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Spatial Perception Imperatives in Virtual Environments: Understanding the Impacts of View Usage Patterns on Spatial Design Decisions in Virtual Reality Systems

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Abstract: Spatial perception in virtual reality systems relies on a number of variables, including how users explore, observe and perceive the spatial factors of a virtual environment. In virtual reality systems, users can assume different types of views for spatial decision-making about the sizes and scales of and relationships among virtual spaces. This research explored the role of view usage patterns in spatial cognition and decision-making in a fully immersive virtual reality system and monitor-based virtual reality system. The focus of study was the impact of using the eye-level view as the only view type in a fully immersive virtual reality system on actual and perceived view usage patterns in a monitor-based virtual reality system. In addition, users' spatial decision-making results were compared with regards to system usage sequence and view type. Quantitative and qualitative data, descriptive and inferential statistical comparisons, and testing of both systems were used to determine the participants' performances concerning view usage patterns and the design outcomes. The results showed a moderate association between the view type utilized for spatial perception in a monitor-based virtual reality system and variations in system usage sequence. In addition, for both systems, variations in system usage sequence, space type, and other characteristics all affected the strength of the linear regressions of the sizes and scales of the design outcomes.

Keywords: virtual reality; fully immersive virtual environment; spatial cognition; systems usage sequence; design decision; view usage patterns

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1. Introduction

This study explored user spatial perception and cognition in two virtual reality (VR) systems with regards to system usage sequence and view use patterns. The goal was to determine how the spatial perception gained by utilizing the eye-level view and resulting spatial decision-making in a fully immersive virtual reality interactive environment (IVRIE) impacted view usage patterns and spatial decision-making in a monitor-based VR environment. Monitor-based VR environments often take the form of desktop systems. In the present research, the desktop-based VR system is referred to as either DT or DT system. This study is comprised of five sections. Section 1 serves as an introduction and includes the research objectives and background of the work. Section 2 presents the methodological framework and methods employed. Section 3 describes the tests applied, analyses conducted, and results obtained. In Section 4, the findings of the study are interpreted and discussed. Section 5 presents the conclusions and future vision.

1.1. Research Statement and Objectives

The objectives of this research focused on precisely defining the impact of eye-level view utilization and the perception of spatial factors on a human scale in IVRIE on user view usage patterns and spatial perception in a DT system, and recognizing differences in user spatial decisions between the two systems studied that resulted from system usage sequence variations and the views employed. The assumption was that if the system usage sequence was IVRIE and then DT, spatial perception within IVRIE would impact the spatial awareness and view usage patterns in the DT system for spatial decision-making (compared with the opposite system usage sequence). In addition, variations in system usage sequence and types of view utilized in both systems would result in variations in users' spatial decision-making and the production of design outcomes from each system. The research questions were as follows:

- Does the perception and cognition of spatial factors of virtual spaces perceived through an eye-level view in IVRIE result in specific patterns of view utilization that are typical for individuals using a DT system?
- Does using the eye-level view in IVRIE for spatial perception enhance awareness of the specific patterns of view utilized for spatial decision-making in a DT system?
- Does use of the eye-level view in IVRIE and available view types in a DT system result in different spatial decision-making in each and variations in the design outcomes produced when system usage sequence is varied?

This research was based on four hypotheses. First, the nature of spatial perception in IVRIE when utilizing the eye-level view and cognition of spatial factors impacts the view usage patterns for spatial perception in a DT system. Second, using the eye-level view in IVRIE for space-related decisions positively impacts user awareness regarding spatial performance in a DT system when the order of system utilization is first IVRIE and then DT. Third, since users utilize the eye-level view and experience a sense of full immersion and perceive spatial factors at eye level in IVRIE, this type of view eliminates the need for an overhead view (including the plan and birds'-eye views) for spatial decision-making. Fourth, spatial decision-making in IVRIE when utilizing the eye-level view results in the production of different design results as reflected in the sizes and scales of designed spaces, compared with spatial decision-making in a DT system and utilizing both the eye-level and overhead views.

1.2. Research Background

Interactive 3D models are a new generation of model introduced by VR utilization in architectural design. These 3D interactive models in VR can offer higher levels of visual complexity. Their interactivity allows users to walk within and around virtual spaces, manipulate them spatially, and observe their spatial changes from various viewpoints, including an eye-level viewpoint [1–3]. In 3D interactive models, and specifically those that are complex and large in scale, being fully immersed in a virtual environment plays a critical role in a user's intuitive perception of many aspects of a scene [4]. VR is an environment that enhances spatial perception; thus, understanding virtual models' complexity and spatial relationships can be easy for VR users [5,6]. Such users tend to perceive the fit of interface elements more accurately, and their estimation of model dimensions has a lower rate of relative error compared with those using a desktop interface [7,8].

The concept of presence in a virtual environment is defined by the roles of major variables, such as the sense of immersion, level of interaction, and control factors. Control factors identify a user's power to complete a task by interacting with the virtual environment. It is assumed that users who perceive themselves as of having more control over task completion in a virtual environment experience higher levels of presence [9]. "Although various non-immersive three-dimensional (3D) systems such as holograms and 3D films can transfer the sense of depth across part of a visual field to an observer, immersive visual displays like head-mounted devices are able to create a sense of presence by offering a visual environment that moves with the viewer" [10].Visual awareness is a factor in visual perception that facilitates user understanding of spatial relationships and elements in virtual environments such as proximity, connection, extension, similarity, shape, and form [11].

Users within a virtual environment can form a cognition map, which is an image of the spatial structure of the environment and all visible spatial relationships. Cognitive maps enable users to recall relative distances, directions, and other spatial characteristics of environments such as depth and form [12,13]. Based on these cognitive maps, users collect information regarding their environment, manipulate that information, establish a plan, and transform that plan into behavioral activities within the virtual environment [14].

The interactivity level of a virtual environment depends on one's experience of a sense of freedom that is based on navigating within that environment and manipulating the surroundings and objects existing within it [1,15]. In virtual environments, the combination of visual perception, spatial cognition, and interaction immerses users in a continuous problem-solving process that forces them to use information about the spatial factors made available within the environment [16,17].

Navigation and way-finding are the result of observers' viewpoints changing and their acquisition of information through their senses about the spatial arrangement of the environment [18–21]. Way-finding cues can improve the perceived quality of the navigation experience within a virtual environment [22,23]. Some studies have found that haptic and audio cues can improve a visually impaired user's ability to navigate within a virtual environment, since these cues enhance spatial awareness and memory [24]. Labeling is another factor that can lead users to engage in additional exploration and enjoy a 3D spatial awareness that focuses their attention on notable features, thus facilitating their navigation through the virtual environment [25–27].

Research has found that among the various virtual environments available, users feel that fully immersive VR settings are more natural and intuitive for exploring the surroundings and collecting spatial data [4,28,29]. The possible viewpoints a user can employ for spatial cognition in a virtual environment are either egocentric or exocentric. Egocentric viewpoints can be used to perceive surroundings when users are in a scenario, such as being inside a room cube. Exocentric viewpoints are used to observe a scenario from outside or above, such as when looking at several cubes from a vertical or horizontal distance [20,30]. Exocentric viewpoints in both immersive VR and monitor-based virtual environments include the plan view, birds'-eye view, and any other view that transfers spatial data to the user while they are observing a scene or space from above in either a straight or angled vertical direction [31–33]. Egocentric viewpoints include the eye-level view, section view, and all viewpoints in which a user can observe their surroundings at the average height of the human body [34]. In egocentric viewsheds, the direction between the observer's eye and the object being perceived is completely horizontal and can cover scenes, spaces, and objects across both short and long distances [35].

Having access to both viewpoint categories in a VR system may provide higher levels of spatial perception and presence for users. The eye-level view is an egocentric viewpoint crucial for human perception when scaling sizes and heights and estimating egocentric distances [36–38]. In IVRIE, users feel fully immersed and can experience a sense of navigation and direct interaction with the environment, and design objects on a human body scale with an instant 360° viewshed [16,39]. When users browse their surroundings and estimate, analyze, and perceive the spatial factors of the virtual environment that they are within, the use of viewpoints on a human scale shapes their spatial perception such that it resembles what they experience in the real world [40]. In monitor-based VR, the actual size of an object does not have any relationship to the size of the screen being used. There is an indirect interaction between the user and virtual space since users rely on touching a control device to control the scene and change view positions [41,42].

The functionality of the human scale viewpoint for enhancing a user's spatial presence may have critically different impacts in a fully immersive virtual environment versus a monitor-based VR system [43,44]. Users can access various types of egocentric and exocentric viewpoints in a VR system, though the characteristics of these environments may vary the way that viewpoint categories transfer spatial data to the user [45,46]. In monitor-based VR, users depend on interfaces such as a mouse to change the viewshed from egocentric to exocentric and vice versa, experiencing different view angles within each. In fully immersive VR systems, users use controllers to change their viewpoint, and with head movement can experience various viewsheds [47–49].

Utilization of the eye-level view enables cognitive experiences on a human scale while observing the surroundings and estimating the spatial factors of a virtual environment [50,51]. In fully immersive VR systems, eye-level view utilization, along with the sense of full immersion and ability to interact with virtual objects, enhances the user's spatial cognition, impacts engagement with the design, and results in an awareness of the spatial characteristics of design decisions [52]. The eye-level view can positively impact spatial decision-making in fully immersive virtual environments, and the findings of research on this topic have shown it to be a critical variable in reducing extreme spatial decisions that often result in inconsistent design and production results [8].

Although research on fully immersive and non-immersive virtual reality systems has increased in recent years, the number of comparative mixed-methods research studies regarding the impacts of these systems' features on user performance and decision-making is low. Studies comparing the functionality of virtual environments for spatial presence and perception when the provider system differs and users utilize these systems together are even scarcer [53]. Thus, while in VR systems spatial presence and types of interaction with design objects vary, determining the role of view types utilized is a critical variable affecting the transfer of spatial data to a user. While users are exploring a virtual environment, perceiving spatial factors, and making spatial decisions, their view usage patterns can be impacted by various factors, such as using different VR systems for spatial design and variations in system usage sequence. Only by understanding what types of views are available in VR systems and to what extent they enhance users' spatial perception and awareness and result in more (or less) logical spatial decisions can the actual efficiency of this feature be identified and the extent to which it benefits users' experience and performance be evaluated.

2. Materials and Methods

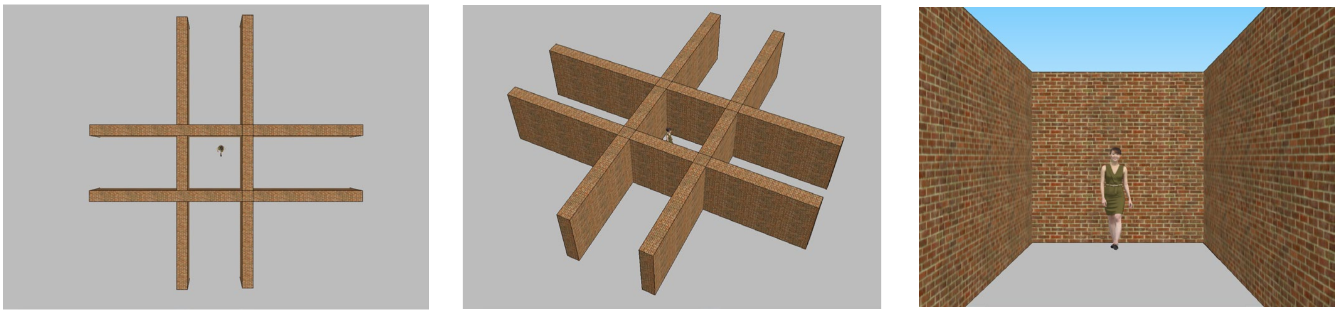
The methodological framework chosen for this study was a sequential mixed-methods research framework. Two phases of the research were designed to collect quantitative and qualitative data and perform analyses. In the first phase, two separate sets of quantitative data were allocated. These included participants' view usage patterns when utilizing a DT system and their design results after using both systems. In the second phase, quantitative data regarding user performance in the DT system when employing a specific view pattern were used to analyze the qualitative data collected. In addition, in this phase, the data concerning system usage sequence variations that were collected from the design outcomes of the sample population after utilizing both systems were analyzed separately.

The sample population was divided into two groups, each following an opposite system usage sequence. The participants in the first group used the DT system first and IVRIE second. The other group utilized the opposite system sequence. Each participant completed the experiment by redesigning the virtual spaces in the first system and then completing the same task in the second. Then, all participants answered questions in a view usage questionnaire (VUQ). Redesigning the spaces based on the utilization of experiential/spatial guidelines meant that participants manipulated the existing structures of a series of open-ended corridors and fully enclosed spaces, pulling or pushing walls and changing their primary sizes. In the open-ended corridors, when participants pushed or pulled either one or both walls, they were able to redesign the space to have a new width that was different from the initial width of the corridor (10 ft.). Similarly, by moving each or all of the walls of the fully enclosed spaces, participants redesigned those spaces to be of a new size that was different from the initial dimensions of the enclosed space (100 sq. ft.). Participants could not change wall height or surface texture. When participants utilized the DT system (either as the first or second system), their view usage patterns were documented and recorded for later inspection and rechecking.

Each participant used two spatial/experiential guidelines for redesigning the models. One guideline was designated for redesigning the enclosed spaces, and the other for the two corridor spaces. Participants used these two guidelines when operating both systems.

2.1. Experiment Design

The experiments were conducted in four steps. In Step 1, the systems and software were tested and virtual models created. SketchUp® (Trimble Inc., Sunnyvale, CA, USA) and VR Sketch® were selected for the DT system and IVRIE, respectively. The screen recorder Camtasia® (TechSmith Corp., Okemos, MI, USA) was used to record participants' performances when utilizing SketchUp® and the DT system. The DT system was a high-performance computer equipped with a 32″ monitor and mouse. Participants used the system to manipulate the models, change viewpoints, and shift between different view types. In IVRIE, participants used an Oculus Quest 2 device set. A customized version of the VR Sketch® program enabled a control menu of touch controllers to set the eye-level view as the only type available when participants were wearing the headset and working in IVRIE. When using the SketchUp® software and DT system, participants were able to change viewpoints, rotating and observing the models from different angles by scrolling the scroll wheel on the mouse and clicking on areas. Figure 1 presents the three view types that each participant utilized for manipulating and redesigning the models when working with SketchUp® and the DT system.



(**a**) (**b**) (**c**)

Figure 1. Three types of views utilized by participants for spatial decision-making when using the DT system: (**a**) plan, (**b**) birds'-eye, and (**c**) eye-level.

Regardless of the system usage sequence, participants completed the DT section of the experiment by sitting at a desk and the IVRIE section by putting on a headset and walking around the experiment room. Participants were divided into two groups, each with opposite system usage sequences. One group used the DT system first and IVRIE second, while the other utilized the opposite system sequence. The opposite system usage sequence was tested to identify its impact on view usage patterns in the DT system when that system was used first and all view types were available, or as the second system (after IVRIE) and using only the eye-level view for spatial decision-making. Figure 2 illustrates the experiment setup and view types used in each system to redesign the models.

Two similar sets of models were developed; each consisted of two corridor spaces with initial widths of 10 feet and enclosed spaces with initial dimensions of 10 feet by 10 feet (100 sq. ft.). All the interior and exterior surfaces of one enclosed space and one corridor space appeared in a plain color. The other two spaces were covered with a patterned texture. In each space, a human figure was included to provide a spatial guideline, helping participants recognize the size of the space. The texture and two spaces of the same size (i.e., two open-ended corridors) with two types of surface textures were included to test and clarify the impact of texture's presence or absence on differing view usage patterns with regards to spatial decision-making when using a DT system. Figure 3 presents one set of models developed, along with their initial sizes and sequences.

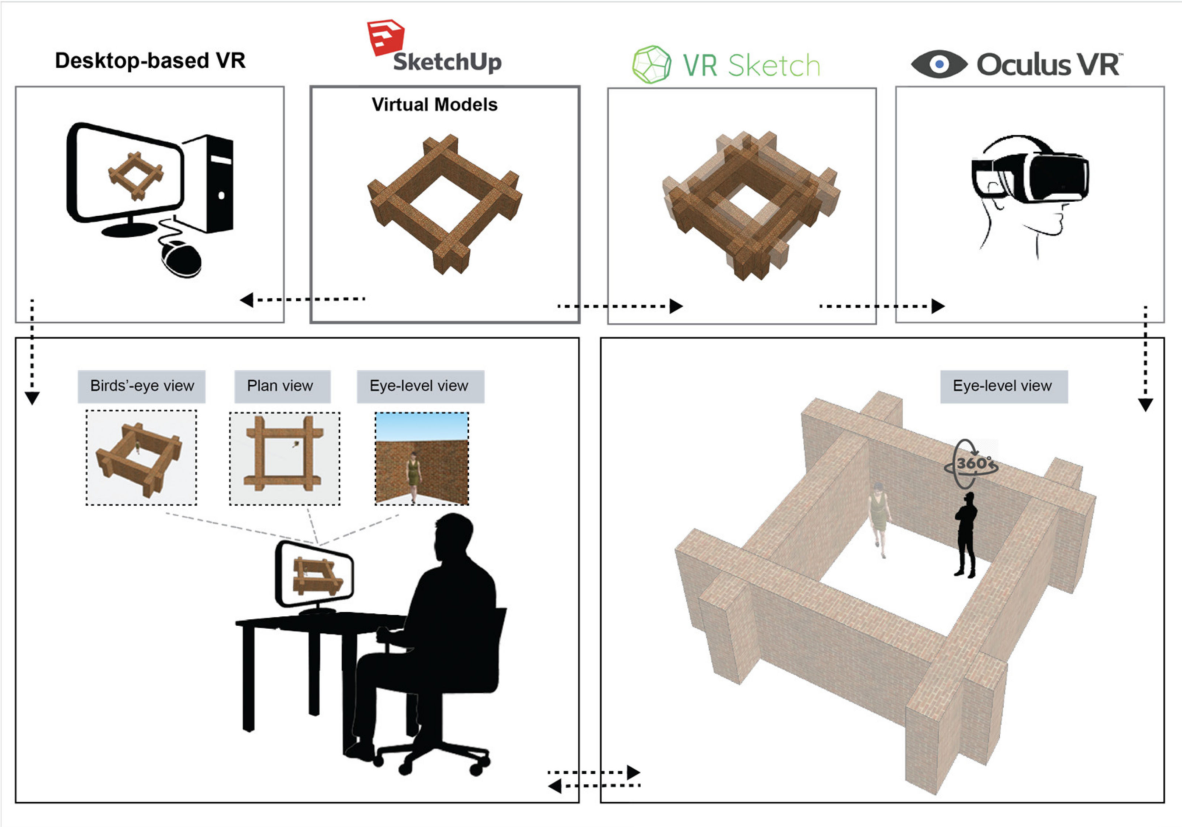


Figure 2. Experiment setup schema and view types used in each system.

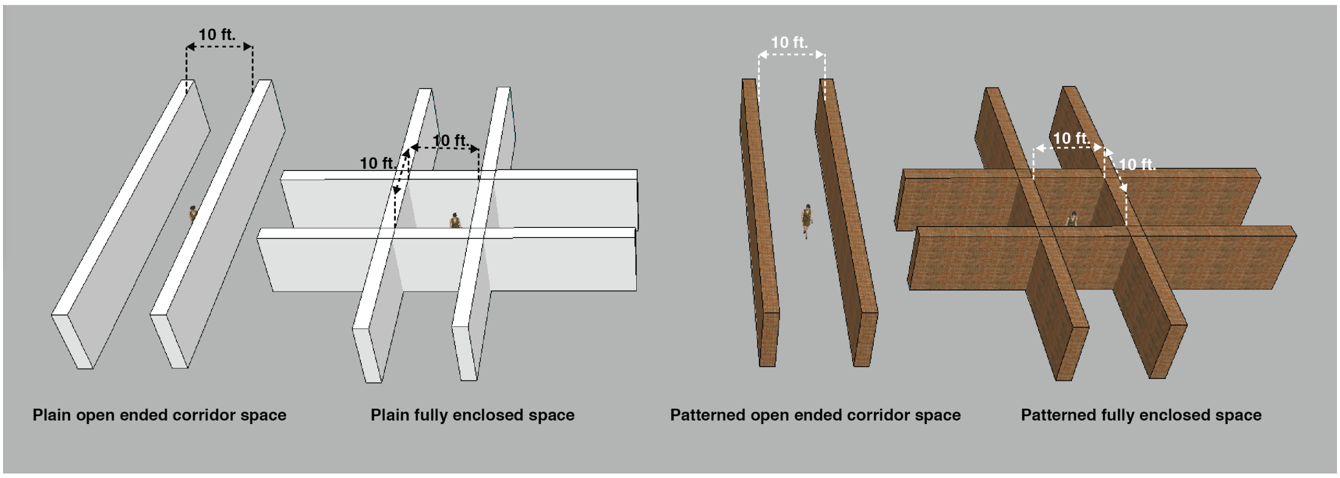


Figure 3. A set of models developed for the experiments.

In the second step, the guidelines and VUQ were finalized and the sample population recruited. Two spatial/experiential guidelines were allocated to the corridor spaces and the others to the enclosed spaces. Each was comprised of information regarding space function, feeling, and the number of users (see Appendix B). Each participant used the guidelines to redesign the four spaces in the first system, and then used them again to redesign the four spaces in the second system.

The VUQ was comprised of four questions. In three, participants evaluated their experience using the eye-level view in IVRIE for their spatial decision-making, as well as their perceived need for an overhead view (either plan, bird's-eye, or both). The other question focused on the systems usage sequence and its impact on perceived view usage patterns when operating the DT system. The goal was to determine and compare the perceived and actual view usage patterns when using the DT system when half the sample population went from the DT system to IVRIE and the other half did the opposite (see Appendix A).

In Step 3, data collection was completed, including gathering and saving each participant's space designs in both systems. These were saved as .skp files. Additionally, the view usage patterns when using the DT system were recorded and the VUQs collected. From the measurements of each participant's design results, eight numeric values were tabulated regarding the sizes and widths of the enclosed spaces and open-ended corridors. The view usage patterns when using the DT system, as represented by the number of times each participant used the birds'-eye, plan, and eye-level views, were converted into a percentage scale for statistical analysis. The participants' answers to the VUQ were converted into a numeric scale for Step 4′s statistical analysis and testing. Figure 4 presents the phases of the experiment.

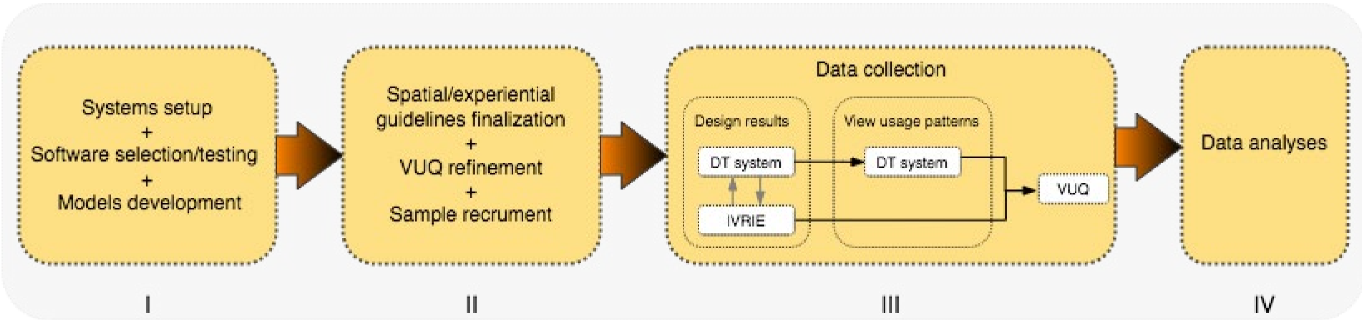


Figure 4. The phases of the experiment.

2.2. Sample Profile and Data Diversity

The sample size for this research study was 65 participants, including undergraduate and graduate students in architecture, landscape architecture, and civil engineering. All participants had used SketchUp® before and were familiar with head-mounted devices.

The data collected concerning participants' view usage patterns while using the DT system were comprised of the number of times each participant used the birds'-eye, plan, and eye-level views. The participants' performances were observed and documented by the researchers at the time of experiment completion and recorded using Camtasia® for further recounting and rechecking. The number of times each participant utilized each view type was converted into a percentage scale for statistical analysis.

The quantitative data regarding design outcomes was based on size measurements of the spaces participants designed in both systems. Each participant redesigned eight spaces, two-open ended corridors and two fully enclosed spaces each in the DT system and IVRIE. The widths of the open-ended corridors and inner areas of enclosed spaces were utilized for statistical testing.

The source of the qualitative data was the VUQ. This measure included four questions designed to gather participants' evaluations regarding the view types utilized in both systems. Data collected via the VUQ were converted into a numeric scale and utilized in statistical tests concerning the view usage patterns employed in the DT system.

3. Results

The data analysis and results of this study are presented below in two parts. The first part includes all of the tests and statistical analyses of view usage patterns employed in the DT system and their relationship to variations in system usage sequence and space type, as well as correlations between the perceived and actual view usage patterns in the DT system and user perceptions regarding the helpfulness of using different views in IVRIE. The second part includes the test results and linear regression analyses of the design outcomes from utilizing IVRIE and the DT system, especially with regards to variations in system usage sequence and the views utilized in each system for spatial decision-making.

3.1. View Usage Patterns for Spatial Design in the DT System

The analysis of the view usage patterns for spatial design when using the DT system relied on the quantitative and qualitative data collected regarding participants' actual view usage patterns, along with their evaluations of the necessity of using various view types in IVRIE for spatial perception and decision-making.

3.1.1. View Usage Patterns in the DT System and the Impacts of System Usage Sequence and Space Type

The analysis of view usage patterns in the DT system relied on the calculation and comparison of actual view usage, as observed by the researchers. The quantitative data for this analysis were comprised of the number of times each participant used one of the views available in the DT system, including the birds'-eye, plan, and eye-level views. The view usage pattern for each participant was converted into a percentage scale to calculate the sample population's overall usage patterns in the particular system. Comparisons showed that regardless of variations in system usage sequence and space characteristics (space types were either an open-ended corridor or fully enclosed space, and the texture was either plain or patterned), the birds'-eye view had the highest and eye-level view the lowest usage percentages in the DT system when utilized for spatial perception, cognition, and decision-making. Regarding view utilization, the birds'-eye, plan, and eye-level views had 48.5%, 39.5%, and 12% of the total utilization times, respectively. Figure 5 presents the percentages for all views utilized by the sample when operating the DT system.

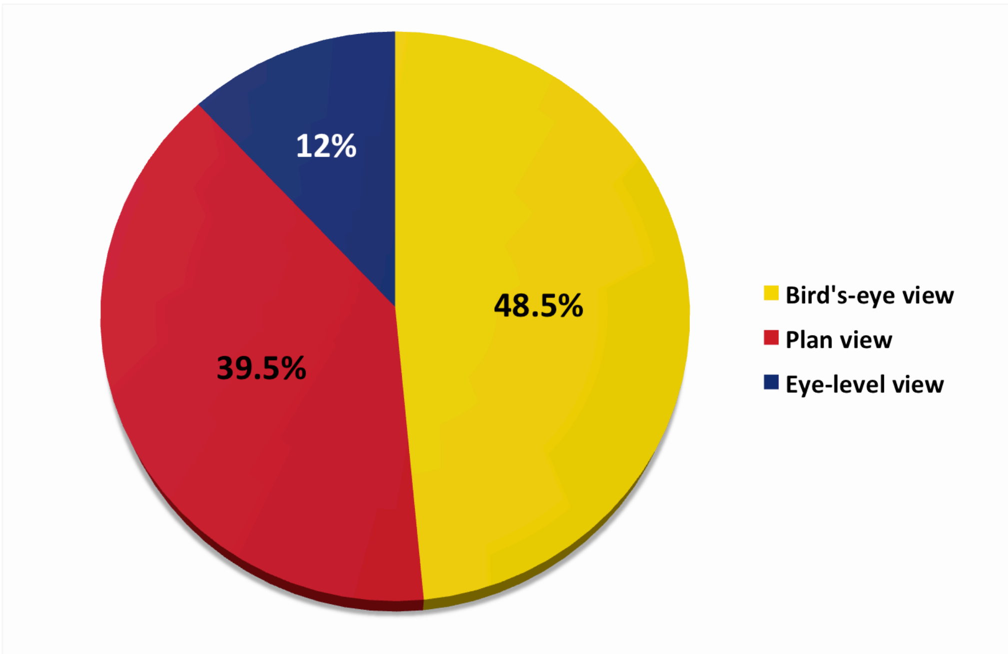
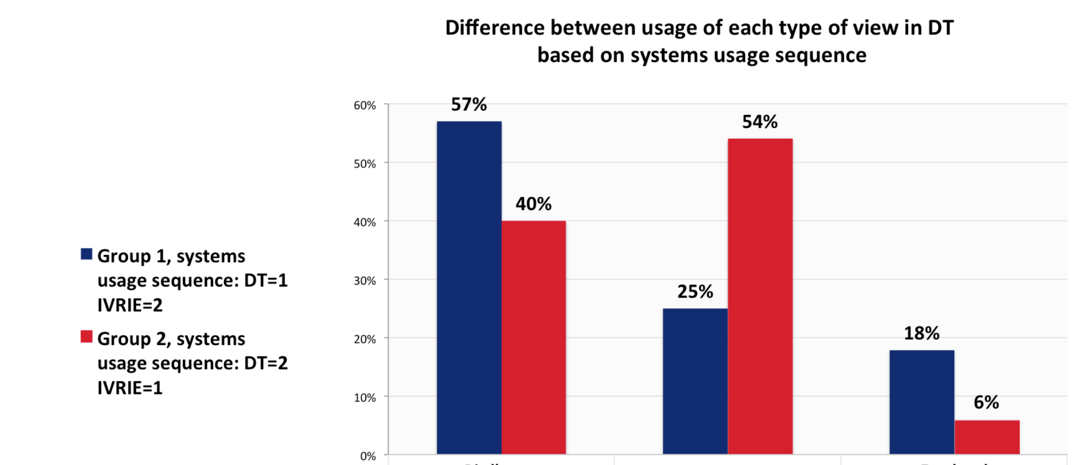


Figure 5. Comparison of the view utilization for the DT system.

A comparison of the view types utilized by participants operating the DT system in either system usage order showed that variations in the system usage sequence did impact view usage patterns. This analysis was based on a comparison of the percentages of utilization for all three available kinds of view for both system-order groups. Group 1 used the DT system first, and then IVRIE. Group 2 followed the opposite usage sequence. The comparison showed that the group using IVRIE first and then DT (Group 2) utilized the eye-level (12%) and birds'-eye (17%) views less often than Group 1.

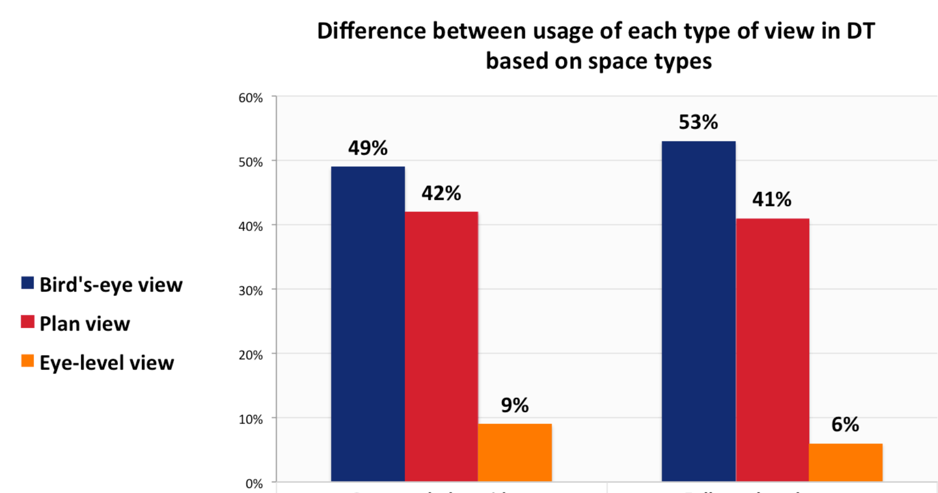
Conversely, the use of plan view by Group 2 was 29% higher than that of Group 1 (54% versus 25%). This comparison indicated that Group 2 (IVRIE first, DT second), who first used the eye-level view exclusively (the only option available in IVRIE for spatial decision-making), relied less when using the DT system on repeating the use of the eye-level view to redesign similar spaces. Indeed, for Group 2, browsing the surroundings, perceiving the spatial factors of the virtual spaces, and engaging in spatial decision-making using the eye-level view in IVRIE impacted their dependency on that same view in the DT system. Similarly, this group's use of the eye-level view in IVRIE decreased their dependency on the birds'-eye view for spatial perception and decision-making when using the DT system. Conversely, on average, the group using the DT system first and IVRIE second (Group 1) relied on the birds'-eye view as their main view for spatial cognition and decision-making. The correlation testing of view usage patterns for either system use order resulted in a Cramer's V of 0.31. A Cramer's V of this level indicates a moderate impact on utilization of the birds'-eye, plan, and eye-level views in the DT system by use of the eye-level view in IVRIE for Group 2. Figure 6 compares the usages of each kind of view for both groups and different system usage sequences.



	Bird's-eye view	Plan view	Eye-level view
Group 1, systems usage sequence: DT=1 IVRIE=2	57%	25%	18%
Group 2, systems usage sequence: DT=2 IVRIE=1	40%	54%	6%

Figure 6. Comparison of view usage patterns in the DT system as impacted by variations in system usage sequence.

The comparisons of the view types used by participants when operating the DT system and based on space type showed that for both types of spaces, the birds'-eye view had the highest percentage of utilization. The comparison also showed that participants used the birds'-eye view to redesign the fully enclosed spaces 4% more often than when designing the open–ended corridors. The usage percentages of the plan view when redesigning both space types were nearly the same (42% and 41%), and when redesigning open-ended corridors, was 3% higher than when redesigning fully enclosed spaces. Figure 7 compares the usages of various view types when redesigning both types of spaces and operating the DT system.



	Open-ended corridors	Fully enclosed spaces
Bird's-eye view	49%	53%
Plan view	42%	41%
Eye-level view	9%	6%

Figure 7. Comparison of view usage patterns in the DT system, based on space type.

3.1.2. System Usage Sequence and Comparison of View Usage Patterns as Represented by User Perception and Observed Data

The analysis of system usage sequence and its impact on the differences between the users' perceived and actual view usage patterns when operating the DT system was based on statistical testing of the two sets of collected data. The first set was the quantitative data collected from the participants' observed/recorded view usage patterns converted to numeric values and a percentage scale. The second set was qualitative data collected from the participants' answers to the second question on the VUQ, the results of which allowed them to be categorized into seven groups based on their perceived view usage patterns when operating the DT system. This question (see the second question in Appendix A) was used to collect participants' perceptions of their view usage in the DT system, including specific kinds of views and combinations of views. Using the seven answer options, participants evaluated their view usage patterns by choosing one type of view as their primary selection. They could select the plan, birds'-eye, or eye-level view, combining these views to different levels or indicate that they utilized all of them equally. The conversion of each answer option from qualitative to quantitative data was achieved by assigning each a numeric value in the form of a percentage, for use in statistical comparisons.

The statistical testing performed to identify the significant and insignificant differences between the perceived and actual view usage patterns for both groups of participants (i.e., each system usage sequence group) was a two-sample t-test. In this test, calculation of the p-value (which provides a statistical evaluation of two population averages or percentages) identified the significance level of the variations in perceived and actual view usage patterns in the DT system for each usage-order group. The level of significance adopted for the test was 0.05; this produced a 95% confidence interval for determining the significance of any differences between the perception and performance of the participants. If the p-value calculated for each participant's perception category was lower than 5%, we concluded that the difference between the means of the two samples (perceived and actual usage of each kind of view) was significant. Thus, the results were not attributed to chance and assumed to be truthful. Table 1 presents the conversion of available answer options to a numeric form, based on their assigned weights on a percentage scale. The table was used as a reference for comparing the perceived and actual view usage patterns for each participant.

Table 1. Assigned percentage weightings for responses to Question 2 of the questionnaire.

Answer Options		Assigned Weights in Percentage			
		Bird's-Eye View	**Plan View**	**Eye-Level View**	**Total**
1	Only used the bird's-eye view	100%	0%	0%	100%
2	Mostly used the bird's-eye view, but also used the eye-level view and plan view a bit	50%	25%	25%	100%
3	Only used the plan view	0%	100%	0%	100%
4	Mostly used the plan view, but also used the bird's-eye view and eye-level view a bit	25%	50%	25%	100%
5	Only used the eye-level view	0%	0%	100%	100%
6	Mostly used the eye-level view, but also used the bird's-eye view and plan view a bit	25%	25%	50%	100%
7	Used the bird's-eye view, plan view, and eye-level view equally	33%	34%	33%	100%

The test results showed that for both system-order groups, the perceived and actual view usage patterns differed significantly. The percentage of participants with significant differences in perceived and actual view usage patterns was higher in Group 1 than Group 2. In addition, the comparisons showed that in Group 1 (using DT first and then IVRIE), there were significant differences between the perceived and actual view usages for all three kinds of views (birds'-eye, plan, and eye-level). Conversely, in Group 2, eye-level view was the only case where perceived and actual usage was significantly different (this was true for 21% of participants).

In Group 1, there were significant differences between the perceived and actual usages of the birds'-eye and plan views for participants who chose "only used the plan view" (9% of Group 1). Additionally, in this group, participants with a perceived view usage of "mostly used the eye-level view, but also used the birds'-eye view and plan view a bit" (21% of the Group 1 population) showed a significant difference between the perceived and actual usages of the birds'-eye and eye-level views. In Group 2, participants with perceived view usage patterns of "mostly used the birds'-eye view, but also used the eye-level view and plan view a bit;" "mostly used the plan view, but also used the birds'-eye view and eye-level view a bit;" and "mostly used the eye-level view, but also used the birds'-eye view and plan view a bit" (79% of Group 2) showed significant differences in their perceived and actual usages of the eye-level view in the DT system. This analysis demonstrates that when the participants started the experiment with IVRIE and their spatial perception was shaped by using the eye-level view, their perceived and actual use of the eye-level view in the DT system were significantly different. Conversely, among the participants in Group 1 (who started the experiment with the DT system), 30%, 9%, and 21% showed significant differences between their perceived and actual usages of the birds'-eye, plan, and eye-level views, respectively. Table 2 presents the significant and insignificant levels of difference between the perceived and actual view usage patterns of both groups. Figure 8 compares the participants' percentages for both groups and notes the significant/insignificant differences in perceived and actual usage for each view.

Table 2. Differences between the Perceived and Actual View Usage Patterns based on System Usage Sequence.

	Answer Options	Group 1 Systems Usage Sequence: DT = 1, IVRIE = 2				Group 2 Systems Usage Sequence: IVRIE = 1, DT = 2			
		Population%	p-Value			Population%	p-Value		
			Bird's- Eye View	Plan View	Eye-Level View		Bird's-Eye View	Plan View	Eye-Level View
1	Only used the bird's-eye view	9%	0.1	0.4	0.2	9%	0.08	0.09	0.4
2	Mostly used the bird's-eye view, but also used the eye-level view and plan view a bit	39%	0.6	0.6	0.2	38%	0.7	0.1	0.00 *
3	Only used the plan view	9%	0.01 *	0.002 *	0.1	13%	0.06	0.06	0.057
4	Mostly used the plan view, but also used the bird's-eye view and eye-level view a bit	9%	0.1	0.4	0.4	16%	1	0.2	0.03 *
5	Only used the eye-level view	0%	-	-	-	0%	-	-	-
6	Mostly used the eye-level view, but also used the bird's-eye view and plan view a bit	21%	0.005 *	0.2	0.004 *	25%	0.5	0.06	0.000 *
7	Used the bird's-eye view, plan view, and eye-level view equally	12%	0.4	0.07	0.7	0%	-	-	-

* indicates a significant p-value.

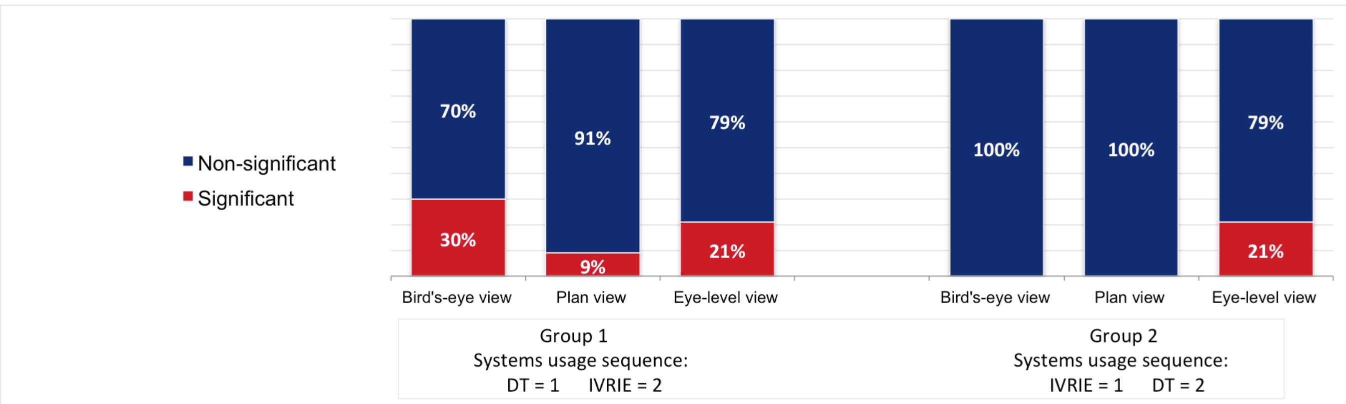
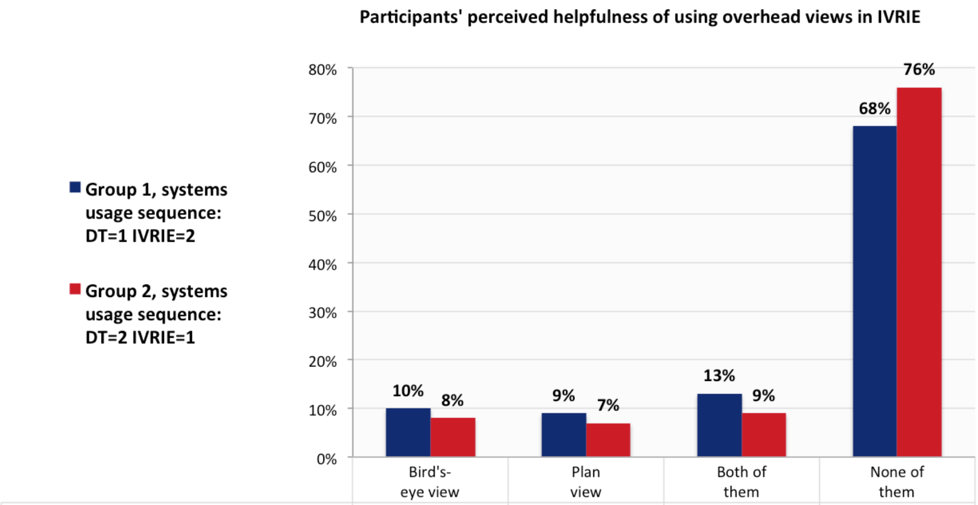


Figure 8. Comparison of both groups of participants' percentages and significant/insignificant differences in perceived and actual usage of each kind of view.

3.1.3. System Usage Sequence and Perceived Helpfulness of the Overhead View in IVRIE

The analysis of the impact of system usage sequence on user perception of the essentiality for spatial design of the overhead view in IVRIE was based on the data collected from participants' evaluations of the overhead and eye-level views in IVRIE. Participants in both groups evaluated the helpfulness of having one, both, or neither of the birds'-eye and plan views for spatial cognition and decision-making when using IVRIE. The comparisons showed that the percentage of participants who perceived the overhead view in IVRIE as helpful was lower in Group 2 than in Group 1.

In Group 1, participants evaluated the helpfulness of using the birds'-eye, plan, and both views in IVRIE as 2%, 2%, and 4%, respectively, values that were lower than those found for Group 2. In addition, the percentage of participants who perceived the overhead view as not essential for spatial decision-making in IVRIE was higher in Group 2 (8%). The results of the comparisons show that having access to the overhead view in IVRIE was perceived as less helpful for spatial design when participants utilized the IVRIE system first; in this case, their spatial perception was shaped by their use of the eye-level view. Additionally, regardless of the system sequence, the majority of participants (76% in Group 2 and 68% in Group 1) did not perceive either the birds'-eye or plan views as helpful in their spatial decision-making. Figure 9 presents the differences in percentages for participants in both groups and with different system usage sequences with regards to the perceived helpfulness of the overhead view in IVRIE.



	Bird's-eye view	Plan view	Both of them	None of them
Group 1, systems usage sequence: DT=1 IVRIE=2	10%	9%	13%	68%
Group 2, systems usage sequence: DT=2 IVRIE=1	8%	7%	9%	76%

Figure 9. Differences in perceived helpfulness of the overhead view in IVRIE for participants in both groups.

3.1.4. Perceived Helpfulness of View Usage Patterns for Spatial Decision-Making in IVRIE

The analysis of perceived helpfulness of the eye-level view as it relates to the perception of dependency on the overhead view in IVRIE was based on the data collected from participants' answers to two VUQ questions that focused on the most efficient view for spatial design in IVRIE. In one question, the participants evaluated the impact of the eye-level view on their feelings about the spaces designed in IVRIE. In the other question, the participants evaluated their need for an overhead view in IVRIE for effective decision-making with regards to spatial feeling. These two questions were designed to identify differences in participants' perceptions of using only the eye-level view or that view in combination with the overhead view when the system usage sequence was varied (see Questions 1 and 4 in Appendix A). First, the participants' evaluations of the eye-level view and their perceived demand for the overhead view in IVRIE were compared between the two groups. Second, the correlation between participants' perceived efficiency of the eye-level view and demand for the overhead view were tested within each group via a Spearman's correlation test.

The comparisons showed that in Group 2, 82% of participants evaluated the eye-level view in IVRIE as "very helpful." On the contrary, in Group 1, only 13% evaluated it as "very helpful." None of the participants in Group 2 evaluated the eye-level view as "not at all helpful," while 19% of participants in Group 1 found this feature unhelpful. In Group 1, those who evaluated the eye-level view as "slightly helpful" were the highest percentage of participants (50%), whereas in Group 2, this evaluation had the lowest percentage (3% of the group population). Figure 10 presents the percentages of participants in both groups, based on their evaluation of using the eye-level view for designing in IVRIE.

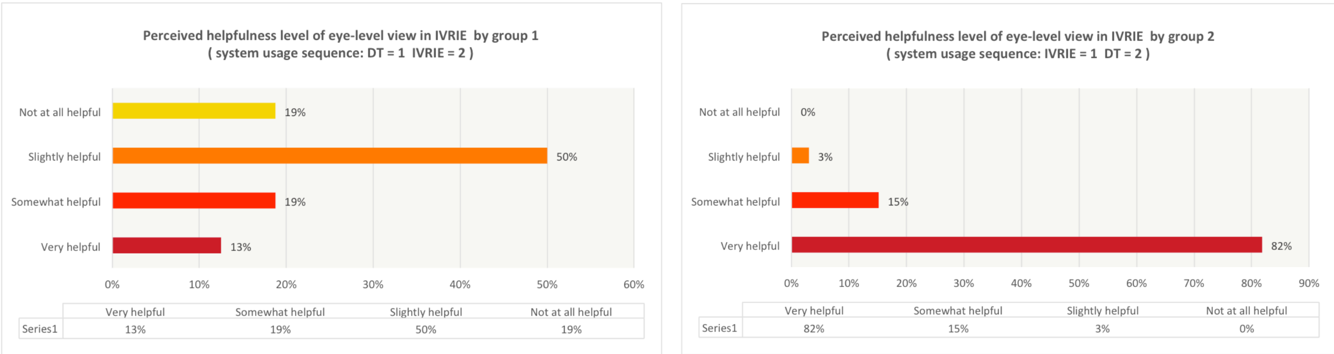


Figure 10. Evaluations of using the eye-level view by groups with opposite system usage sequences.

The comparison of participants' evaluations regarding the need for the overhead view in IVRIE for spatial design showed that no one in Group 2 evaluated it as "very essential." In contrast, in Group 1, 28% of participants evaluated the overhead view as "very essential." In Group 2, participants who considered the overhead view "not at all essential" were the highest percentage (64% of the group population). In Group 1, this percentage was only 16%, the lowest percentage for this group; more participants evaluated it as "somewhat" and "slightly" essential. Figure 11 presents the percentages of participants in each group regarding their opinions about the need for the overhead view.

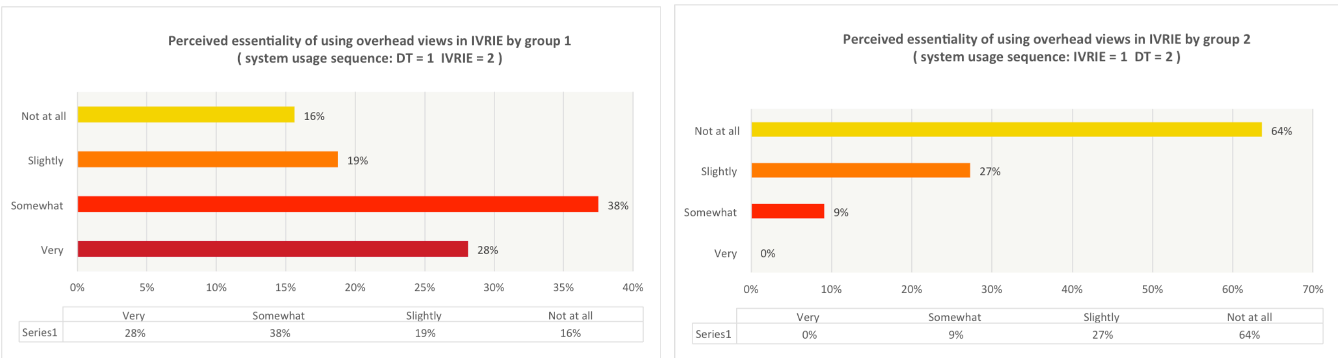


Figure 11. Evaluations of the need for the overhead view for both groups and with opposite system usage sequences.

The Spearman's correlation coefficient and subsequent significance testing of Group 1 participants' perceived helpfulness of the eye-level view and perceived essentiality of the overhead view reflected a weak positive correlation coefficient (rs = 0.36), and the *p*-value calculated (0.03, significant) indicated that the direction and strength of the correlation was not accidental. Likewise, the correlation test for Group 2 reflected a weak positive correlation coefficient (rs = 0.34), and the *p*-value (0.04, significant) specified that the direction and strength of the correlation was not accidental.

3.2. System Usage Sequence and the Impact of View Usage Patterns on Design Outcomes

The analysis of the impact of the view usage patterns on design outcomes when the sequence of system use varied was focused on the identification of the strength and direction of space size variations produced by both groups of participants (utilizing IVRIE and the DT system, but in opposite sequences). The data collected included measurements of each participant's spaces designed in each system. The test was a linear regression that identified the linear correlations among the sizes of each type of space (e.g., plain, open-ended corridors) when designed by a participant in the DT system, and its paired space when designed by the same participant in the IVRIE system. The sizes of the spaces produced by each participant were tested and refined by the application of interquartile ranges (IQR), which detected existing outliers in the collected data (i.e., bad data). The accuracy of the regression test relied on the detection and removal of outliers, which were values far away from other values in a random sample of the population. The outliers detected and removed through the IQR were comprised of all of the out-of-range values in terms of the size of spaces designed by participants using either system. Of the total 520 spaces designed (i.e., eight spaces designed by each of 65 participants, four using one system and four using the other), 20 had out-of-range sizes and were removed, along with their paired spaces designed using the other system.

A linear regression test was performed separately for each group of participants. Then, the results were compared to detect possible differences in the strength and direction of space size variations stemming from system usage sequence and type of view utilized. The test for Group 2 identified linear correlations among the sizes of each type of space (i.e., plain, open-ended corridors) when designed in IVRIE and using the eye-level view, and its paired space designed in the DT system and using the birds'-eye, plan, and eye-level views. Similarly, for the group with the opposite system usage sequence, the test identified a linear correlation between the sizes of the spaces designed in both systems when the view usage pattern shifted from utilizing all available views in the DT system to the eye-level view in IVRIE. For both groups, the size of each type of space (i.e., the plain, open-ended corridors designed by all participants in one group) designed in the first system (i.e., the DT system) were considered independent variables and the sizes of the paired spaces designed in the second system (e.g., IVRIE) were the dependent variables.

In regression statistics, the correlation coefficient (multiple R) is the value that shows how strong the linear relationship is, and the coefficient of determination (R-squared) indicates how much variance in the dependent variable (i.e., the size of a space when designed in the second system) could be accounted for by the independent variable (i.e., the size for the same space when designed in the first system). The results of the linear regression tests for the two open-ended corridors and two fully enclosed spaces by both groups of participants and based on variations in system usage sequence and types of view used are described below.

3.2.1. Linear Correlation of the Widths of Open-Ended Corridors Designed Using Both Systems

The plain, open-ended corridors designated to be wide enough for three people to walk down were first produced by Group 1 in the DT system. This was their first virtual environment and it allowed for use of all three available views: birds'-eye, plan, and eye-level. The corridors were designed for a second time in IVRIE based on the same experiential/spatial guidelines and using only the eye-level view. The correlation value (multiple $R = 0.52$) demonstrated a strong linear correlation between the widths of the plain, open-ended corridors when participants in Group 1 designed them in the DT system first and IVRIE second. The coefficient of determination and calculated R-squared (0.27) revealed that 27% of the variance in the plain, open-ended corridors' widths in the IVRIE system could be accounted for by measures of the same type of corridor width in the DT system. Likewise, the regression statistics for the plain, open-ended corridors designed by Group 2 demonstrated a strong linear correlation (multiple $R = 0.69$) among the widths of this corridor's designs. The calculated R-squared value (0.48) revealed that 48% of the variance in plain, open-ended corridor widths in the DT system could be accounted for by the measures of the corridor widths in IVRIE.

The linear regression model employed the equation Y = 0.37 × X + 11.3 for the corridors' widths designed in IVRIE by Group 1, as predicted by the widths of the corridors designed in the DT system. For Group 2, the linear regression model employed the equation Y = 0.97 × X + 3.57 for the corridor widths designed in the DT system, as predicted by the widths of the corridors designed in IVRIE. A comparison of the linear regression equations shows that although there were strong positive correlations between the widths of the plain corridors designed by both groups in the DT system and IVRIE, the difference in the order of system use impacted the ratio of width variation. Using DT first and then IVRIE (Group 1), the average widths of the plain, open-ended corridors designed in IVRIE and using only the eye-level view for spatial decision–making were lower than the average widths of similar corridors designed in the DT system and utilizing the birds'-eye, plan, and eye-level views. In contrast, for the system usage sequence in which first IVRIE and then DT was used (Group 2), the average widths of the plain, open-ended corridors designed in the DT system and using all available views were higher than the average widths of similar corridors designed in IVRIE and using only the eye-level view. Figure 12 illustrates the linear regression trends for the plain, open-ended corridors for groups with different system usage sequences.

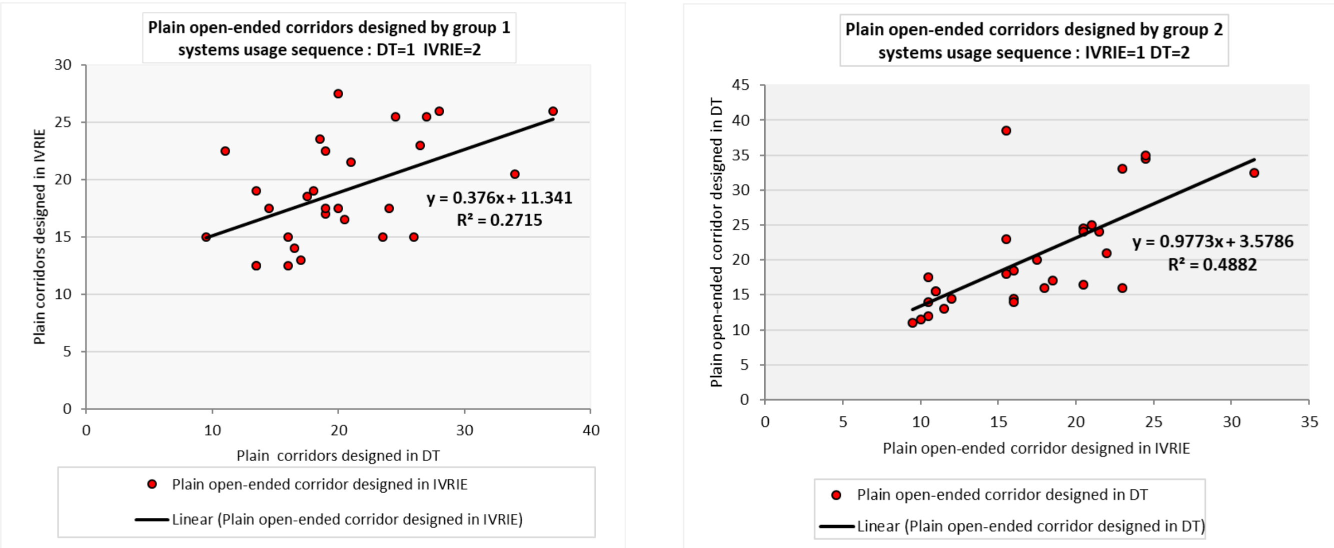


Figure 12. Linear regression trends for plain, open-ended corridors designed in IVRIE and the DT system by both groups of participants.

To design the patterned, open-ended corridors large enough for three people to walk down, the participants in Group 1 utilized all available views in the DT system and the eye-level view in IVRIE. Group 2 repeated the same process for designing these corridors, but with an opposite system usage sequence and types of view. The correlation value (multiple R = 0.69) demonstrated a strong linear correlation between the widths of the patterned, open-ended corridors when participants in Group 1 designed them in the DT system first and IVRIE second. The coefficient of determination and calculated R-squared value (0.47) revealed that 47% of the variance in patterned, open-ended corridor widths in the IVRIE system could be accounted for by measures of the same type of corridor width in the DT system. Likewise, the regression statistics for these corridors, designed by Group 2 and with the opposite system usage sequence, demonstrated a strong linear correlation (multiple R = 0.63) between the widths of the corridors. The calculated R-squared value (0.39) revealed that 39% of the variance in patterned, open-ended corridor widths in the DT system could be accounted for by the measures of the same corridor widths designed in IVRIE.

The linear regression model employed the equation Y = 0.52 × X + 7.43 for the corridor widths designed in IVRIE by Group 1, as predicted by the widths of the corridor designed in the DT system. For Group 2, the linear regression model employed the equation Y = 0.95 × X + 4.69 for the corridor widths designed in the DT system, as predicted by the widths of the corridors designed in IVRIE. A comparison of the linear regression equations showed that although there were strong positive correlations between the widths of the patterned corridors designed by both groups and in both systems, the difference in system order impacted the ratio of corridor width variation. Using DT first and then IVRIE (Group 1), the average widths of the patterned, open-ended corridors designed in IVRIE and using only the eye-level view for spatial decision–making were lower than the average widths of similar corridors designed in the DT system and using all three available views. Conversely, with the system usage sequence of first IVRIE and then DT (Group 2), the average widths of the patterned, open-ended corridors designed in the DT system and using all views were higher than the average widths of similar corridors designed in IVRIE and using only the eye-level view. Figure 13 illustrates the linear regressions for the patterned, open-ended corridors for groups with different system usage sequences.

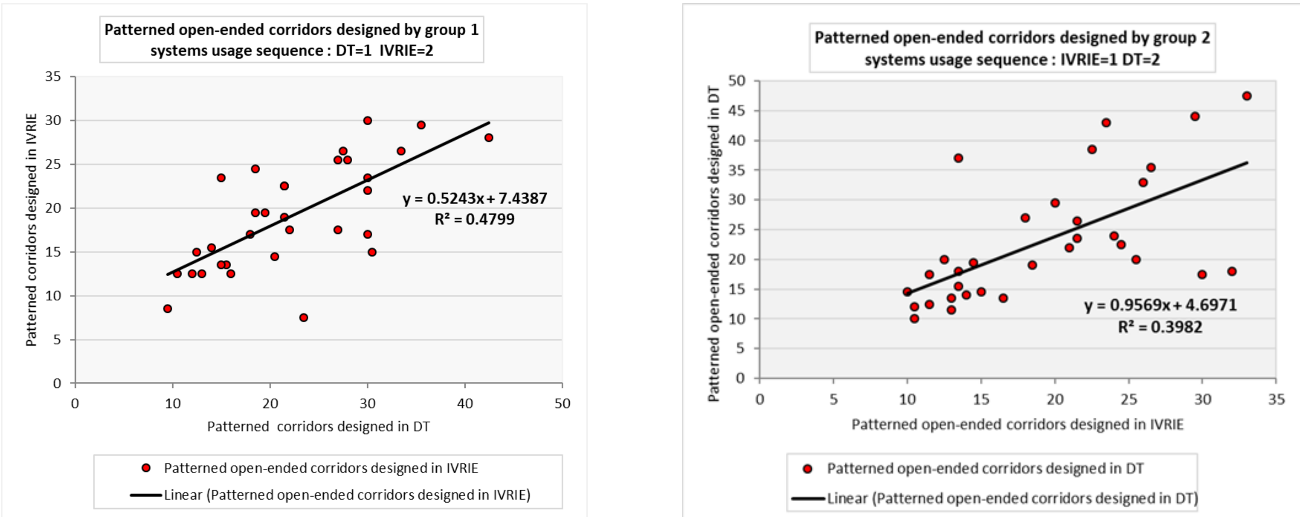
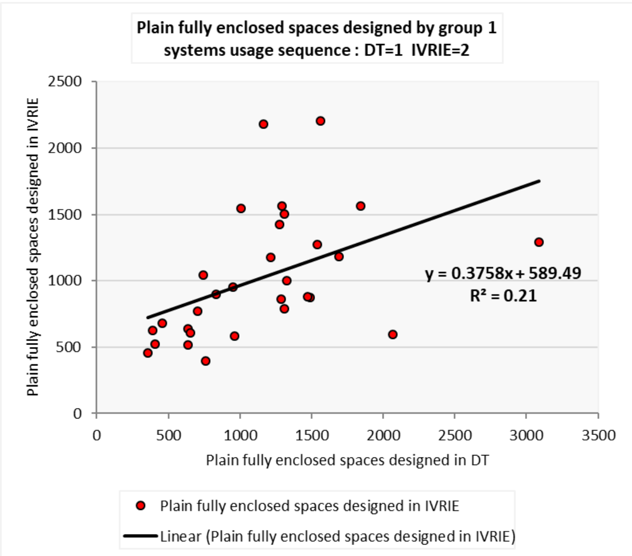


Figure 13. Linear regressions for patterned, open-ended corridors designed in IVRIE and the DT system by both groups of participants.

3.2.2. Linear Correlations among the Sizes of the Fully Enclosed Spaces Designed Utilizing Both Systems

The plain, fully enclosed spaces, designated to be comfortable for gatherings of 10 people, were produced by Group 1 in the DT system first, utilizing all three available views (i.e., birds'-eye, plan, and eye-level). These enclosed spaces were designed for the second time in IVRIE, according to the same experiential/spatial guidelines and utilizing only the eye-level view. The correlation value (multiple R = 0.45) demonstrated a moderate linear correlation between the (inner area) sizes of the spaces when participants in Group 1 designed them in the DT system first and IVRIE second. The coefficient of determination and calculated R-squared value (0.21) revealed that 21% of the variance in space size in the IVRIE system could be accounted for by measures of the same type of space in the desktop system. Likewise, the regression statistics for the plain, fully enclosed spaces produced by Group 2 demonstrated a strong linear correlation (multiple R = 0.74) among the sizes of the enclosed spaces. The calculated R-squared value (0.56) revealed that 56% of the variance in plain, fully enclosed space sizes in the DT system could be accounted for by measures of the same spaces produced in IVRIE.

The linear regression model employed the equation Y = 0.37 × X + 589.4 for the plain, enclosed spaces designed in IVRIE by Group 1, as predicted by the sizes of the enclosed spaces designed in the DT system. For Group 2, the linear regression model employed the equation Y = 1.05 × X + 188.8 for the sizes of the enclosed spaces designed in the DT system, as predicted by the enclosed spaces designed in IVRIE. A comparison of the linear regression equations showed that although there were strong positive correlations between the sizes of the spaces designed by both groups in the DT system and IVRIE, variations in system usage sequence impacted the ratio of space size variation. With the system usage sequence of DT to IVRIE (Group 1), the average sizes of the plain, fully enclosed spaces designed in IVRIE and using only the eye-level view for spatial decision–making were lower than the average sizes of similar enclosed spaces designed in DT and using all three available views. In contrast, with a system usage sequence of IVRIE to DT (Group 2), the average sizes of the spaces designed in the DT system and utilizing all available views were higher than the average sizes of similar enclosed spaces designed in IVRIE and using only the eye-level view. Figure 14 illustrates linear regressions for the plain, fully enclosed spaces designed by both groups and according to different system usage sequences.



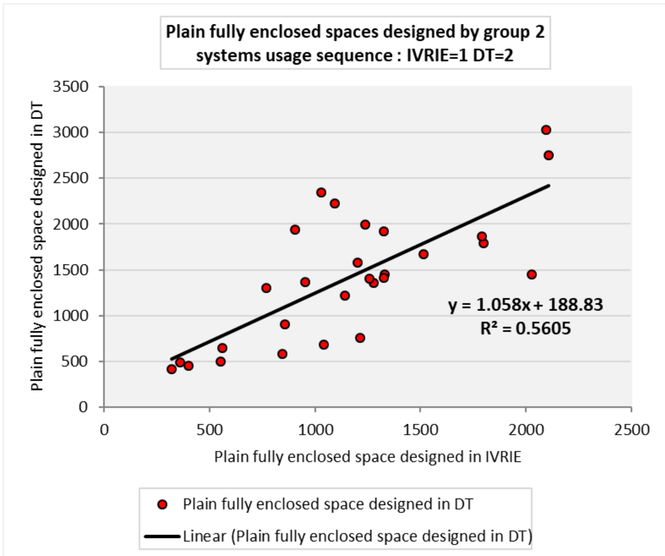


Figure 14. Linear regressions for plain, fully enclosed spaces designed by both groups in IVRIE and the DT system.

The patterned, fully enclosed spaces designed to be comfortable for gatherings of 10 people were first produced by Group 1 using all available views in the DT system and then only the eye-level view in IVRIE. Group 2 repeated the same process for designing these enclosed spaces, but with the opposite system usage sequence and types of view. The correlation value (multiple R = 0.76) demonstrated a strong linear correlation between the (inner area) sizes of the patterned, fully enclosed spaces when participants in Group 1 designed them in the DT system first and IVRIE second. The coefficient of determination and calculated R-squared value (0.58) reveal that 58% of the variance in space size in the IVRIE system could be accounted for by measures of the same type of enclosed space in the DT system. Likewise, the regression statistics for these enclosed spaces designed by Group 2 and with the opposite system usage sequence demonstrated a strong linear correlation (multiple R = 0.65) among the sizes. The calculated R-squared value (0.43) reveals that 64% of the variance in the sizes of the patterned, fully enclosed spaces in the DT system could be accounted for by the measures of the space sizes in IVRIE.

The linear regression model employed the equation $Y = 0.58 \times X + 334.7$ for the sizes of enclosed spaces designed in IVRIE by Group 1, as predicted by the sizes of the enclosed spaces designed in the DT system. For Group 2, the linear regression model employed the equation $Y = 1.44 \times X - 57.3$ for the sizes of the enclosed spaces designed in the DT system, as predicted by the sizes of the enclosed spaces designed in IVRIE. A comparison of the linear regression equations shows that although there were strong positive correlations between the sizes of the spaces designed by both groups in both the desktop system and

IVRIE, the difference in the order of system utilization impacted the ratio of enclosed space size variations. With the system usage sequence of DT to IVRIE (Group 1), the average sizes of the patterned, fully enclosed spaces designed in IVRIE and using only the eye-level view for spatial decision–making were lower than the average sizes of similar enclosed spaces designed in DT and using all three available views. Conversely, with a system usage sequence of IVRIE to DT (Group 2), the average sizes of the spaces designed in the DT system and using all views were higher than the average sizes of similar spaces designed in IVRIE and using only the eye-level view. Figure 15 illustrates the linear regressions for patterned, fully enclosed spaces for groups with different system usage sequences.

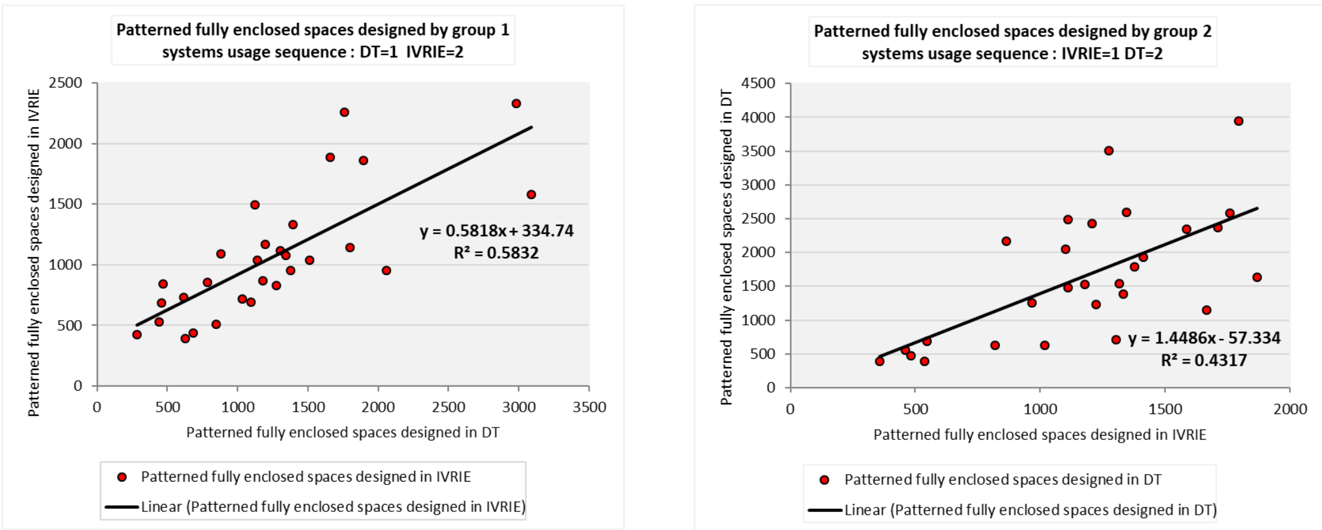


Figure 15. Linear regressions for patterned, fully enclosed spaces designed in IVRIE and the DT system by both groups of participants.

The comparison of open-ended corridor widths designed by both groups and regardless of differences in the order of system used and views employed shows that the average widths of the patterned, open-ended corridors were higher than those of the plain ones. Similarly, the sizes of the patterned, fully enclosed spaces produced by both groups and regardless of system order were on average higher than those of the plain, fully enclosed spaces. Table 3 presents the regression statistics for the open-ended corridors and fully enclosed spaces designed by both groups and using both systems.

Table 3. Regression Statistics for the Open-Ended Corridors and Fully Enclosed Spaces Designed in Both Systems.

Sample Division	Systems Usage Sequence	Space	Texture	Regression Statistics		Regression Model
				Multiple R	R Square	
Group 1	DT = 1 IVRIE = 2	Open-ended corridor	Plain	0.52	0.27	Y = 0.37 × X + 11.3
			Patterned	0.69	0.47	Y = 0.52 × X + 7.43
		Fully enclosed space	Plain	0.45	0.21	Y = 0.37 × X + 589.4
			Patterned	0.76	0.58	Y = 0.58 × X + 334.7
Group 2	IVRIE = 1 DT = 2	Open-ended corridor	Plain	0.69	0.48	Y = 0.97 × X + 3.57
			Patterned	0.63	0.39	Y = 0.95 × X + 4.69
		Fully enclosed space	Plain	0.74	0.56	Y = 1.05 × X + 188.8
			Patterned	0.65	0.43	Y = 1.44 × X − 57.3

4. Discussion

This research explored users' spatial perceptions and view usage patterns in two VR systems (IVRIE and a DT system) for spatial decision-making and the effects of system usage sequence on the design results. The goal was to determine how the spatial perception gained using the eye-level view in IVRIE impacted the view usage patterns and spatial decision-making demonstrated when using the DT system, as well as how variations in system usage sequence and view usage patterns impacted the design results from both systems. Two sets of quantitative data and one set of qualitative data were collected and analyzed. The quantitative data were collected from the sample population's view usage patterns when using the DT system and measurements of spaces designed in both systems. The qualitative data were collected via a questionnaire.

The data from the view usage patterns when using the DT system were first analyzed exclusively to identify the percentage of each type of view used and determine the effect of system usage sequence. These data were then analyzed to identify the relationship between users' perceived and actual view usage patterns in the DT system and their evaluations of the functionality and usability of view types in IVRIE. The quantitative data collected from measuring the design results were analyzed to identify linear regressions between the design outcomes of both systems as determined by variations in system usage sequence view type.

The hypotheses and findings are summarized below. First, it was hypothesized that spatial perception in IVRIE when utilizing the eye-level view and cognition of spatial factors on a human scale impacts the view usage patterns and spatial perception in the DT system. The findings support this hypothesis and reveal a moderate association between the view usage patterns in the DT system and variations in system usage sequence from IVRIE to DT (or vice versa). Second, it was proposed that using the eye-level view in IVRIE for spatial decisions positively impacts user awareness with regards to spatial performance in the DT system when the order of system utilization was IVRIE to DT. The results of the comparisons support this hypothesis, showing that with the system usage sequence of IVRIE to DT, the gap between users' perceived and actual views utilized in the DT system was less than when the system usage sequence was reversed. The third hypothesis was that when users utilize the eye-level view and perceived spatial factors on a human scale in IVRIE, they do need the overhead view for spatial decision-making (when using that system). The findings do not support this hypothesis and instead show that regardless of the system usage sequence, a high percentage of participants perceived that an overhead view in IVRIE would be helpful for their spatial decision-making. The fourth hypothesis was that spatial decision-making in IVRIE when utilizing the eye-level view results in different design results with regards to the size and scale of the spaces designed, compared with spatial decision-making in the DT system when using both the eye-level and overhead views. The findings support the hypothesized differences in design outcomes and reveal that with the system usage sequence of IVRIE to DT, the spatial decisions of the users were different with regards to the sizes and scales of the designed spaces.

The findings can be summarized as follows:

- Of the available views in the DT system, the birds'-eye view had the highest and eye-level view the lowest percentages of usage for spatial perception and spatial decision-making.
- There was a moderate association between the use of the birds'-eye, plan, and eye-level views in the DT system and variations in using DT as the first system and IVRIE as the second or vice versa.
- With a system usage sequence of IVRIE to DT, the percentage of participants with a significant difference between their perceived and actual use of the eye-level views when designing in the DT system was 58% higher than among the participants with the opposite order of systems use.
- Variations in the system usage sequence impacted the users' perception of the helpfulness of the overhead view in IVRIE. A comparison showed that the percentage

of participants who perceived having the overhead view in IVRIE as helpful was lower when they used IVRIE first and DT second, compared with those following the opposite system usage sequence.

- There were strong linear regressions between the widths of open-ended corridors designed by participants when utilizing DT first and IVRIE second. In this sequence, the birds'-eye, plan, and eye-level views were utilized in the DT system and then the eye-level view was used in IVRIE.
- When utilizing DT first and then IVRIE for redesigning the spaces, there was a strong linear regression between the sizes of fully enclosed spaces when the texture was present and a moderate linear regression when the texture was absent.
- With a system usage sequence of IVRIE to DT, there were strong linear regressions between the widths of open-ended corridors and sizes of fully enclosed spaces, regardless of the absence or presence of texture.

The findings of this study could be utilized in further research focusing on enhancing user spatial perception and performance in VR systems impacted by more functional combinations between the levels of immersion, types of interaction, and view usage patterns. In addition, in the research focusing on identifying the role of factors impacting the enhancement of spatial memory in VR systems, the findings of this study regarding user awareness of utilized view types in the DT system when system usage sequence varied could be useful.

Technical Limitations

In the methodology and experimental design of this study, it was assumed that the spatial perception gained using the eye-level view in IVRIE would impact the view usage patterns and spatial decision-making demonstrated when using the DT system. It was also assumed that the variations in system usage sequence and view usage patterns would impact the design outcomes utilizing both systems. One of the limitations in the methodology was the impact of spatial memory on view usage patterns in the DT system for the participants who completed the experiments utilizing IVRIE first and DT second. Some participants mentioned that they did not need to use the eye-level view when redesigning the spaces in the DT system since they still could remember the spatial feeling within the spaces obtained by utilizing the eye-level view in IVRIE. Another limitation was that a few participants who completed the experiment with the system usage sequence of DT to IVRIE mentioned that they totally ignored the presence or absence of texture when using different view types for redesigning the spaces in the DT system. Adding some details regarding texture differences in the spatial/experiential guidelines could make participants aware of them and affect their view usage patterns and spatial decision-making in the DT system. The last limitation was that when using SketchUp®software in the DT system for redesigning the spaces, the software did not have any control option to prevent users zooming out a large distance from objects when using birds'-eye or plan view. Some participants zoomed out the birds'-eye or plan view up to distances where spaces appeared as small dots or even disappeared. They needed the experiment conductor's assistance to bring back their viewsheds to the point that they could continue working on the models. This technical limitation impacted some participants' completion time of the experiment compared with others.

5. Conclusions and Future Vision

Research on architectural design using mixed methods to explore user performance and the ability of VR systems to enhance design learning is still in the initial stages. Using two VR systems for spatial design, the goal of the present work was to determine the impact of the eye-level view in IVRIE on view usage patterns for spatial perception and decision-making in a DT system. Another goal was to identify the impact of using the eye-level view in IVRIE and overhead and eye-level views in the DT system on user spatial decision-making within each system and on the design results. The data collected regarding participants' view usage patterns in the DT system showed that, on average, each participant shifted between the birds'-eye, plan, and eye-level views 30 times when redesigning fully enclosed spaces. When redesigning the open-ended corridors, the average number of shifts was 20. Thus, the total number of view-type changes made by the 65 participants was about 6500, which was adequate for drawing conclusions about the impact of using the birds'-eye, plan, and eye-level views in the DT system on eye-level view use in IVRIE. With regards to the impact of view type on design outcomes when the sequence of system use differed, a linear regression test was used to determine the linear correlations among the sizes of 500 spaces, 250 designed in IVRIE and 250 designed in the DT system. Based on the results, it was concluded that view usage patterns in VR systems directly impact user spatial perception and result in different decisions being made.

The findings of this study could be utilized in future research identifying the impacts of VR systems and their features on users' spatial decision-making. In addition, the results could be used in studies examining the use of VR systems as environments to enhance user performance with regards to the perception of spatial relationships and arrangements, shapes, volumes, and space capacities. Such work would allow the development of more accurate design solutions and the production of sustainable design results in the fields of architecture, engineering, and construction.

Although this study included a human figure in the spaces as a spatial guideline to help participants recognize the primary scale of the spaces, it may have been better to utilize human figures of different body sizes, rather than a fixed human figure throughout. Many participants mentioned that their spatial decisions would have differed if the human figure (an average-sized female 5.6 feet tall) was replaced with a taller or shorter person. These comments often emerged in response to the open-ended corridors, rather than the fully enclosed spaces. In addition, using different textures in the patterned spaces (i.e., lighter/darker colors or simpler/more complex patterns) may affect the number of shifts among viewpoints for spatial decision-making in DT systems.

Future research will explore user performance regarding view usage patterns and spatial decision-making while working on more spatially complex spaces, as well as the effect of access to the overhead view in IVRIE.

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Abbreviations

VR	Virtual Reality
IVRIE	Immersive Virtual Reality Interactive Environment
DT	Desktop system
3D	Three-dimensional

Appendix A. View Usage Questionnaire

Views Usage Perception Questionnaire
Please answer the following questions

1. When making decisions about the size and spatial feeling of your designed spaces, how helpful was it to you to have an eye-level view in IVRIE?

   ☐ Very helpful ☐ Somewhat helpful ☐ Slightly helpful ☐ Not at all helpful

2. When working on redesigning spaces in the desktop system, about how much of your time did you spend using the bird's eye or plan view versus the eye-level view?

   ☐ Only used the bird's eye view
   ☐ Mostly used the bird's eye view, but also used the eye-level view and plan view a bit
   ☐ Only used the plan view
   ☐ Mostly used the plan view, but also used the bird's eye view and eye-level view a bit
   ☐ Only used the eye-level view
   ☐ Mostly used the eye-level view, but also used the bird's eye view and plan view a bit
   ☐ Used the bird's eye view, plan view, and eye-level view equally

3. What type of other views in IVRIE would be helpful to complete the design tasks?

   ☐ Birds' eye view ☐ Plan view ☐ Both of them ☐ None of them

4. When making decisions about the feeling of your designed spaces in the immersive VR system, did you feel that you need to see the spaces from above to accomplish the task effectively?

   ☐ Very ☐ Somewhat ☐ Slightly ☐ Not at all

Thank you for your participation in this research study.

Appendix B. Spatial/Experiential Guidelines

In this set of models, there are four different spaces consisting of two open-ended corridors and two enclosed spaces. None of the spaces have roofs.
Please follow the guidelines to redesign the given spaces.

1. Design corridor number 1 to be wide enough for three people to comfortably walk down, either in a line or side by side.
2. Design enclosed space number 1 to be spacious enough for ten people to gather and comfortably stand at a personal distance from each other.
3. Design corridor number 2 to be wide enough for three people to comfortably walk down, either in a line or side by side.
4. Design enclosed space number 2 to be spacious enough for ten people to gather and comfortably stand at a personal distance from each other.

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