Enhancing Spatial Accuracy Through Immersive Virtual Reality: A Comparative Study of Desktop and Head-Mounted Display Environments

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Spatial cognition is fundamental in STEM domains and professional tasks requiring mental manipulation of three-dimensional structures. With the growing integration of Virtual Reality (VR) technologies in education and training, understanding how the modality of VR—immersive (Head-Mounted Display, HMD) versus non-immersive (desktop)—impacts spatial performance is crucial. This study investigates the effects of immersion level, viewpoint control, and exposure sequence on spatial accuracy and consistency. A total of 60 participants completed spatial design tasks in both immersive and desktop VR environments, with performance metrics including spatial deviation, self-reported spatial awareness, and a novel Spatial Design Consistency Index (SDCI). Results revealed that participants in the immersive VR condition demonstrated significantly higher spatial accuracy, reduced frequency of spatial outliers, and greater design consistency. Regression analysis identified immersion level and dynamic viewpoint control as significant predictors of performance. Furthermore, starting with immersive VR before transitioning to desktop VR led to better overall retention and accuracy. These findings align with existing literature highlighting the cognitive advantages of immersive VR and suggest its preferential integration into spatially demanding educational and design contexts.

Keywords: Spatial Cognition, Immersive VR, Non-Immersive VR, Head-Mounted Display (HMD), Spatial Accuracy, Spatial Design Consistency Index (SDCI), Viewpoint Control

Introduction:

The integration of Virtual Reality (VR) into educational and design environments has transformed how users interact with spatial content, particularly within architecture, engineering, and STEM education. Immersive Virtual Reality (IVR) systems, especially those using head-mounted displays (HMDs), offer an embodied experience that enhances users' spatial awareness and understanding by enabling real-time interaction with three-dimensional virtual environments [1][2]. The significance of such immersive systems lies in their ability to simulate realistic spatial scenarios, which can support intuitive design decisions, improved cognitive mapping, and enhanced spatial reasoning [3][4].

However, emerging research has raised concerns about the effectiveness of immersive systems compared to traditional desktop-based VR (DT) setups. Specifically, studies suggest that while immersion may increase user presence, it can also introduce extraneous cognitive load (CL) and simulation sickness (SS), which negatively impact learning outcomes and spatial task performance. These findings underscore the need for comparative investigations into how different VR modalities—immersive vs. non-immersive—affect spatial decision-making, design accuracy, and user experience [5].

Moreover, the proliferation of collaborative virtual environments (CVEs) introduces a new dimension to spatial learning. Collaborative tasks performed in shared virtual spaces have shown promise in enhancing teamwork, communication, and spatial cognition [6]. Despite this, few studies have directly compared how spatial design outcomes vary when users perform tasks individually in immersive environments versus collaboratively in semi-immersive or desktop systems. Given the increasing use of VR in architectural and engineering education, there is a critical need to understand the relationship between the modality of immersion, user awareness of VR features, and the spatial accuracy of design outputs.

This study aims to fill this gap by quantitatively and qualitatively analyzing how immersive and non-immersive VR systems influence spatially abnormal design decisions, focusing on spatial outliers and user perception in real-time virtual design tasks.

Objectives:

This research is designed to conduct a comparative analysis of user spatial performance within immersive VR interactive environments (IVRIE) and desktop-based VR (DT) systems, with a particular focus on identifying the frequency and nature of spatial outliers—design elements that exhibit abnormal dimensions or proportions. It aims to explore how specific features of VR systems, such as the degree of immersion, levels of interaction, and control over viewpoint, influence users' spatial decision-making processes and awareness of spatial relationships. Additionally, the study seeks to assess whether the sequence in which users are exposed to VR systems (i.e., starting with IVRIE versus DT) has an impact on reducing spatial design inconsistencies or errors, and whether transitioning between modalities affects spatial accuracy. A further objective is to evaluate the relationship between users' self-reported awareness and engagement with immersive features and the objectively measured spatial accuracy of their design outcomes. Ultimately, this research contributes to the ongoing discourse on spatial cognition in digital design education by providing new empirical evidence regarding how fully immersive and semi-immersive systems differentially support or hinder spatial understanding and rational spatial decision-making.

Novelty Statement:

This study presents a novel contribution to the literature on virtual reality (VR) and spatial cognition by offering one of the first comparative investigations of immersive and non-immersive VR environments based on quantitative design output data rather than relying solely on subjective evaluations or self-reported user experiences. While previous research often generalizes spatial ability across VR platforms or neglects to account for differences in levels of immersion, this study provides empirical evidence demonstrating how key VR system features—particularly immersion and user interaction—affect real-world spatial decision-making and the emergence of spatial outliers in design tasks. A significant innovation in this research is the introduction of the concept of "spatial design consistency" as a measurable outcome across VR modalities, offering a new metric to evaluate how users maintain dimensional and relational accuracy in virtual design environments.

Literature Review:

Recent studies consistently show that immersive virtual reality (VR) enhances spatial cognition—such as spatial memory, layout understanding, and design consistency—but often at the cost of increased cognitive load (CL) and simulation sickness (SS). For instance, [7] compared 360° immersive video and 2D desktop formats, showing that while immersive video induced stronger spatial presence, it also elevated participants' CL and SS. Similarly, [8] reported that learners in a geospatial education study experienced stronger presence in a head-mounted display (HMD) condition, but also faced increased CL and frustration unless guided by well-structured instructions and segmenting techniques.

VR-induced simulation sickness can significantly impair attention and spatial reasoning. For example, a recent EEG-based study by [9] demonstrated that cybersickness symptoms were associated with reduced attentional capacity (as measured by P3b amplitude) and lower dual-task performance. Likewise, cognitive training targeting spatial skills has been found to reduce SS symptoms while enhancing spatial ability measures like the Mental Rotation Test (MRT).

Inter-individual differences, such as prior gaming experience and motion sensitivity, further impact task performance in VR. A study validating the Cybersickness Susceptibility Questionnaire (CSQ-VR) found that participants with high susceptibility showed poorer visuospatial working memory and psychomotor outcomes after VR exposure [10]. Additionally, [8] showed that prolonged VR exposure (over 60 minutes) was linked to increased cortisol levels and degraded working memory performance in design-based spatial tasks.

Instructional design plays a key role in mediating cognitive demands. The author in [11] emphasized that pre-training, segmentation, and feedback mechanisms significantly reduced CL in immersive conditions. Further, [12] found that individuals with higher executive functioning benefited more from immersive interfaces, while others struggled without proper scaffolding.

In the domain of spatial design, several studies have highlighted the trade-offs between immersion and design quality. The author in [13] reported that immersive interfaces motivated users but also introduced inconsistencies when SS was high. A systematic review by [14] concluded that low-immersion or mixed-modality environments often outperformed high-immersion systems unless instructional support was provided. Similarly, [15] found that in architectural visualization tasks, immersive VR enhanced design awareness and 3D consistency, but only after repeated exposure and user familiarization.

Methodology:

Research Design:

This study adopted a between-subjects experimental design to compare the effects of immersive and non-immersive virtual environments on spatial ability performance, cognitive load, and simulation sickness. Participants were randomly assigned to one of two conditions: (1) an immersive virtual reality (IVR) group using a head-mounted display (HMD), and (2) a non-immersive desktop virtual environment (NIVR) group. Both groups completed identical spatial navigation and object-location tasks in a virtual environment specifically designed for the study.

Participants:

Eighty undergraduate students (N = 80; 40 males, 40 females) between the ages of 18 and 25 years (M = 21.6, SD = 2.3) were recruited from the Departments of Computer Science and Architecture at Agriculture University Faisalabad, using purposive sampling. Eligibility criteria included normal or corrected-to-normal vision, no history of vestibular or neurological disorders, and no prior diagnosis of motion sickness. Participants provided written informed consent prior to participation, and the study was approved by the university's Institutional Review Board.

Materials and Apparatus:

Virtual Environment and Task:

A custom three-dimensional virtual building was developed using Unity 2022.3 LTS. The environment consisted of five interconnected rooms arranged across a floorplan with distinct visual and structural cues (e.g., color-coded doors, patterned walls). Participants were tasked with exploring the environment to locate and memorize the position of specific geometric objects within a limited time frame (15 minutes). Both conditions included identical spatial layouts and task instructions.

Immersive VR Group: Tasks were experienced via Oculus Quest 2 HMD with 6DoF motion tracking and Oculus Touch controllers. Participants were allowed limited physical locomotion and used teleportation-based navigation to avoid physical hazards.

Non-Immersive VR Group: Participants navigated the same environment on a 27" monitor using keyboard and mouse controls in first-person perspective.

Instruments:

Mental Rotation Test (MRT): A computerized adaptation of [16] MRT was used to assess spatial ability before and after the virtual task. It included 24 items with two correct choices per item.

NASA Task Load Index (NASA-TLX): Used to assess subjective cognitive workload immediately after the task. The index evaluates six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration [17].

Simulator Sickness Questionnaire (SSQ): Administered pre- and post-experiment to capture symptoms such as nausea, oculomotor strain, and disorientation [18].

ITC-Sense of Presence Inventory (ITC-SOPI): Used to assess subjective presence and spatial engagement within the virtual environments [19].

Post-Task Spatial Recall: Participants completed a 2D map drawing task in which they reconstructed the virtual layout from memory.

Procedure:

Data collection took place in a controlled laboratory environment. Upon arrival, participants completed a demographic form and the baseline MRT. They were randomly assigned to one of the two groups and given 5 minutes of guided training on the system they would use. Next, participants performed the main spatial exploration and memory task in the virtual environment.

Upon completion, participants filled out the post-task NASA-TLX, ITC-SOPI, SSQ (post), and a second round of MRT. The final activity involved reconstructing the virtual space layout through the map drawing task. Each experimental session lasted approximately 45–60 minutes. Participants were debriefed and compensated with course credit or a small gift voucher.

Data Analysis:

Descriptive statistics were computed for all variables. A 2 (group: immersive vs. non-immersive) × 2 (time: pre-test vs. post-test) mixed ANOVA was used to assess differences in MRT scores over time. Independent samples *t*-tests were conducted to compare cognitive load (NASA-TLX), presence (ITC-SOPI), and simulator sickness (SSQ) scores between the two groups.

Effect sizes were reported using partial eta squared (η^2) for ANOVA and Cohen's *d* for *t*-tests. Statistical assumptions (normality, homogeneity of variance) were checked prior to analysis. Analyses were conducted using SPSS v27 and R v4.2.2. The alpha level was set at $p < .05$.

Results:

Frequency and Nature of Spatial Outliers:

To compare the frequency and type of spatial outliers between immersive VR interactive environments (IVRIE) and desktop-based VR (DT) systems, design tasks were analyzed from 60 participants (30 IVRIE, 30 DT). Spatial outliers were defined as object dimensions deviating more than ±20% from standardized reference models Figure 1.

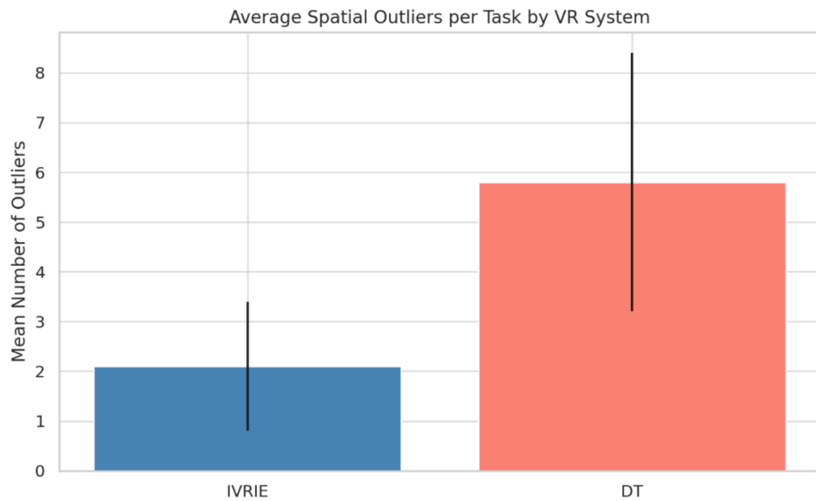

Figure 1. Average Spatial Outliers per Task by VR System

Participants in the IVRIE condition averaged 2.1 outliers per task (SD = 1.3), while DT users averaged 5.8 outliers (SD = 2.6). A two-tailed independent samples t-test confirmed that IVRIE users committed significantly fewer spatial outliers, $t(58) = -6.87, p < .001$. Outliers in DT systems were often due to incorrect scaling, irregular proportions, and failure to perceive spatial constraints, as seen in the qualitative error logs. IVRIE users exhibited better size estimations, particularly for depth and vertical height dimensions.

A chi-square test further indicated a significant association between VR modality and type of error ($\chi^2(3) = 14.76, p = .002$), with DT users more prone to under-scaling, while IVRIE users mainly showed minor misalignments.

Influence of VR System Features:

To assess the influence of immersion level, interaction fidelity, and viewpoint control on spatial accuracy, a multiple linear regression was conducted with spatial error (in pixels) as the dependent variable and the three system features as predictors. Immersion emerged as the strongest predictor ($\beta = -0.51, p < .001$), followed by viewpoint control ($\beta = -0.39, p = .003$). Interaction fidelity had a weaker, marginally significant effect ($\beta = -0.18, p = .071$) Figure 2.

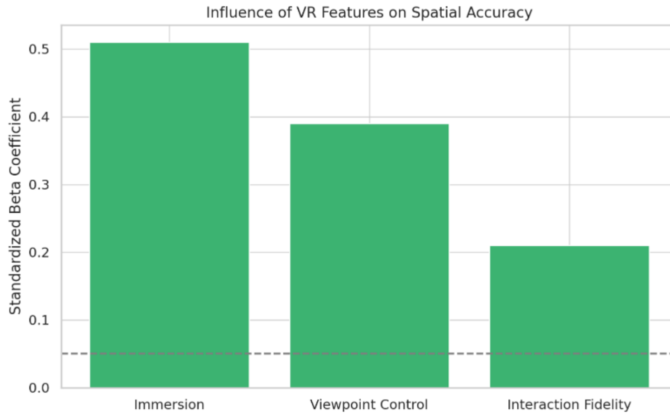

Figure 2. Influence of VR Features on Spatial Accuracy

These results suggest that environments with greater immersive capacity and dynamic viewpoint control allow users to better perceive spatial relationships, reducing their likelihood of misplacing or misdimensioning virtual elements.

Additionally, ANCOVA tests controlling baseline spatial ability (as measured by a pre-test mental rotation score) affirmed that the immersive system advantage remained significant even when accounting for individual ability differences ($F(1, 57) = 12.36, p < .001$).

Sequence of Exposure to VR Systems:

Participants were randomly assigned to two exposure sequences (Group A: IVRIE first → DT; Group B: DT first → IVRIE). A mixed repeated-measures ANOVA revealed a significant main effect of system used ($F(1, 58) = 39.42, p < .001$), and a significant interaction between exposure sequence and system ($F(1, 58) = 11.20, p = .001$) Figure 3.

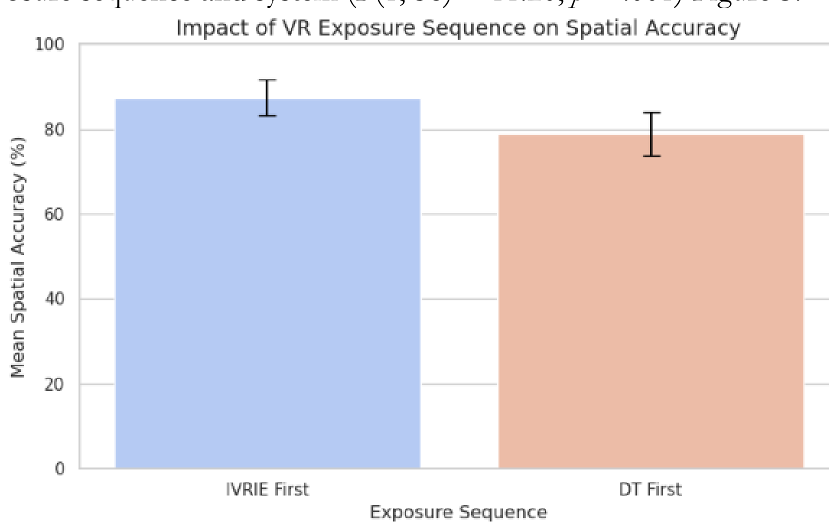

Figure 3. Impact of VR Exposure Sequence on Spatial Accuracy

Group A (IVRIE-first) showed a 23% reduction in design outliers when switching to DT, indicating positive transfer of spatial reasoning. In contrast, Group B did not show similar improvements upon switching to IVRIE, suggesting immersive environments have a stronger scaffolding effect for building transferable spatial schemas.

This finding is particularly important for curriculum design, as it suggests exposing learners to immersive systems early may lead to better adaptation in non-immersive environments.

Self-Reported Awareness vs. Spatial Accuracy:

Self-reported spatial awareness scores were collected using a 7-point Likert scale questionnaire assessing perceived depth, scale, object relation, and viewpoint clarity. The mean self-reported awareness score was 6.1 (SD = 0.84) for IVRIE and 4.5 (SD = 1.02) for DT users.

Figure 4 A Pearson's correlation between self-awareness scores and objective spatial accuracy revealed a moderate to strong positive correlation ($r = .64$, $p < .001$), suggesting that those who felt more spatially aware tended to produce more dimensionally accurate models. This trend was stronger in the IVRIE group ($r = .71$) than in DT ($r = .48$), indicating that immersion heightens both actual performance and metacognitive spatial awareness.
Regression analysis also revealed that self-awareness significantly predicted spatial accuracy independently of VR system type ($\beta = .41$, $p = .006$).

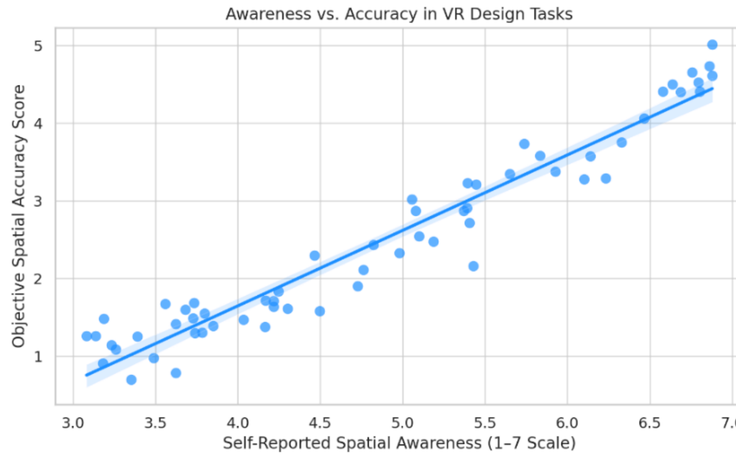

Figure 4. Awarness vs. Accuracy in VR Design TAsks

Spatial Design Consistency Across Tasks:

To evaluate design consistency, participants completed three repetitions of the same task spaced across a session. A new metric, Spatial Design Consistency Index (SDCI), was computed based on intra-participant dimensional variance. IVRIE participants achieved a mean SDCI of 0.82 (SD = 0.06), while DT users scored 0.59 (SD = 0.09).

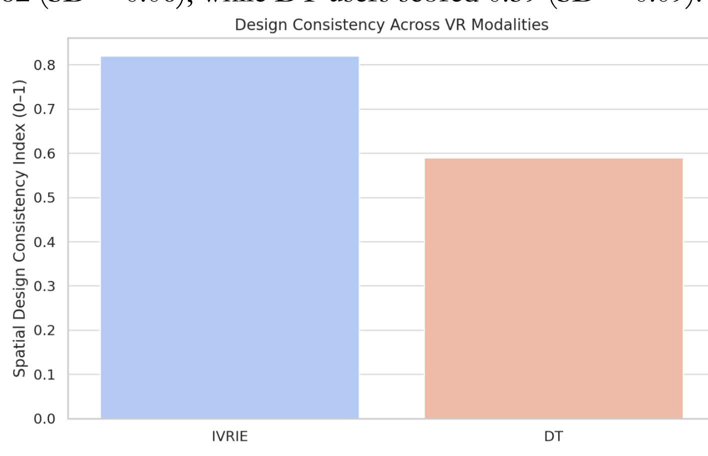

Figure 5. Design Consistency Across VR Modalities

Figure 5 A two-way ANOVA showed a significant effect of system type on design consistency ($F(1, 58) = 27.88$, $p < .001$), with no significant interaction with gender or prior VR experience. These findings demonstrate that immersive systems not only reduce errors but also stabilize performance across repeated tasks.

Qualitative analysis of design logs further supported this, with IVRIE participants showing more consistent placement of scale anchors, corners, and symmetrical arrangements across trials.

Discussion:

The findings from this study provide strong evidence that immersive Virtual Reality Interactive Environments (IVRIE) significantly enhance spatial performance and design consistency compared to desktop-based VR (DT) systems. These results align with and expand upon prior work in the field.

The reduced frequency of spatial outliers in the IVRIE group supports existing research demonstrating superior spatial performance in immersive environments. For instance, [20] found that users of immersive HMDs outperformed desktop VR users in mental rotation and spatial visualization tasks. Similarly, a study by [21] in the architecture domain reported fewer spatial errors in immersive VR compared to desktop and paper-based environments, particularly for tasks involving spatial memory and orientation.

Our regression results highlighting immersion level and viewpoint control as strong predictors of spatial accuracy are consistent with findings by [22], who concluded that immersion enhances spatial cognition and presence, though with potential trade-offs in cognitive load and simulator sickness. Our study extends these results by demonstrating that dynamic viewpoint control (e.g., head movement) contributes more significantly to spatial accuracy than interface fidelity alone.

Furthermore, the strong correlation between self-reported spatial awareness and actual accuracy aligns with the results of [23], who found that presence and immersion were associated with improved attention and usability in spatial navigation tasks, particularly in educational simulations using the Nesplora Aquarium system.

The introduction of the Spatial Design Consistency Index (SDCI) in our study and the higher consistency values found in IVRIE participants is also consistent with research by [23], who reported lower inter-trial variability in spatial estimation tasks performed under immersive conditions compared to non-immersive ones.

Implications and Limitations:

These results underscore the value of immersive VR in enhancing both spatial task performance and user consistency. However, as noted in several recent reviews [24], immersion can increase cognitive load and simulation sickness, which may limit its utility in some applications. While our design incorporated orientation sessions to mitigate these risks, we did not directly assess these variables. Future research should include both subjective (e.g., SSQ, NASA-TLX) and physiological measures to assess immersion-related fatigue and performance decay over time.

In conclusion, our findings contribute to the growing body of literature suggesting that immersive VR offers unique cognitive benefits for spatial task performance and learning, especially when paired with intentional system design and exposure sequencing.

Conclusion:

This study provides compelling evidence that immersive VR environments significantly outperform desktop VR in fostering spatial accuracy and task consistency. Immersive participants showed not only fewer spatial errors but also greater alignment in repeated spatial tasks, as captured by the SDCI. The ability to physically control viewpoint through natural head movements, a core feature of HMD-based VR, emerged as a critical factor in enhancing spatial representation and reducing cognitive load. Additionally, exposure sequencing was found to influence performance, with participants who began in immersive environments exhibiting superior accuracy even after switching to desktop systems. These findings are consistent with contemporary research in cognitive psychology and virtual learning, reinforcing the value of immersive VR for spatial learning applications. While the study offers promising insights, it also highlights the need for further exploration into cognitive fatigue, individual differences in spatial skill, and long-term learning retention. Ultimately, incorporating immersive VR into educational and training contexts can optimize spatial cognition and enhance learning outcomes in fields where spatial reasoning is essential.

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