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Differences in Distance Perception and Spatial Impression in Immersive Virtual Space: Effects of Object Direction

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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 employed a 5-point scale to rate the perceived distance to an object (distance perception) and to evaluate their impression of the space's openness and the object's presence (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. 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.

Keywords**:** immersive virtual reality; virtual environment; distance perception; impression evaluation; view direction; head-mounted display

1. Introduction

Immersive 3D virtual environments are increasingly used across disciplines, enabled by accessible software, cost-effective head-mounted displays (HMDs), and advanced communication technologies. However, virtual spaces often fail to accurately replicate reality, as users report discomfort and discrepancies in spatial perceptions, such as dimensions and texture, compared to real environments. This study examines differences in perception between a physical space and an immersive HMD-based virtual replica, using a planar display (DP) version as a baseline reference.

Studies have investigated factors influencing user experience in virtual reality (VR) and developed various VR content creation methods. Some research has explored augmented reality (AR)-specific perceptual factors and cognitive benefits of virtual environments. However, these efforts have treated virtual environments as substitutes for real space without identifying key perceptual differences. To address this gap, this study examines differences between real space and HMD-based virtual space in "perceived distance" and "impression." A controlled experiment was conducted in a simple room with minimal furnishings to focus on personal space, providing insights for designing immersive architectural spaces.

We compare perceived distance and impression across real, HMD, and DP conditions. Given evidence that HMD spaces are perceived as narrower than real ones [1, 2], we hypothesized that distances would be perceived shorter and object presence more pronounced in VR. To obtain findings on whether directional arrangement affects these perceptual differences, we varied the object's direction relative to subjects.

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 posted 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 possible. The dimensions and layout were drawn from commercially available furniture dimensions and design reference books [3].

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 (Fig. 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.

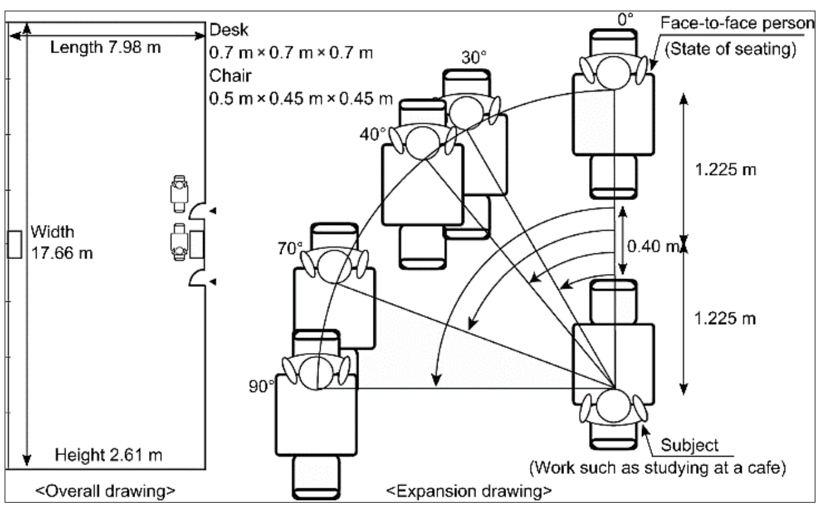

Fig. 1: Plane of the experiment space. The left figure shows the entire laboratory space, and the right figure shows the positions of the participants and the objects.

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 provide information on 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 (Fig. 2).

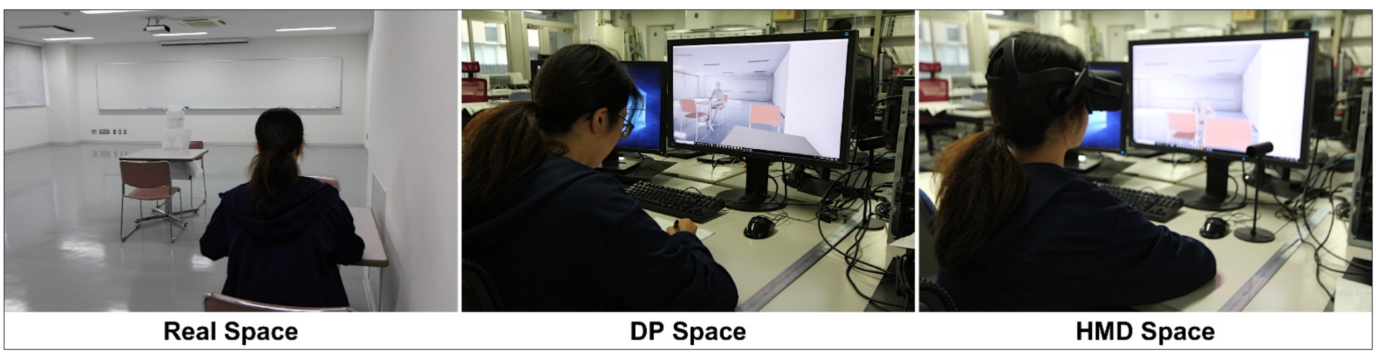

Fig. 2: State of experiment. The images show the participants experiencing and responding to each space.

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 HMD 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 (Fig. 3). The following procedure was used for each experience space.

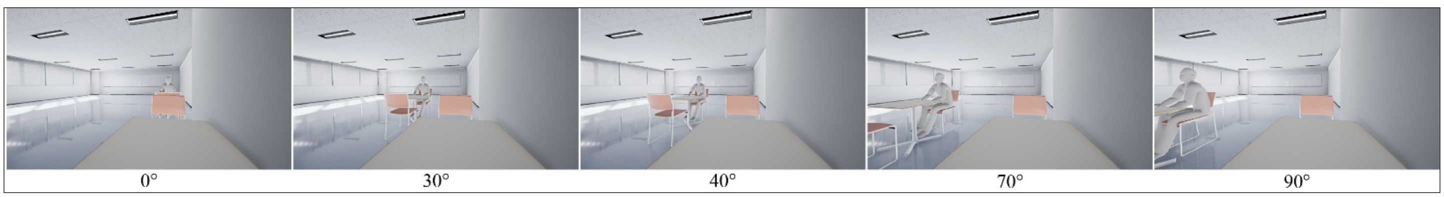

Fig. 3: 3D representation of real-time rendering. Real-time rendering is used in DP space and HMD space. The images depict what the participants see when they look straight ahead while seated at each level.

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, 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.

3. Results and Discussion

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

3.1. Distance Perception

Table 1 shows averages and standard deviations of the participants' responses after they were asked about the distance to the object they viewed. Values are rounded to the third decimal place. The average values for all levels (using all values without level distinction) were 2.426 m for real space, 2.374 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 DP space and HMD space were reversed, and the trend with level change in the three types of spaces was one of perceiving shorter distances as the angle increased.

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.	2.426	2.374	2.266
	SD	0.668	0.815	0.745

Next, on examining real space and HMD space in Fig. 4 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.

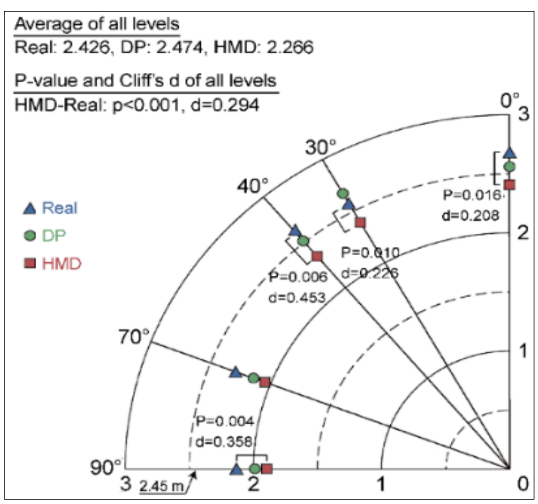

Fig. 4: Average, effect size, and p-value for all levels (distance perception). The figure plots the average values of real space, DP space, and HMD space for each level in distance perception. In the upper left corner, the average of all levels and the effect sizes and p-values of the test results for real space and HMD space are shown.

3.2. Openness of Space

Table 2 shows averages and standard deviations of the participants' responses upon being asked to rate the Oppressiveness/Openness to the object they viewed on a 5-point scale. Values are rounded to the third decimal place. 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.

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

		Real	DP	HMD
0°	Ave.	2.906	2.585	2.189
	SD	0.937	1.235	0.879
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

Next, looking at real space and HMD space in Fig. 5, 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.

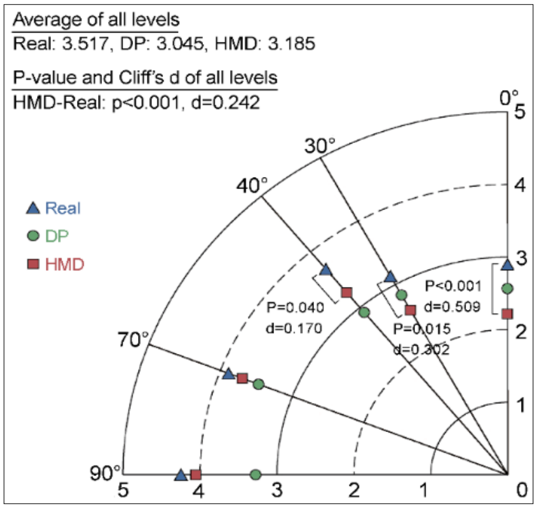

Fig. 5: Average, effect size, and *p*-value for all levels (openness of space). The figure plots the average values of real space, DP space, and HMD space for each level in the openness of space. In the upper left corner, the average of all levels and the effect sizes and *p* -values of the test results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

3.3. Presence of the Object

Table 3 shows averages and standard deviations of the participants' responses upon being asked to rate the Presence/No Presence of the object they viewed on a 5-point scale. Values are rounded to the third decimal place. 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 did real space. However, when examining each level, we found that HMD space showed a larger response value than real space at 70° and 90°, HMD space > DP space > real space at 0°, HMD space > real space > DP space at 30° and 40°, and real space > HMD 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.

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

Next, on examining real space and HMD space in Fig. 6, 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.

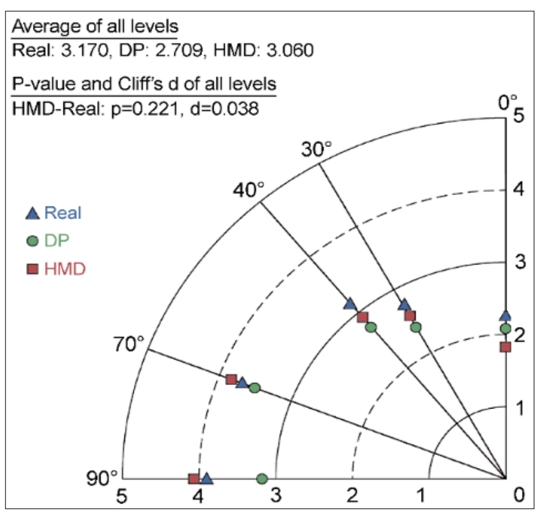

Fig. 6: Average, effect size, and p-value for all levels (presence of the object). The figure plots the average values of real space, DP space, and HMD space for each level in the presence of the objects. In the upper left corner, the average of all levels and the effect sizes and p-values of the test results for real space and HMD space are shown.

4. 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 distance was 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. [4, 5]. 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.

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