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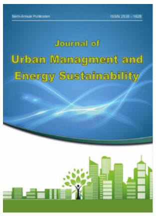

ORIGINAL RESEARCH PAPER

Modeling Psychological Interactions in Virtual Architecture: A Mediating Analysis of Sensory–Visual Perception Using PLS-SEM

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ABSTRACT

This study was conducted with the aim of modeling the psychological interactions between the designer and the user in virtual architectural space and examining the role of these interactions in the formation of sensory–visual perception. Despite the expansion of the use of virtual reality technologies, augmented reality, and interactive environments in architecture, understanding how environmental features are transformed into the user's perceptual experience still faces conceptual and analytical gaps. Accordingly, the present research explains this process by presenting a structural model based on three constructs: "virtual architecture," "psychological interactions," and "sensory visual perception." The research method is based on a quantitative approach and the use of structural equation modeling with the partial least squares method. Data were collected through a questionnaire with the participation of 250 students and individuals familiar with virtual architectural environments. The results showed that virtual architecture has a positive and significant effect on psychological interactions, and these interactions also have a direct and strong effect on sensory–visual perception. In contrast, the direct effect of virtual architecture on perception, in the presence of the mediating variable, was weaker and reported with a negative direction, while the total effect remained positive. These findings indicate that spatial perception in virtual environments is not formed directly, but rather through the user's active cognitive, behavioral–social, and educational engagement with the environment. The framework presented in this study can serve as a basis for designing interactive virtual environments, especially in architectural education.

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INTRODUCTION

In recent years, the rapid development of virtual reality (VR) technologies and interactive digital environments has significantly transformed the ways in which space is perceived, represented, and experienced in architecture. These technologies enable users to engage with simulated environments prior to the physical realization of architectural projects, allowing for immersive interaction with spatial elements (Radianti et al., 2020; Pellas et al., 2021). Within this evolving context, virtual reality has progressed beyond a purely representational tool and has emerged as an experience-oriented platform in which users actively participate in the formation of spatial perception (Makransky & Petersen, 2021). Despite these advancements, a considerable body of existing research has primarily focused on technical characteristics such as visual realism, immersion, and rendering quality, while comparatively limited attention has been given to the cognitive and psychological mechanisms underlying spatial experience (Allcoat & von Mühlenen, 2020; Suh & Prophet, 2021). This has resulted in a tendency to conceptualize the relationship between environmental features and perception as direct and linear. However, empirical evidence increasingly suggests that spatial experience in virtual environments is shaped through complex interactions between environmental attributes and users' mental processes (Riva et al., 2020; Grassini & Laumann, 2020). Recent studies highlight the importance of constructs such as presence, immersion, and cognitive engagement in influencing the quality of user experience in virtual environments. Nevertheless, these constructs alone are insufficient to fully explain how perception is formed (Baceviciute et al., 2022; Krokos et al., 2020). Spatial experience becomes meaningful only when users are able to actively process environmental information through cognitive, behavioral, and emotional mechanisms (Chen et al., 2023; Li et al., 2023). This perspective suggests that psychological interactions are not merely secondary factors but rather central mechanisms in the formation of perceptual experience.

In the context of architectural education, virtual environments have been increasingly adopted to enhance spatial understanding and design learning. However, research indicates that the effectiveness of these environments is highly dependent on the design of interaction and the level of cognitive engagement they facilitate (Parong & Mayer, 2020; Jensen & Konradsen, 2020). Environments that impose excessive cognitive load or restrict user interaction may reduce learning efficiency, even when they exhibit high visual quality (Ki et al., 2024; De Witte et al., 2025). Accordingly, there is a need to move beyond environment-centered approaches and toward models that place psychological processes at the core of analysis. In response to this need, the present study aims to explain the relationship between virtual architecture, psychological interactions, and sensory–visual perception by proposing a structural model in which psychological interactions function as a mediating variable. This model seeks to clarify how environmental features are transformed into perceptual experiences through user engagement processes. Virtual architecture, as an interactive environment, enables users to experience and evaluate spatial configurations prior to their physical realization. In such environments, users are not passive observers but active agents engaged in the process of spatial experience. Previous studies indicate that the quality of user experience depends on factors such as immersion, realism, interactivity, and design coherence (Radianti et al., 2020; Pellas et al., 2021). However, increasing immersion does not necessarily enhance experience; when poorly designed, it may increase cognitive load and reduce perceptual efficiency (Makransky & Petersen, 2021; Ki et al., 2024). Recent design approaches emphasize the importance of interaction and user experience in virtual environments. These approaches suggest that virtual architecture should be designed to actively engage users and provide conditions for meaningful perception (Zhao et al., 2022; Suh & Prophet, 2021). From this perspective, virtual architecture is not merely a final product but an interactive platform in which spatial experience emerges through the dynamic interaction between the user and the environment.

MATERIALS AND METHODS

Psychological interactions refer to a set of cognitive, behavioral, and emotional processes through which users engage with virtual environments. These processes include spatial understanding, navigation, decision-making, behavioral participation, and cognitive engagement, all of which contribute to shaping user experience (Chen et al., 2023; Yang et al., 2023). In this sense, psychological interactions function as a mediating mechanism that processes environmental information and transforms it into meaningful experience. Empirical studies demonstrate that the level of user interaction directly influences the quality of perception and learning (Parong & Mayer, 2020; Allcoat & von Mühlenen, 2020). Within this framework, psychological interactions can be conceptualized as the "engine of experience," playing a central role in activating cognitive and perceptual processes. This view aligns with contemporary theories of user experience and interactive learning, which emphasize the active role of individuals in constructing meaning (Riva et al., 2020; Baceviciute et al., 2022). Sensory–visual perception in virtual environments is an active and dynamic process involving the reception, processing, and interpretation of spatial information. Contrary to traditional perspectives that consider perception as passive, recent research indicates that perception in virtual environments emerges from the interaction between the user and the environment (Li et al., 2023; Chen et al., 2023). In this context, the quality of perception depends on factors such as spatial clarity, perceptual coherence, environmental analysis, and user experience. Cognitive engagement and active interaction play a crucial role in enhancing these aspects (Krokos et al., 2020; Grassini & Laumann, 2020). Therefore, sensory–visual perception should not be understood solely as an outcome of environmental features, but rather as the result of an interactive process in which users actively construct meaning. (Fig. 1)(Tab. 1)

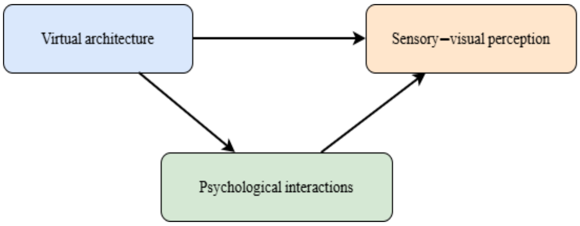

Figure 1: Initial conceptual model

Table 1: Constructs, Components, and Representative Items

Construct	Component	Representative Items
Virtual Architecture	Immersion and Simulation	Environmental realism; quality of lighting and shadows; accuracy of 3D modeling
	Interface Efficiency	Ease of use; clarity of controls; system response speed
	Multi-user Communication	Real-time user interaction; communication quality; support for teamwork
	Spatial Structure	Readability of spatial organization; clarity of pathways; understanding of spatial hierarchy
	Compatibility and Proportion	Proportional relationships; scale compatibility; alignment of elements with function
	Design Coherence	Integration of form and function; coordination of spatial elements; visual coherence of the environment

Psychological Interactions	Educational Principles	Alignment with educational objectives; facilitation of conceptual learning; appropriate instructional structure
	Learning Participation	Engagement in the learning process; educational interaction; active involvement
	Supportive Learning Tools	Availability of assistive tools; access to supplementary information; support for interactive learning
	Cognitive Capacity	Navigation ability; understanding of spatial relationships; formation of mental maps
	Behavioral–Social Interaction	Active interaction with the environment; group participation; behavioral responses to space
Sensory–Visual Perception	Perceptual Clarity	Clarity of spatial understanding; perception of depth and distance; accurate scale recognition
	Perceptual Coherence	Integration of mental imagery; continuity of spatial elements; overall perceptual harmony
	Improvement of Spatial Analysis	Ability to analyze space; evaluation of environmental structure; understanding spatial relationships
	Enhancement of Design Skills	Increased creativity; improvement in spatial design skills; development of ideation

Methodology

This study was conducted with the aim of explaining the relationships among virtual architecture, psychological interactions, and sensory–visual perception, using a quantitative approach within a descriptive–analytical research design. The conceptual framework of the study is structured as a three-construct model, in which psychological interactions are considered as a mediating variable, and their role in transferring environmental effects to perceptual outcomes is examined. To test the proposed model and analyze the relationships among constructs, Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed. The selection of this method was based on the predictive nature of the study, the complexity of the model structure, and the presence of multidimensional constructs. This approach enables the simultaneous evaluation of both the measurement model and the structural model, while also offering greater flexibility in handling data distribution and sample size limitations. Furthermore, its focus on explaining and predicting relationships among constructs makes it particularly suitable for studies aimed at developing and testing conceptual models. The research data were collected through a structured questionnaire designed based on the conceptual framework of the study and the results of the prior phase (component extraction). The questionnaire consisted of a set of items developed to measure different dimensions of the main constructs. All items were measured using a five-point Likert scale, allowing respondents to indicate the degree of their agreement with each statement. The statistical population included students and professionals in the field of architecture and design who had experience working with digital environments and spatial simulation tools. Sampling was conducted using purposive and convenience methods, and in total, approximately 200 valid responses were used for analysis. Considering the requirements of the PLS-SEM method and the complexity of the model, this sample size was deemed sufficient to obtain stable and reliable results. In the data analysis phase, the evaluation was conducted in two main stages. First, the measurement model was assessed to examine the reliability and validity of the constructs. Then, the structural model was analyzed to investigate the relationships among variables. In this stage, path coefficients were calculated to determine the strength and direction of relationships, and their significance was tested using the bootstrapping method. In addition, indicators such as the coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2) were used to evaluate the performance of the model. Finally, to examine the mediating role of psychological interactions, mediation analysis was conducted with a focus on direct, indirect, and total effects. This analysis provided a more precise understanding of how the effects of virtual architecture are transferred to sensory–visual perception and clarified the actual role of psychological interactions within the structure of the model.

DISCUSSION AND FINDINGS

In the first step, the measurement model was evaluated. The results indicated that all first-order constructs exhibited acceptable internal consistency. Cronbach's alpha values ranged from 0.725 to 0.893, and composite reliability values ranged from 0.846 to 0.933. In addition, the average variance extracted (AVE) for all constructs exceeded 0.648, confirming adequate convergent validity. Factor loadings were generally within acceptable ranges, with most values exceeding 0.70. However, a few items with lower loadings were retained in the model due to their conceptual importance in covering the dimensions of the constructs. To assess the overall adequacy of the data prior to structural analysis, the KMO index was reported as 0.942, and Bartlett's test of sphericity was significant ($\chi^2 = 9534.189$, df = 990, $p < 0.001$). These results indicate that the data possess sufficient correlations for factor analysis and structural modeling. Furthermore, discriminant validity was examined using the Fornell–Larcker criterion and the HTMT index. The results confirmed that the constructs exhibit adequate empirical distinctiveness and can be retained as separate variables within the model. (Fig. 2)

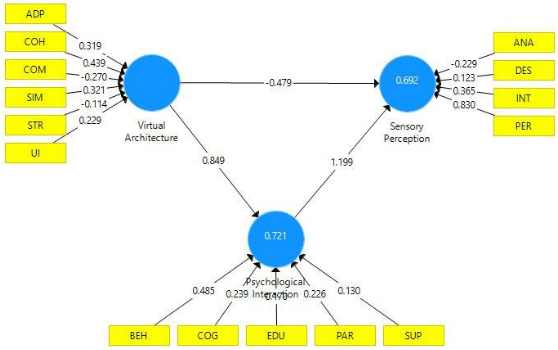

Figure 2: Structural model results based on PLS-SEM

In the evaluation of the structural model, path coefficients indicated that virtual architecture has a strong and highly significant positive effect on psychological interactions ($\beta = 0.849$, $t = 41.935$, $p < 0.001$). Similarly, psychological interactions showed a very strong positive effect on sensory–visual perception ($\beta = 1.199$, $t = 19.570$, $p < 0.001$). In contrast, the direct path from virtual architecture to sensory–visual perception, although statistically significant, exhibited a negative coefficient ($\beta = -0.479$, $t = 6.663$, $p < 0.001$). This pattern suggests that spatial perception in virtual environments follows a mediation-driven mechanism. The coefficient of determination (R^2) was 0.721 for psychological interactions and 0.692 for sensory–visual perception, indicating substantial explanatory power of the model. Effect size analysis revealed that the impact of virtual architecture on psychological interactions was very large ($f^2 = 2.580$), and the effect of psychological interactions on sensory–visual perception was also substantial ($f^2 = 1.302$). In contrast, the direct effect of virtual architecture on perception was at a moderate level ($f^2 = 0.208$). The Q^2 index was 0.447 for psychological interactions and 0.253 for sensory–visual perception, confirming the predictive relevance of the model. Mediation analysis demonstrated that the indirect effect of virtual architecture on sensory–visual perception through psychological interactions is very strong. The total effect of virtual architecture on perception was calculated as 0.539, indicating that although the direct path is weaker and negative, the indirect path accounts for the primary transmission of effects. This finding highlights that psychological interactions are not merely a simple mediator, but rather the structural core of the research model. (Fig. 3) (Tab. 2)

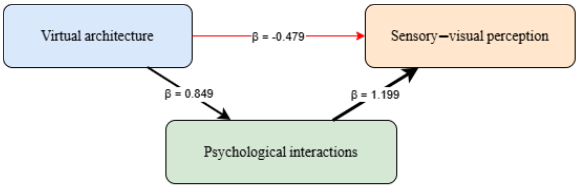

Figure 3: Mediating effect of psychological interactions

Table 2: Measurement Model Evaluation Results

Component	Cronbach's Alpha	rho_A	Composite Reliability	AVE
ADP	0.877	0.877	0.924	0.802
ANA	0.893	0.895	0.933	0.824
BEH	0.773	0.775	0.870	0.692
COG	0.878	0.878	0.925	0.803
COH	0.779	0.784	0.873	0.698
COM	0.884	0.887	0.928	0.811
DES	0.889	0.889	0.931	0.818
EDU	0.862	0.864	0.916	0.784
INT	0.772	0.773	0.869	0.689
PAR	0.773	0.777	0.868	0.687
PER	0.879	0.880	0.926	0.805
SIM	0.840	0.853	0.902	0.755
STR	0.772	0.780	0.870	0.692
SUP	0.725	0.721	0.846	0.648
UI	0.740	0.753	0.856	0.667

The results presented in Table 2 indicate that all components of the model meet acceptable thresholds for reliability and convergent validity. High values of composite reliability and AVE suggest that the measurement items consistently capture the intended conceptual dimensions. These results provide a solid basis for proceeding to discriminant validity assessment and structural model analysis. (Tab. 3)

Table 3: Summary of Discriminant Validity

Indicator	Result	Interpretation
Fornell–Larcker Criterion	Confirmed	Square root of AVE for each construct exceeded its correlations with other constructs
HTMT	Confirmed	Values were within acceptable thresholds
KMO and Bartlett Test	Confirmed	KMO = 0.942 and Bartlett's test was significant

Based on the results in Table 3, discriminant validity is confirmed, indicating that each construct is empirically distinct from others. The simultaneous confirmation of the Fornell–Larcker criterion and HTMT index demonstrates that the conceptual structure of the model is both coherent and sufficiently differentiated. Therefore, the conditions required for structural model analysis are satisfied.(Tab. 4)

Table 4: Structural Model Results

Path	β	T	P	Result
Virtual Architecture → Psychological Interactions	0.849	41.935	<0.001	Significant
Psychological Interactions → Sensory–Visual Perception	1.199	19.570	<0.001	Significant
Virtual Architecture → Sensory–Visual Perception	-0.479	6.663	<0.001	Significant

The results presented in Table 4 indicate that all main paths in the model are statistically significant. This confirms that the relationships defined within the conceptual framework are empirically supported and can be analyzed within a coherent structural system. (Tab. 5)

Table 5: Coefficient of Determination, Effect Size, and Predictive Relevance

Indicator	Construct/Path	Value	Interpretation
R^2	Psychological Interactions	0.721	High explanatory power
R^2	Sensory–Visual Perception	0.692	High explanatory power
f^2	Virtual Architecture → Psychological Interactions	2.580	Very large effect
f^2	Psychological Interactions → Perception	1.302	Very large effect
f^2	Virtual Architecture → Perception	0.208	Moderate effect
Q^2	Psychological Interactions	0.447	Adequate predictive relevance
Q^2	Sensory–Visual Perception	0.253	Adequate predictive relevance

The indicators in Table 5 demonstrate that the model has strong explanatory and predictive capabilities. High R^2 values indicate that a substantial proportion of variance in endogenous constructs is explained by the model. (Tab. 6)

Table 6:Direct, Indirect, and Total Effects

Path	Direct Effect	Indirect Effect	Total Effect
Virtual Architecture → Psychological Interactions	0.849	–	0.849
Psychological Interactions → Sensory–Visual Perception	1.199	–	1.199
Virtual Architecture → Sensory–Visual Perception	-0.479	1.018	0.539

Overall, the structural model results indicate that relationships among the constructs follow a clear pattern in which psychological interactions play a central role in effect transmission. Comparison of direct and indirect effects reveals that indirect pathways dominate the formation of sensory–visual perception, emphasizing the importance of mediation mechanisms. Additionally, differences in effect sizes indicate that not all relationships contribute equally to explaining the dependent variables, with some paths having a more decisive role. Model fit and predictive indicators further confirm that the proposed structure is capable of effectively explaining and predicting variable behavior. These findings demonstrate that the proposed model is not only statistically valid but also serves as a robust analytical framework for examining spatial experience in virtual environments. The analyses presented in this section provide a foundation for deeper interpretation and for deriving theoretical and practical implications in the discussion section.

RESULT AND CONCLUSION

The results obtained from the structural model analysis indicate that sensory–visual perception in virtual architectural environments is not the outcome of a simple and direct process, but rather is formed through a multi-layered, mediation-driven mechanism. In this process, psychological interactions act as a central element, playing a decisive role in transforming environmental characteristics into perceptual experience. This finding challenges traditional environment-centered approaches and demonstrates that focusing solely on visual quality or environmental realism is insufficient for achieving a deep spatial experience. The analysis revealed that the relationship between virtual architecture and psychological interactions is highly significant, highlighting the important role of environmental features in activating users' cognitive and behavioral processes. However, more critical than this relationship is the very strong influence of psychological interactions on sensory–visual perception. This suggests that spatial perception is not formed directly from the environment, but rather emerges through the user's active engagement with it. In other words, users are able to achieve a deeper understanding of space only when they actively participate in the interaction process. On the other hand, the results showed that the direct effect of virtual architecture on perception is weaker compared to its indirect effect. This pattern indicates that increasing environmental complexity or quality, without effective interaction design, does not necessarily lead to improved perception. In some cases, it may even increase cognitive load and reduce perceptual efficiency. This finding underscores the critical importance of interaction design in virtual environments.

The mediation analysis further demonstrated that a substantial portion of the effect of virtual architecture on perception is transmitted through psychological interactions. This indicates that psychological interactions are not merely an intermediary variable but rather a key structural element within the model, functioning as the "engine of experience." This perspective provides a new framework for understanding spatial experience in virtual environments, in which user interaction is considered the central axis of analysis. From a practical standpoint, the findings suggest that the design of virtual environments should extend beyond visual representation and focus on creating conditions that facilitate active user engagement. This includes designing comprehensible spatial paths, developing interactive scenarios, and providing supportive tools that enhance cognitive involvement. In this framework, the quality of spatial experience depends on the environment's ability to activate psychological interactions. Overall, the findings of this study indicate that architectural experience in virtual environments is the result of an interaction-driven process in which users play an active role in constructing meaning. This insight can serve as a foundation for developing new approaches in digital architectural design and virtual reality-based learning environments. (Fig. 4)

The findings of this study confirm that the proposed model demonstrates satisfactory validity and reliability and is capable of explaining the relationships among virtual architecture, psychological interactions, and sensory–visual perception within a coherent structural framework. The results of the measurement model indicated adequate internal consistency and convergent validity across all constructs, while the structural model revealed statistically significant relationships among latent variables. These findings support the robustness of the conceptual model and its ability to provide a meaningful explanation of how spatial perception is formed in virtual architectural environments. A more detailed analysis of the structural relationships highlights the critical role of psychological interactions as the central mechanism in shaping perceptual experience. The results indicate that perceptual outcomes are strongly influenced by cognitive and perceptual dimensions such as visual–lighting quality, perceptual coherence, and users' cognitive capacity. At the same time, interactive, educational, and communicative components function as facilitating factors that enhance user engagement and deepen the experiential process. This suggests that spatial perception in virtual environments is a multidimensional phenomenon emerging from the dynamic interaction between environmental characteristics, user capabilities, and the quality of interaction design. Overall, the study emphasizes the necessity of adopting an integrated approach to the design of virtual environments, in which visual, cognitive, perceptual, and interactive dimensions are simultaneously and coherently addressed. The proposed model provides a valuable analytical framework for evaluating and optimizing user experience in virtual architectural design and can assist designers in making more informed decisions. Furthermore, this framework offers a foundation for future research on human–environment interaction in digital spaces and contributes to improving design education, enhancing creativity, and increasing the effectiveness of design processes.

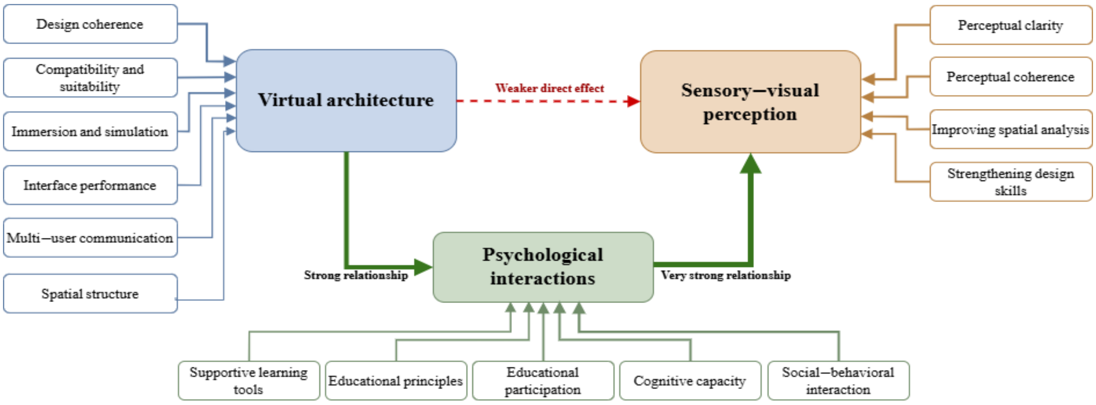

Figure 4: An integrated conceptual framework of psychological interaction in virtual architecture

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