space had a smaller response value than real space. However, when examining each level, we found that HMD space showed a larger response value than real space at 70° and 90°, real space > DP space > HMD space at 0°, real space > HMD space > DP space at 30° and 40°, and HMD space > real space > DP space at 70° and 90°, with a larger or smaller value as the angle changed. A common trend with the changing levels of the three types of spaces corresponded to response values increasing as the angle increased.

Next, on examining real space and HMD space in Figure 9, we found that multiple comparison tests for all levels showed no significant difference between the two groups ($p = 0.221$, Cliff's $d = 0.038$). Furthermore, multiple comparison tests for each level showed no clear significant differences.

The above analysis based on the descriptive statistics showed that HMD space tended to be more perceptive than real space in the oblique direction from the front (0 to 40°) and less perceptive than real space from the oblique direction to the side (70 to 90°) in terms of the presence of the object being viewed. However, it is difficult to say whether there was a clear difference between HMD space and real space, as no significant difference was observed from the estimated statistics.

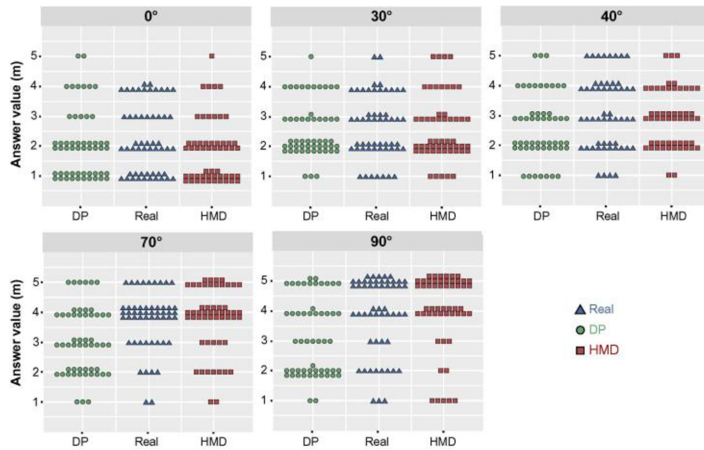

Figure 8. Answer values of angle levels by experience spaces (presence of the object). The following is a plot of the response values when asked to rate Presence/No Presence of the object being viewed on a 5-point scale.

Table 3: Average/standard deviation (presence of the object).

		Real	DP	HMD
0°	Ave.	2.302	2.057	1.887
	SD	1.142	1.123	1.003
30°	Ave.	2.698	2.585	2.623
	SD	1.074	0.920	1.068
40°	Ave.	3.170	2.642	2.925
	SD	1.193	1.083	0.968
70°	Ave.	3.755	3.075	3.792
	SD	0.950	1.113	1.088
90°	Ave.	3.925	3.189	4.075
	SD	1.286	1.275	1.242
Average of all levels	Ave.	3.170	2.709	3.060
	SD	1.291	1.179	1.339

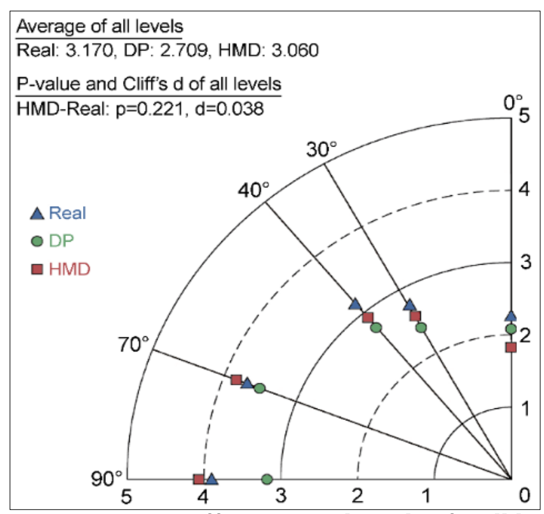

Figure 9. Average, effect size, and p-value for all levels (presence of the object). The figure plots the average values for each level in the presence of the objects. In the upper left corner, the average of all levels and the effect sizes and p-values of the test results for real space and HMD space are shown.

3. 4. Relationship between Distance and Openness

To investigate whether the perceptual compression of distance directly influences the emotional evaluation of the space, we analyzed the correlation between perceived distance and openness ratings using Spearman's rank correlation coefficient. The analysis was performed on the entire dataset ($n = 265$) for each space.

The results showed no significant correlation in the HMD space ($\rho = -0.042$, $p = 0.498$). Similarly, no significant correlations were found in the Real space ($\rho = -0.111$, $p = 0.071$) or the DP space ($\rho = 0.072$, $p = 0.241$). Although both perceived distance and openness varied systematically with the angle of the object (as observed in the comparison of means), the lack of correlation at the individual trial level suggests that these two factors are evaluated independently.

4. Discussion

4. 1. Interpretation of Spatial Perception and Impression

Regarding the overall trends of the "perception of distance" and "sense of openness of space," HMD space was perceived as being shorter than real space, as hypothesized, and a sense of oppression was felt by the participants. This is consistent with the results of our previous study, in which partitions were placed at three locations surrounding them, and the distance was varied in a concentric manner [30, 31]. However, there was no significant difference in the "presence of the object." When examining the average values for all levels, we found that HMD space tended to be more perceptible than real space; it was more perceptible at 0°, 30°, and 40° and less perceptible at 70° and 90°, but there were no significant differences at any level. This could be because the dummy dolls used as visual objects did not change the direction of their faces or move and because they were oriented in the same direction regardless of the change in level.

As the angle increased, the "perception of distance" became shorter, and the "sense of openness of space" and the "presence of the object being viewed" tended to increase. Therefore, it can be inferred that the participants judged the distance to the object itself in terms of perception, while they evaluated the space of the entire field of view in terms of impression.

Furthermore, the correlation analysis revealed that perceived distance and the sense of openness are not statistically linked at the individual trial level. This implies that the "oppressive sensation" reported in HMDs is not solely a product of underestimating distances to specific objects. Instead, it suggests that spatial perception (distance) and spatial impression (openness) are governed by different cognitive mechanisms, with the latter likely being more influenced by field-of-view limitations or the overall immersive nature of the device.

4. 2. Practical Implications for VR and Architectural Design

Based on the findings, we provide the following recommendations for VR developers and architects:

1. Compensation for Spatial Compression: Architects using VR for interior design reviews should account for the consistent underestimation of distance, particularly in the frontal direction (0°). To prevent clients from perceiving the virtual space as smaller or more oppressive than the actual design, it may be effective to slightly scale up the 3D model or adjust the viewing parameters to simulate a more realistic sense of spaciousness.
2. Layout Considerations: The feeling of oppression is most significant when objects are placed directly in front or at oblique angles up to 40°. For VR-based signage planning or workspace design, critical visual elements should be positioned with careful consideration of this "oppression zone." Designers might need to ensure greater clearance distance in VR compared to real-world standards to maintain a comfortable spatial impression.

5. Conclusion

This study examined how perceived distance and spatial impression differ among real space, HMD space, and DP space in a simplified personal space setting. Results showed that distances were consistently underestimated in HMD space compared to real space, with statistically significant differences across all object directions ($p < 0.05$). The largest underestimation occurred when the object was positioned directly in front (0°), suggesting a direction-dependent compression effect in immersive VR. Spatial openness was rated lower in HMD space, particularly at oblique angles (0° – 40°), where significant differences from real space were observed. These trends indicate immersive environments can distort spatial perception due to altered depth cues, field of view limitations, and display characteristics inherent to HMDs.

The observed distance underestimation in HMD space aligns with recent findings by Kelly et al. [33, 34]. While these studies focused on device-related factors such as resolution and field of view, the present study explores how object placement direction (0° – 90°) affects both distance perception and spatial impression, offering novel insights into perceptual dynamics and design implications for immersive spaces.

The presence of the object did not significantly differ among the three spaces. However, as object angle increased, participants perceived it as closer, while rating the environment more open and the object less present. These patterns suggest distance perception focuses on the object, whereas spatial impression is influenced by field of view and openness. These findings highlight that spatial perception and spatial impression are governed by different cognitive mechanisms, and their sensitivity to directional placement should be carefully considered in immersive environment design. Future work should develop perception- and spatial-impression-aware calibration methods and standardized evaluation protocols for immersive visualization and rendering.

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