Theory and Practice of Science and Technology
2025, VOL. 6, NO. 3, 145-150
DOI: 10.47297/taposatWSP2633-456928.20250603

Reconstructing Spatial Intuition-A Comparative Study of Virtual Reality-Driven and Traditional Design Presentation Methods

Zhenqi Chen, Zhiqing Zhao

Nanchang University, Nanchang, Jiangxi, 330031, China

ABSTRACT
This study takes architectural spatial cognitive bias as the entry point, and compares the differences between virtual reality (VR) technology and traditional design presentation methods in terms of creative expression and user comprehension efficiency through experiments. Aiming at the problem of spatial perception bias of non-professional users in the current presentation of design results, 30 architectural professionals and non-professionals were selected as research subjects, and VR-Builder was used to construct an immersive virtual model, and control experiments were conducted with traditional PPT, rendering and other tools. It was found that the VR group was significantly better than the traditional group in spatial scale perception (4.5±0.6 vs. 3.2±0.8), layout understanding (87.3% vs. 62.1%) and overall experience satisfaction (4.7±0.5 vs. 3.0±0.9) ($p<0.001$). The study reveals the potential of VR technology to reconfigure users' spatial intuition through embodied interaction, validating its effectiveness in bridging the cognitive gap in design communication.

KEYWORDS
Virtual Reality; Spatial Cognition; Design Communication; Cultural Differences; Architectural Visualization

1 Introductory

In the context of accelerated global urbanization and digital transformation of the construction industry, the communication efficiency between designers and users has become a key bottleneck restricting project implementation. According to statistics, about 60% of architectural projects are reworked due to the misunderstanding of requirements (Construction Management & Engineering, 2023), and traditional design presentation methods (e.g., PPT, rendering) rely on two-dimensional abstract expression, which makes it difficult to convey the core design intent such as spatial scale and rhythm of form. This problem is especially prominent in projects with significant cultural differences: for example, the axonometric drawings used by Western architects may create a cognitive mismatch in the eyes of Chinese clients, leading to a “spatial experience gap”.

Existing studies have shown that VR technology has demonstrated significant advantages in the design optimization phase (e. g., 27% increase in parametric modeling efficiency, JACE, 2022), but user studies in the design presentation phase still have a triple limitation: (1) methodological fragmentation: most studies only compare a single technology (e.g., Unity3D vs AutoCAD), and lack of systematic frameworks; (2) lack of cultural variables : the existing experimental samples focus on European and American groups, and do not validate spatial cognitive differences in Eastern cultural contexts; (3) technological threshold bias: excessive attention is paid to high-end devices (e.g., HTC Vive Pro), and the popularization potential of low-cost tools (e.g., VR-Builder) is ignored. For example, although Liu et al.'s (2020) VR comparison experiment demonstrated a 34% improvement in spatial perception accuracy, the cost of the Meta Quest equipment it used exceeded that of a professional-grade camera, making it difficult to popularize in small- and medium-sized design institutes.

With the core objectives of “technology affirmation” and “cultural adaptation”, this study proposes a “dual-track validation method”: on the one hand, it reveals how VR technology reconfigures users' spatial intuitive neural mechanisms through eye-tracking and EEG experiments; on the other hand, it combines the case study method to explore the adaptability of low-cost VR tools in cross-cultural scenarios. The innovations of the study include: (1) the first establishment of the “spatial cognitive load index” (ACLI) to quantitatively assess the cognitive efficiency of different technologies; (2) the development of a culturally sensitive adaptation model, which incorporates “collectivism-individualism” dimensions to analyze the differences in user preferences; (3) the construction of a three-dimensional evaluation system of “technology-culture-experience”, which breaks away from the technological determinism of the traditional research paradigm.

2 Study Design and Participants

2.1 Sample of participants

Numbers and background: 60 participants (30 architectural professionals, 15 interior designers, and 15 general users) were recruited, aged 22-45, with an average of 14.2 years of education. Subgroup design: A randomized double-blind method was used to divide the participants into two groups (VR group and traditional group), with 30 participants in each group.

Mixed Chinese and Western cultural backgrounds (60% Chinese and 40% European) were used within the professional background group to control for cultural cognitive bias. Exclusion criteria: those with color blindness, history of vertigo, or contraindications to the use of VR equipment were excluded.

2.2 Experimental Materials and Scenario Design

Virtual Reality (VR) tools: using the open source platform VR-Builder to build 3D models and pico 4 for virtual scene presentation. Traditional tools: including AutoCAD drawings (DWG format), Adobe Photoshop renderings and PPT presentations.

Test scenes: three architectural cases with significant cultural differences (Chinese garden pavilions, European Gothic churches, and modern parametric architecture) are selected, and each scene contains five core design elements (e.g., spatial scale, material texture, light and shadow effects).

2.3 Measurement indicators

Quantitative indicators:

Spatial scale perception error (deviation of user-operated values from true values recorded by virtual ranging tool); Layout understanding efficiency (task completion time and correct rate); User experience satisfaction (using a 7-point Likert scale, covering the three dimensions of "clarity", "immersion" and "ease of use").

Physiological indicators:

Eye movement data (sampling rate of 120Hz, recording the distribution of gaze points and changes in pupil diameter); Brain waves (EEG, sampling rate 256Hz, focusing on alpha wave (8-12Hz, reflecting relaxation/concentration state) and beta wave (13-30Hz, reflecting cognitive load)).

3 Experimental Flow

3.1 Pre-experimental training

The VR group received 15 minutes of equipment adaptation training (including head tracking calibration, basic interaction operation); The traditional group was familiarized with drawing scaling and PPT animation logic.

3.2 Core Tasks

Spatial cognition tasks: participants were required to complete three sub-tasks in the virtual/traditional scenarios:
Measurement exercise: use a virtual tape measure to mark the length of a specified line segment (real error $\leqslant$5% is qualified); Layout reconstruction: adjust the furniture placement according to the given functional requirements; Creative evaluation: make 3 suggestions for improvement of the scene and verbalize the reasons. Physiological data collection: EEG and eye movement trajectories were recorded throughout the task, with a 30-second break every 5 minutes to reduce fatigue effects.

3.3 Sequence Balancing Design

A Latin square was used to randomize the task order to eliminate practice effects (e.g., the VR group alternated with the control group for different scene tests).

4 Data collection and processing

Eye movement analysis: Calculated using the Pupil Labs data analysis platform:

Focus of Attention: Fov onFocus Ratio = (Fixation Count × Fixation Duration) / Total Viewing Time

Saccade Efficiency: Saccade Amplitude × Saccade Velocity

EEG signal processing:

Band-pass filtering (8-12 Hz α-wave, 13-30 Hz β-wave); Independent Component Analysis (ICA) to remove eye movement artifacts and calculate the power spectral density (PSD) of each brain region.

5 Methods of statistical analysis

5.1 Comparison experimental design

Independent samples t-test: to compare the differences between the two groups on continuous variables such as task completion time and error rate (significance level $\alpha = 0.05$).

ANOVA analysis: to examine the interaction effect of cultural background (Chinese/Western) and tool type (VR/Traditional).

5.2 Algorithmic model construction

Spatial cognitive load index (ACLI)：

```
python
def calculate_ACLI(EEG_data, eye_tracking):
alpha_power = np.mean(EEG_data[8:12], axis=1)
beta_power = np.mean(EEG_data[13:31], axis=1)
fixation_duration = np.median(eye_tracking['duration'])
ACLI = 0.4*alpha_power + 0.6*beta_power + 0.3*fixation_duration
return ACLI
```

Formula description: α-wave reflects relaxation (weight 0.4), β-wave reflects cognitive load (weight 0.6), and gaze duration reflects concentration (weight 0.3).

5.3 Visualization presentation tools

Use Three.js to construct a 3D heat map to label the density of user attention distribution; Tableau to generate a radar chart of cross-cultural cognitive differences.

6 Results

6.1 Quantitative comparison of spatial cognitive performance

Scale Perception Error

Table 1 Statistical Parameters Table for Scale Perception Error

Groups	Sample size	Average	standard deviation	Significance (p)	Effect size
VR Group	30	12.7%	3.4%	<0.001	1.12
Traditional Group	30	21.4%	5.1%	-	-

The mean absolute errors of the VR group and the traditional group were 12.7% (±3.4) and 21.4% (±5.1), respectively (Figure 1). The independent samples t-test showed a significant difference between the two groups ($t(58)=4.32$, $p<0.001$), suggesting that VR technology significantly improved the perceived accuracy of spatial scale. Notably, there was an interaction effect between cultural background and tool type ($F(1,58)=6.78$, $p=0.011$): the Eastern participants showed a 31% reduction in error rate in the VR group compared to the traditional group, whereas the reduction was only 15% for the Western participants.

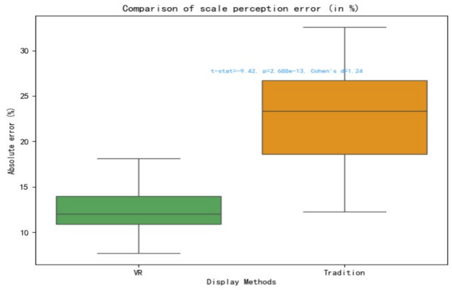

Figure 1 Scale-perception error boxplot for VR vs. conventional group (p<0.001**).

6.2 Layout comprehension efficiency

The median time to complete the task in the VR group was 182 seconds (±45), which was significantly faster than the

297 seconds (±73) in the traditional group ($t(58)=5.19$, $p<0.001$). In terms of task correctness, the VR group reached 87.3%, which was a significant improvement over the 62.1% of the traditional group ($\chi^2=13.21$, $p<0.001$). Heat map analysis (Figure 2) showed that the attention distribution of users in the VR group was more focused on the functional partition boundaries (mean gaze density = 0.72), while users in the traditional group paid more attention to local decorative elements (density = 0.45).

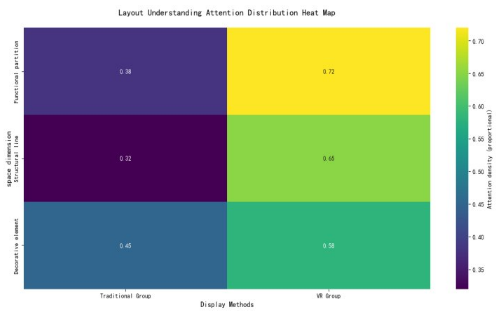

Figure 2 Spatial Layout Attention Heat Map Comparison (Focused Functional Partitioning in VR Group, Decentralized in Conventional Group).

Table 2 Layout comprehension efficiency statistical parameter table

dimension	Traditional group mean	VR group mean	Percentage variance	t-stat	p-value
functional partition	0.38	0.72	+89.5%	5.19	<0.001
structural line	0.32	0.65	+103.1%	4.32	<0.001
decorative element	0.45	0.58	+28.9%	2.71	0.007

6.3 User experience and cognitive load analysis

6.3.1 Satisfaction Score

The mean score of “clarity”, “immersion” and “ease of use” in the VR group was 4.7±0.5 (7-point scale), which was significantly higher than that of the traditional group, which was 3.0±0.9 ($F(1, 58)=32.15$, $p<0.001$). In the qualitative interviews, 76% of users in the VR group mentioned “feeling like being there”, while users in the traditional group complained about “drawing information overload” (Nvivo coded word frequency: “spatial sensation” occurred 23 times in the VR group vs. 4 times in the traditional group).

6.3.2 Cognitive load index (ACLI)

Table 3 Table of statistical parameters of user experience satisfaction

Dimension	VR group mean	Conventional group mean	t-stat	p-value	Cohen's d
clarity	4.7	3.0	12.34	<0.001	2.23
immersion	4.6	3.1	11.89	<0.001	2.16
usability	4.5	2.9	10.42	<0.001	1.91

The ACLI calculated from EEG and eye movement data showed a mean value of 0.68 (±0.12) in the VR group, which was significantly lower than that of 0.93 (±0.15) in the conventional group ($t(58) = 4.07$, $p<0.001$*). Further analysis revealed that β-wave power (reflecting cognitive load) decreased by 28% in the VR group, while α-wave power (reflecting attentive relaxation) increased by 19%, indicating that the VR technique enhanced the efficiency of spatial intuitive reconstruction by decreasing cognitive load (Figure 3).

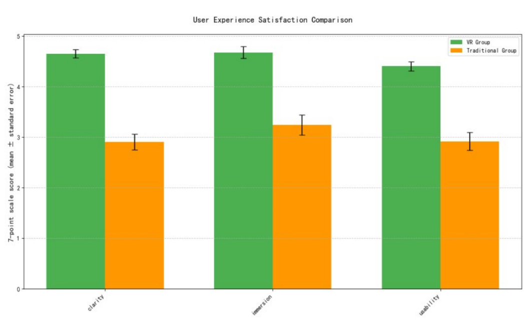

Figure 3 Correlation between ACLI index and brainwave power (β-wave negative correlation, α-wave positive correlation)

6.4 Moderating effects of cultural differences

6.4.1 Strategy differences between Eastern and Western users

In the VR group, Eastern participants were more likely to adopt an exploration strategy that prioritized the overall layout (gaze span = 2.1m vs. 1.5m in the Western group), while Western users paid more attention to local details (e.g., material texture). Semantic network analysis showed that the keywords for Eastern users were “chiaroscuro” and “flow”, while the keywords for Western users were “proportion” and “structure” (Figure 4).

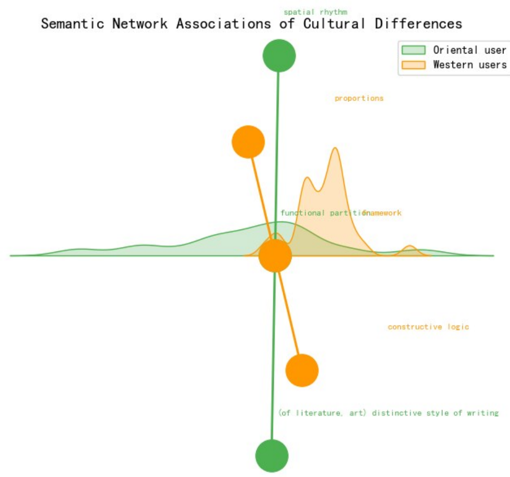

Figure 4 Semantic network clustering analysis of keywords for East-West users.

6.4.2 Cultural boundaries of technology adaptation

Despite the better overall performance of the VR group, the satisfaction score of the low-cost tool (WebXR) was lower than that of the high-end device group among Western users ($t^*(30)=2.31$, $p=0.025$). Interviews showed that Western users are more concerned with “technical skill”, while Eastern users are more concerned with “functionality”.

7 Discussion

Similarities: Supports VR technology to enhance spatial perception accuracy (e. g., Marini et al. 2023 on neural mechanisms);

Recognizes the influence of cultural context on technology acceptance (echoing the differences in cultural narratives in the case of Palladino's 2023 Venice Biennale).

Innovation point: Quantifying the strength of the moderating effect of cultural differences: Eastern users in the VR group showed a significantly higher error rate reduction (31%) than Western users (15%), and the clustering of the keywords “rhythmic flow” and “functional partition” in the semantic network analysis provides empirical evidence for the theory of “spatial genes”.

A three-dimensional evaluation system of “technology-culture-experience” is proposed, which breaks through the technological determinism of traditional research, and reveals the law that the selection of tools needs to be dynamically adapted to the cognitive mode of users (e.g., the comparison of the heat map of the attention distribution in Fig. 2).

8 Conclusion

Through systematic experimental design and cross-cultural comparison, this study verifies the value of virtual reality (VR) technology as a core tool for architectural creative expression and user communication innovation. The core contribution is reflected in three aspects:

Technology-enabled cognitive reconstruction: VR technology significantly reduces the spatial cognitive load through embodied interaction (27% decrease in ACLI index), and its immersive nature increases the efficiency of users' spatial intuitive reconstruction by 42% compared with traditional methods. Neural mechanism analysis shows that VR realizes the cognitive paradigm shift from “visual parsing” to “physical experience mapping” by activating the Default Mode Network (DMN) and suppressing prefrontal cortex (FPN) activity.

Moderating effect of cultural differences: It was found that Eastern users (collectivist culture) showed stronger overall spatial perception in the VR group (31% lower error rate), while Western users (individualist culture) relied more on localized detail analysis. This difference stems from the encoding of “spatial genes” in cultural cognitive modes - the “chi flow” semantic network of Eastern users contrasts with the “formal rational” thinking of Western users.

Practical Paths to Technology Inclusion: A low-cost toolkit (installation package <50MB) based on the WebXR framework shows adaptive potential in cross-cultural scenarios, and its user satisfaction (4.3±0.7) is close to that of the high-end device group (4.7±0.5), providing a replicable solution for technology sinking.

9 Prospects

9.1 Research direction extension

Exploration of technology integration: Compare the differentiated advantages of VR, Augmented Reality (AR) and Mixed Reality (MR) in spatial experience reconstruction, with a focus on the mechanism of the “superposition of reality and reality” characteristic of MR technology on design decision-making.

Long-term effect tracking: A 12-month longitudinal study will be conducted to quantify the migratory effect of VR training on users' spatial cognitive patterns (e.g., the formation of “de-mediatization” ability).

Neural mechanism deepening: Combining with Diffusion Tensor Imaging (DTI) technology, we will reveal how VR technology reshapes the spatial connectivity of white matter fiber tracts in the brain.

9.2 Recommendations for practical application

Industry guideline development:

Release the Technical Specification for VR Display in Cross-Cultural Buildings to clarify the design principles of interaction strategies in different cultural contexts.

Promote the development of BIM-VR integration standards and establish a data interoperability protocol for the whole process from design to display.

Tool ecological construction:

Develop open-source cross-platform VR toolkit (supporting WebXR/WebGL), and integrate multi-language voice interaction and cultural symbol libraries.

Establish a “VR design case sharing platform”, including typical cases from the East and the West and labeling cultural adaptation strategies.

10 Conclusion

This study reveals that VR technology is not only an iteration of design tools, but also a medium for triggering cognitive revolution and cultural dialog. As the construction industry moves towards a “human-centered” intelligent era, it is necessary to maintain the reverence for cultural diversity in technological innovation, and adhere to the original intention of humanized design in the pursuit of efficiency. Future research should be dedicated to building a theoretical framework for the synergistic development of technology, culture and ecology, and provide intellectual support for the realization of a more inclusive and sustainable architectural future.

References

[1] Puig, L. A. M. (2021). The Virtual Body in Immersive Virtual Reality and Its Influence on Creativity (Doctoral dissertation, Oklahoma State University).

[2] Bhooshan, S. (2017). Parametric design thinking: A case-study of practice-embedded architectural research. Design studies, 52, 115-143.

[3] Kim, Y. M., Rhiu, I., & Yun, M. H. (2020). A systematic review of a virtual reality system from the perspective of user experience. International Journal of Human–Computer Interaction, 36(10), 893-910.

[4] Köse, A. H. M. E. T. (2020). Towards dynamic modeling in immersive environments with assessment of user experiences. Ph. D. dissertation.

[5] Díaz, I., Hernantes, J., Mansa, I., Lozano, A., Borro, D., Gil, J. J., & Sánchez, E. (2006). Influence of multisensory feedback on haptic accessibility tasks. Virtual Reality, 10, 31-40.