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Research on Virtual Architectural Space Design Based on "Mirror" VR Experiment

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Abstract: Virtual Reality (VR) technology offers immersive and interactive embodied experiences, yet cybersickness hinders comfort. While enhancing embodiment may ease it, systematic virtual space design optimization from embodied cognition is lacking. This study uses VR experiments to verify mirror exposure can boost embodiment and reduce cybersickness in virtual architectural spaces. It then proposes spatial and interactive optimizations for VR architectural environments. After introducing VR experiment backgrounds, procedures, contents, and results, based on findings, focusing on game architectural spaces with "window mirrors" as the core, two optimization directions are put forward. At the spatial level, adjust scale distance, furniture arrangement, and landscape courtyard configuration to optimize social space layout, balancing aesthetics and performance. At the interactive level, design adjustable mirror clarity, transparency, and multi - posture adaptation to enhance interaction while balancing performance. Following "theoretical framework - experimental verification - data analysis - application transformation", the study identifies the embodiment - cybersickness correlation in virtual environments via VR experiments, proposes a virtual architectural space optimization design scheme, and improves VR user experience in aspects like spatial scale, movement logic, and interaction, providing a practical paradigm for virtual space design guided by embodied cognition theory.

Keywords: Embodiment; Cybersickness; Virtual Reality; Virtual Architectural Space Design

1. Introduction

1.1 Background

With the rapid development of information technology, Virtual Reality (VR), as an emerging interactive medium, is profoundly transforming various fields such as human-computer interaction, entertainment experience, education and training, and healthcare. Compared with traditional media (e.g., books, movies, television), the core features of VR lie in its immersion, interactivity, and imagination, enabling users to enter the virtual environment in an "embodied" manner and obtain a more realistic and autonomous experience. However, VR experiences can cause an uncomfortable physical state known as cybersickness (CS), with symptoms including dizziness, nausea, and eye movement disorders during CS. This issue seriously affects players' immersion and comfort.

As an important carrier of the virtual environment, virtual architectural space differs essentially from real architectural space in terms of design logic, technical implementation, and user experience. For instance, real architecture is strictly constrained by physical laws (gravity, material mechanics) and functional requirements (lighting, ventilation), while virtual architectural space is entirely defined by digital rules, which can break through real-world limitations and realize surreal structures. In the interactive dimension, traditional architectural theories cannot be directly applied to virtual architectural spaces.

Virtual avatars, as the interface between the real world and the virtual world [1], are reconstructing the paradigm of human-computer interaction. The design of virtual architectural spaces not only needs to meet functional and aesthetic requirements but also needs to target virtual avatars. However, current research mostly focuses on technical implementation or single sensory experiences, with few studies analyzing architectural space design from the perspective of embodied cognition.

1.2 Cybersickness

In the field of cybersickness (CS) research, several important theories have been proposed to explain its underlying mechanisms (Figure 1). Among them, the earliest and most widely accepted is the Sensory Conflict Theory [2], which holds that cybersickness arises from a mismatch between sensory information and the brain's expectations. On this basis, the Postural Instability Theory [3] emphasizes the role of postural control, suggesting that cybersickness occurs when the human body fails to maintain stability in the virtual environment [4].

The "Poison Theory" [5] proposes from an evolutionary perspective that cybersickness is a protective response triggered when the brain misinterprets sensory conflicts as potential poisoning threats. The newly proposed Sensory Reweighting Theory [6] focuses on the brain's mechanism of recalibrating conflicting sensory inputs, and discomfort arises when this process malfunctions.

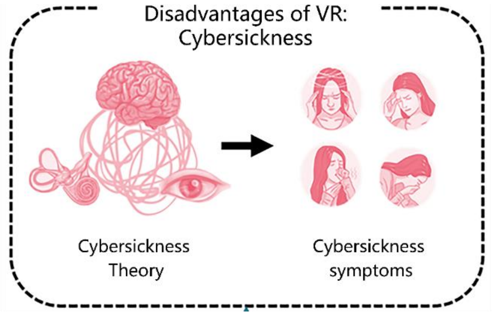

Figure 1. Schematic Diagram of Cybersickness Theories and Symptoms
(Source: self-drawn by the authors)

1.3 Sense of Embodiment

Previous studies support the view that "presence" (i.e., the feeling of "being there" in the virtual environment) is negatively correlated with cybersickness [7]. As a core element of presence, the sense of embodiment has become an important research direction.

The Sense of Embodiment (SoE) is defined as "the perception that arises when the properties of body B are processed as if they were the properties of one's own biological body" [8]. It includes three key dimensions: self-location (referring to the spatial experience of being within one's body, focusing on the relationship between the self and the body), agency (referring to the feeling of controlling overall movement, encompassing actions, control, intentions, movement choices, and subjective volitional experiences), and body ownership (referring to the perception of attributing the body to oneself) [8]. Studies have shown that the use of virtual avatars can enhance users' subjective presence, immersion, and illusion of existence in the virtual world [9]. Therefore, researching the impact of the sense of embodiment in virtual game architectural space design is of great significance for optimizing the virtual game environment and improving players' immersion.

1.4 Mirror Exposure

Existing studies have put forward various methods to enhance the sense of embodiment, with visual feedback being particularly critical. Parallel studies in real environments have demonstrated that mirror stimulation can significantly enhance self-referential cognition [10], and empirical evidence shows that this effect is related to the enhancement of self-perception. These findings jointly establish the important position of mirrors as self-awareness regulators, which can affect self-representation at the perceptual level [11]. Despite in-depth research on the psychological effects of mirrors in real environments and the impact of virtual avatars on behavioral perception, their potential influence on cybersickness has not been systematically investigated.

The study explores the impact of embodiment on the design of virtual game architectural spaces through VR experiments, and then attempts a series of virtual architectural space designs. It aims to enhance players' embodiment, reduce the occurrence of cybersickness (CS), and improve players' gaming experience and satisfaction through architectural design.

2. Methods and Processes

2.1 Research Procedures

(1) Review the inducing mechanisms, influencing factors of cybersickness in VR environments, and embodied cognition theory, analyze users' perception-motor coordination characteristics in virtual spaces, and compare different cybersickness measurement methods.

(2) Design a controlled experiment, combining biological signal measurement (EDA, HRV, RESP, and eye-tracking) and psychological assessments (SSQ, FMS, IPQ) to explore the impact of the sense of embodiment on cybersickness.

(3) Sort, classify, and preprocess the collected physiological and psychological data, construct a

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high-quality dataset reflecting the correlation characteristics between the sense of embodiment and cybersickness, and lay the foundation for data analysis.

(4) Conduct normality tests on the dataset, use SPSS to explore the correlation between physiological indicators and subjective questionnaires through Pearson correlation analysis, and analyze the physiological and psychological differences between environments with and without mirrors using independent sample t-tests.

(5) Based on the experimental results regarding the correlation between the sense of embodiment and virtual cybersickness, propose optimization cases and improvement suggestions for the virtual space architectural environment, providing theoretical support and design schemes for improving the user experience of virtual reality technology.

2.2 VR Experiment

The experiment was conducted by having subjects wearing physiological monitoring devices experience a virtual architectural space [12]. The virtual environment was created using Unity, and participants used HTC head-mounted displays connected to a computer with specific configurations. The experimental process is shown in Figure 2. To investigate the impact of mirrors on embodiment, the experiment set up a mirror group (Group M) and a non-mirror group (Group N) for comparison. Where participants could control their movement and perspective in the virtual environment using a joystick and head rotation (Figure 3). A total of 46 people participated, with 24 in Group M and 22 in Group N. In the experiment, psychological measurements included the Simulator Sickness Questionnaire [13] (to assess cybersickness symptoms [14]), Functional Movement Screen (rapid scoring every 3 minutes), and Igroup Presence Questionnaire [15] (to assess embodiment); physiological measurements involved recording Electrodermal Activity, Heart Rate Variability, Respiratory Rate [16] [17], and eye-tracking data via ErgoLAB V3.0[18][19].

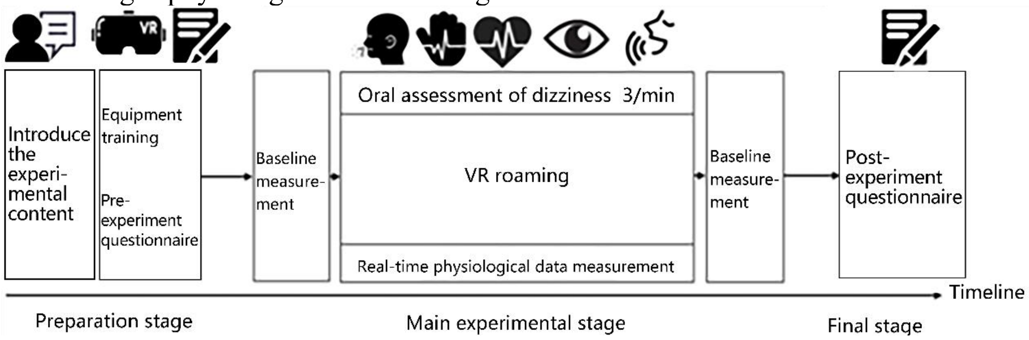

Figure 2. Experimental Flowchart
(Source: self-drawn by the authors)

Figure 3. Experimental Scene Diagram

2.3 Experimental Results

To quantify the impact of mirror exposure on SoE and CS, we conducted independent samples T-tests and Pearson correlation analysis on multimodal datasets. These multimodal findings empirically validate that mirror exposure enhances SoE while alleviating CS, providing a physiological-psychological foundation for translating experimental insights into spatial interventions. As the focus of this study is to explain how to apply experimental results to design, the experimental analysis process will not be repeated here. The experimental results will only be presented as follows:

1) Mirror exposure enhances the sense of embodiment: Group M scored higher in dimensions such as spatial presence and engagement, and the duration of mirror gaze was positively correlated with the sense of reality, indicating that mirrors strengthen users' identification with the virtual body and spatial

localization through visual feedback [20].

2) Mirror exposure alleviates cybersickness: Group M exhibited lower EDA [21] (a physiological stress indicator), more stable respiration, and lower SSQ scores, and engagement was negatively correlated with cybersickness symptoms, suggesting that the enhanced sense of embodiment may reduce the discomfort of cybersickness [22].

3. Design Practice

3.1 Spatial Optimization

3.1.1 Spatial layout and size distance

Taking a simple cubic living room as an example, the original two small windows were transformed into floor-to-ceiling windows (Figure 4), and then the mirror and window functions were integrated into a "window-mirror" composite design. In mirror mode, the interface functions as a mirror, reflecting the user's mirrored indoor environment; in window mode, the interface acts as glass, reflecting the user's mirror image and the environment outside the window. This transformation not only effectively avoids the visual abruptness of traditional large mirrors but also significantly expands the field of view of the virtual environment, visually enlarging the space. In terms of spatial layout, the traditional central tea table arrangement was shifted to an enclosed design centered on the window-mirror, forming a minimum activity area of 3m × 3m through furniture configuration.

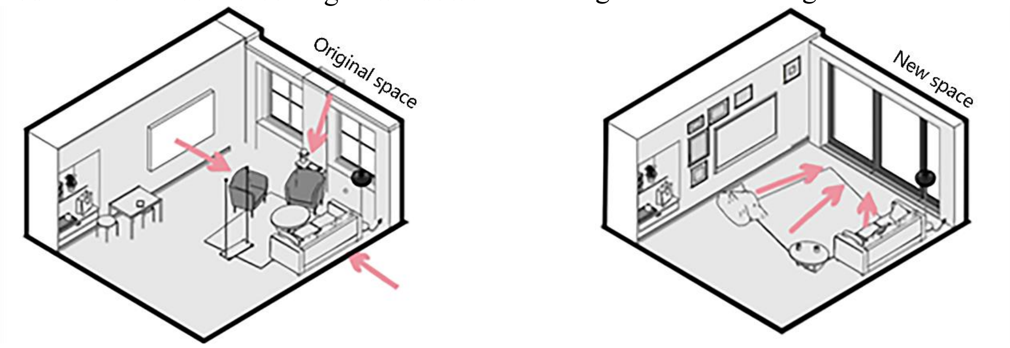

Figure 4. Addition of Window-mirror and Change of Layout Center
(Source: self-drawn by the authors)

To ensure users' free movement and social interaction [23] within the minimum activity area (3m × 3m) (Figure 5), priority is given to keeping the core activity area unobstructed, avoiding fixed obstacles. If functional requirements necessitate placing fixed items, they should be equipped with intelligent hiding switches to ensure users can flexibly adjust the spatial layout according to actual needs. This design strategy can maintain the immersion of the VR environment, effectively prevent collision interference, and optimize users' social experience [24].

This size design is based on multiple considerations: a length of 3m can meet the spatial needs of 2-3 people for comfortable social interaction; a width of 3m comprehensively considers the full-body mirror observation distance (1-2m) and the back buffer area (1m), which not only compensates for users' lack of perception of the space behind them in the VR environment [25] but also ensures mirror clarity and a comfortable distance. Meanwhile, based on technical implementation considerations (Figure 6), the mirror display range is controlled within 4m to ensure imaging quality (fading gradually beyond this range). This design not only makes the interaction transition more natural and smooth but also effectively saves system performance resources.

3.1.2 Furniture layout optimization scheme

In VR social space design, carpets can serve as effective space-dividing elements, and it is recommended to prioritize solid-color styles - this design decision is based on user behavior observation: users generally show a tendency to avoid textured floors in virtual environments. Laying carpets in the activity area can not only clearly define functional zones but also visually guide users to stay and interact naturally. This layout method meets the functional needs of space organization, fully considers users' psychological preferences and behavioral characteristics in the VR environment, and creates an immersive space more in line with VR social characteristics. Considering that most players engage in VR social interaction in a sitting posture, and studies have shown that the level of cybersickness in a standing posture is significantly higher than in a sitting posture [26], it is recommended to choose low-profile furniture (such as cushions, bean bag sofas, low coffee tables, etc.) for sitting furniture configuration to optimize the user experience. In terms of space atmosphere creation, curtains are used to reduce the abruptness of the window-mirror boundary, and green plant elements are added to enhance the scene's affinity. Soft materials can be used to create a relaxed spatial atmosphere (Figure 7). The scheme combines functional needs with psychological comfort from the perspective of user behavior patterns, creating an immersive space more in line with VR social characteristics.

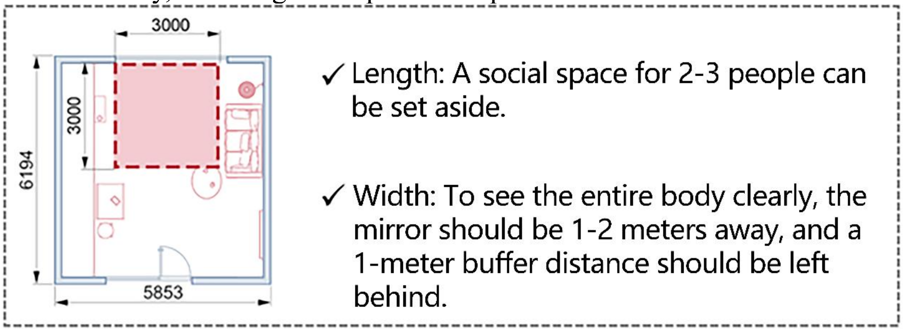

Figure 5. Schematic Diagram of the Minimum Activity Area (3m × 3m)
(Source: self-drawn by the authors)

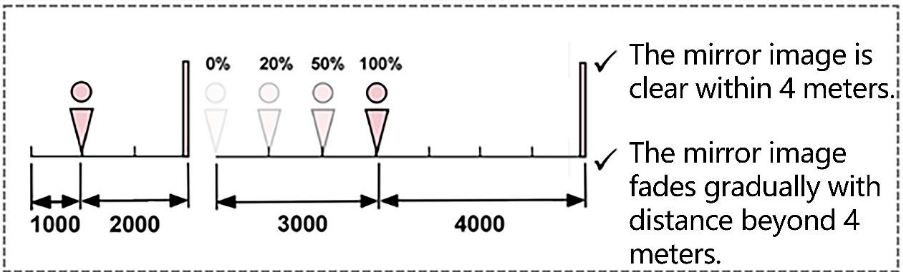

Figure 6. Schematic Diagram of Fading Distance
(Source: self-drawn by the authors)

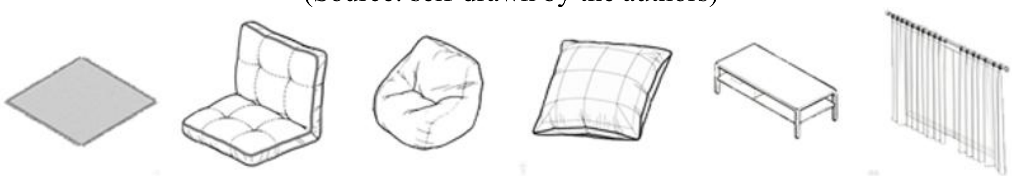

Figure 7. Schematic Diagram of Furniture Selection
(Source: self-drawn by the authors)

3.1.3 Internal and external space and window selection

The introduction of window-mirrors has substantially reconstructed the spatial structure, creating two interrelated yet distinct functional areas - the virtual indoor space formed by reflection and the outdoor landscape space presented by transmission (Figure 8). For this unique spatial division, we propose a systematic optimization scheme: for the indoor environment, an enclosed furniture layout strategy is adopted, making physical furniture and virtual mirror images form a harmonious virtual-real enclosed echo, enhancing the user's immersive experience.

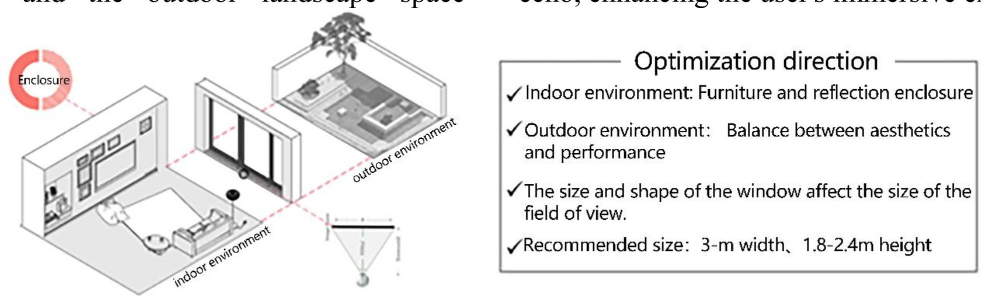

Figure 8. Schematic Diagram of Internal and External Spaces
(Source: self-drawn by the authors)

For the outdoor environment, to achieve a better balance between aesthetic performance and system performance, a hierarchical courtyard landscape system was constructed, optimizing the allocation of performance resources by controlling the environment scale (Figure 9). Specifically, three levels of landscape schemes are provided: 1) A miniature courtyard environment, suitable for small indoor spaces, with the lowest performance overhead; 2) A plant courtyard as a universal choice, balancing vegetation density and rendering load; 3) A waterscape courtyard, creating an excellent atmosphere through water reflection and flow effects, suitable for medium and large space needs. This stepped design scheme not only ensures a gradient of visual experience from simplicity to richness but also achieves a gradient of performance consumption from low to high, allowing creators to freely select the most suitable landscape configuration according to hardware compatibility.

Figure 9. Schematic Diagram of Recommended Landscapes
(Source: self-drawn by the authors)

As a key interface connecting the virtual and real, the size design of the window is particularly important. The larger the window size, the wider the expanded field of view and the larger the mirror exposure area. The recommended specification is 3000mm in width and 1800-2400mm in height, suitable for 3-4 people(Figure 10). Meanwhile, flexible selection space for other window types is reserved to ensure the design scheme can adapt to diversified usage scenarios.

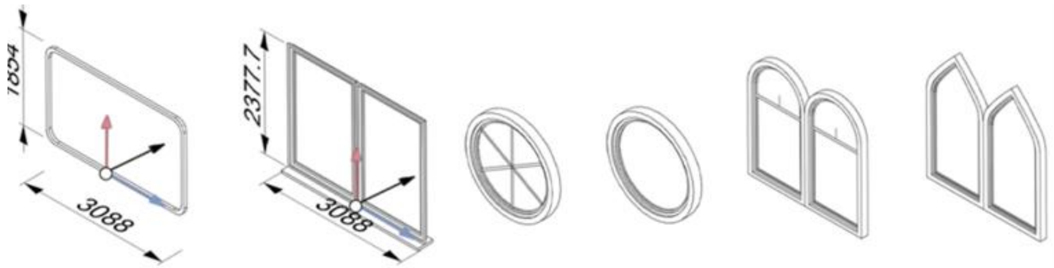

Figure 10. Schematic Diagram of Window Styles
(Source: self-drawn by the authors)

3.2 Interactive Optimization

At the interactive level: The basic interaction layer provides three core functions: (1) A mode switching system [27] that supports dynamic conversion of interface functions between window mode and mirror mode(Figure 11). In mirror mode, the interface presents a complete reflective surface, clearly mapping the user and their indoor environment; when switching to window view mode, the interface converts to a transparent composite medium, which can maintain the user's mirror reflection while displaying the extended view of the outdoor landscape. This dual-mode design not only eliminates the sense of spatial oppression caused by a single mirror but also effectively expands the spatial dimension at the visual perception level through the virtual-real integrated interface processing method. While maintaining interface coherence, the system provides users with a spatial experience transition from closed to open, perfectly balancing the dual needs of privacy and transparency;

(2)Posture adaptation design [28]: A combination scheme of vertical floor-to-ceiling windows and horizontal skylights is designed for different usage scenarios such as standing, sitting, and lying postures, which can be switched by users(Figure 12). Starting from the user's behavior pattern, it organically combines functional requirements with space design to meet diversified needs and create an immersive space more in line with the characteristics of VR social interaction. (3) The fade-out mechanism connects the mirror display range with distance. This design not only makes the interaction transition more natural and smooth but also helps save system performance resources [29].

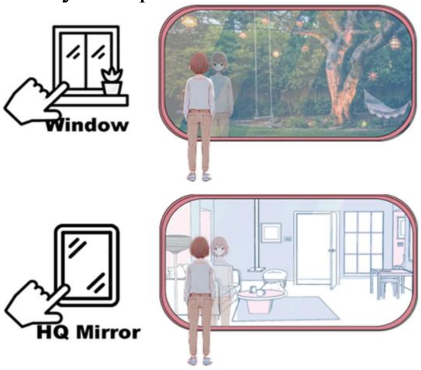

Figure 11. Schematic Diagram of Mode Switching

(Source: self-drawn by the authors)

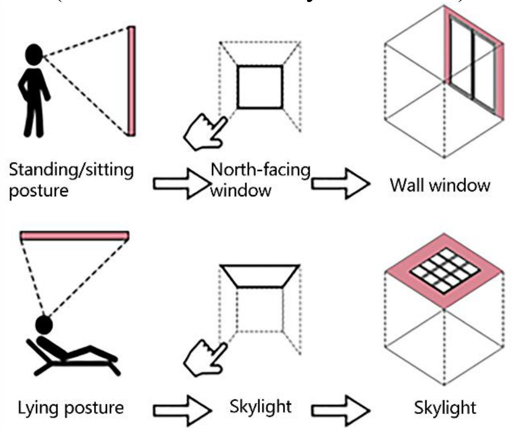

Figure 12. Schematic Diagram of Posture Adaptation Design

(Source: Self-drawn by the author)

Advanced functions are as follows: (1) Adjustment of reflection environment transparency: Users can adjust it from 0 to 100 infinitely. At 0% transparency, only the user's main body is reflected; at 50%, a semi-transparent environment reflection is presented (the user remains clear); at 100%, the entire environment and the user are reflected completely. By independently regulating the reflection intensity of the user's main body and environmental elements, the priority management of visual information is realized, so that the user's image is always in the visual focus. Users can reduce visual interference, making it easier to observe postures and expressions and focus on social interaction. (2) Adjustment of mirror imaging clarity: The high-quality (HQ) mode uses anti-aliasing rendering to present a delicate and high-definition mirror image, while the low-quality (LQ) mode presents a blurred mirror image through down sampling. It optimizes performance under the premise of ensuring basic recognizability. High-definition mirror images are clearer but consume more performance resources, while low-definition ones, although blurred, save performance resources. (3) Weather feedback system: It responds to environmental changes in real-time in the window view mode - on sunny days, the interface presents a prism iridescence effect with bird calls in the background; on rainy days, it presents water marks, raindrops, and atomization effects with rain sounds in the background. Through visual and auditory stimuli, users will feel that the virtual environment is more credible, thereby enhancing the sense of embodiment (Figure 13).

Figure 13. Schematic Diagram of Advanced Interaction

(Source: Self-drawn by the author)

3.3 Case Application

3.3.1 Indoor Case Application

The indoor scheme takes small spaces as the basic unit, mainly based on the following considerations: First, considering that the current VR technology has high requirements for computer hardware performance, the small space design can effectively reduce performance consumption and ensure the compatibility of devices with different configurations. Second, multiple small space units can be flexibly combined according to actual needs to achieve space expansion. In specific cases (Figure 14), the scheme carries out differentiated designs for three types of rest scenarios: the living room (square), the bedroom (irregular shape), and the studio (rectangular). It meets the needs of different usage scenarios through diversified space forms while maintaining the unity of the overall design language. This design strategy optimizes the space scale, ensures compatibility with mid-to-low-end devices, and brings users diversified scene experiences through diversified space form design.

For public activity areas such as studios and living rooms, priority is given to adopting the panoramic window mirror system on the short-side walls. Through the floor-to-ceiling windows and the short sides, an open visual experience is created within a limited depth. For private spaces such as bedrooms, it is recommended to adopt a composite interface design of TV + mirror on the long-side walls, which not only meets the needs of media playback and viewing but also avoids the sense of space oppression caused by traditional full-length mirrors through layout. This precise matching based on space scale and usage scenarios realizes the dual optimization of functional requirements and psychological comfort. It also provides an extended idea of combining indoor mirrors with other item interfaces.

Figure 14. Axonometric Drawing of Indoor Renovation Scenario
(Source: Self-drawn by the author)

Compared with the bedroom, the bedroom and the studio have added skylights to adapt to the needs of different playing postures. The studio, as a public space, may accommodate more people, so the skylight is set as a long window with a larger light intake, which is suitable for bright public spaces. The bedroom, as a private space, is set with a short window to maintain the privacy of the space.

Space separation and combination: Since people usually gather in groups when chatting, a space can have multiple groups, so separation is needed to leave space. The bedroom is more private, so glass partitions are used for separation, and the studio, as a public space, uses furniture for separation. If more people need to be accommodated, these three groups of spaces can be combined with each other to create new spaces (Figure 15). The comparison shows that the renovated scenes (Figures 16) not only improve functionality and aesthetics but also realize resource optimization through systematic design. This framework can be extended to various VR scenarios, providing a universal reference for VR social space design.

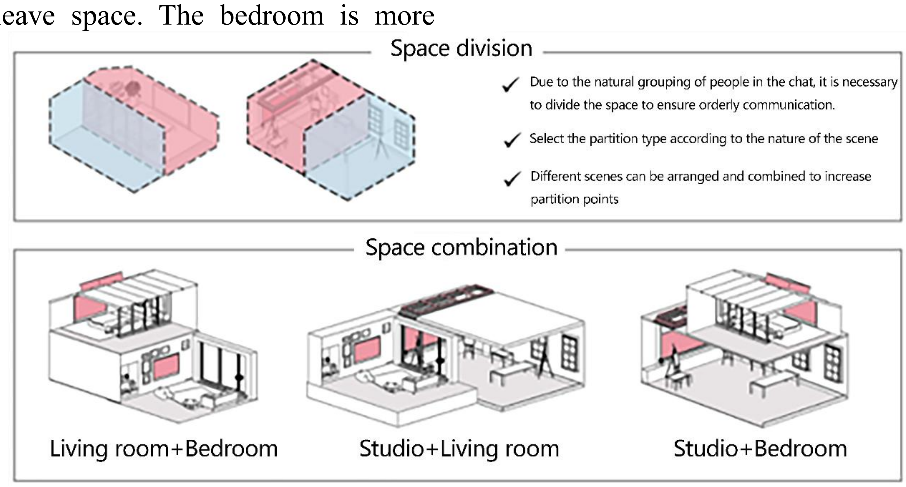

Figure 15. Schematic Diagram of Space Separation and Combination
(Source: Self-drawn by the author)

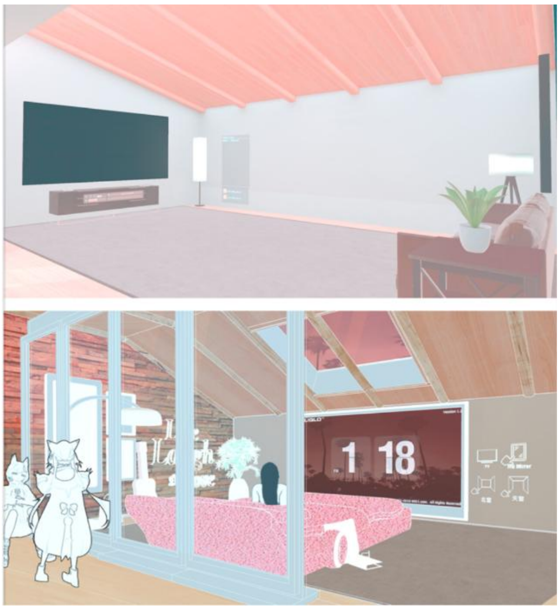

Figure 16. Comparison of Bedroom Scenes Before and After Renovation
(Source: Self-drawn by the author)

3.3.2 Outdoor case application

In outdoor spaces, water bodies can be used as tools to increase the reflective bodies exposed by mirrors outdoors. Therefore, this design provides three spatial schemes of different scales: small space courtyard, medium space swimming pool bar, and large space star orbit court. The small courtyard is suitable for intimate conversations among small groups, and the sense of enclosure brings a sense of security; the medium-sized swimming pool bar has an open nature that encourages relaxed social interaction; the large star orbit court is suitable for group activities or immersive experiences, with the vast starry sky and flowing water curtain creating a meditation atmosphere. Users can choose scenes with different atmospheres according to their own needs:

(I)Small space courtyard: The vertical water curtain wall design provides mirror exposure visually, and the sound of water improves the sense of spatial positioning, comprehensively enhancing the sense of embodiment. The entrance leads directly to the water curtain wall, with an activity space in front of it, and tables and chairs placed on one side of the activity space. The wall where the water curtain wall is located is partially left blank to extend the vision to the tables and chairs. Combined with the garden, rail flower beds, and corridor frame design, the space is semi-enclosed. The hollow design makes the space more transparent and plays a role in enclosing and dividing the space, creating a comfortable social atmosphere suitable for small groups to gather (Figure 17). This courtyard can also be combined with the indoor scheme of this design to increase scene diversity.

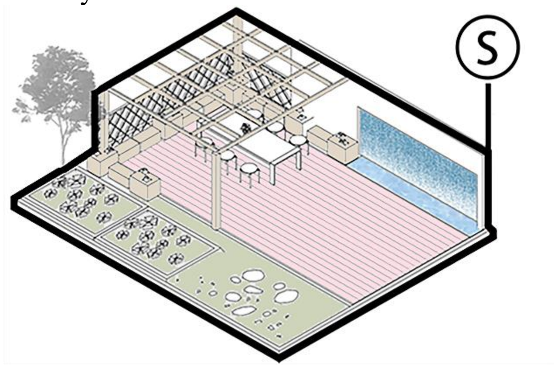

Figure 17. Axonometric Drawing of Courtyard Scene
(Source: Self-drawn by the author)

Figure 18. Axonometric Drawing of Swimming Pool Bar Scene
(Source: Self-drawn by the author)

(II)Medium space swimming pool bar: The arc-shaped bar is combined with one side of the swimming pool. The concentric arc layout of the bar and the swimming pool forms a "centripetal gravitational field", which naturally guides people to gather. At the same time, the curve weakens the social oppression of the right-angle space and promotes informal interaction. A horizontal swimming pool is set in the center to reflect the user's reflection, increasing mirror exposure to enhance the sense of embodiment. Step mode: The height of the center of the swimming pool is -1500m, and the height of the bar stools in the water on the right is -600m (Figure 18). The height of the lounge chairs by the pool is 0m (Figure 19). The stepped height difference increases the interest of the venue. Users can interact with the bar normally from the ground and also in the swimming pool to increase fun. Lounge chairs and tables and chairs are set by the pool to increase space gathering points and disperse the crowd in the venue.

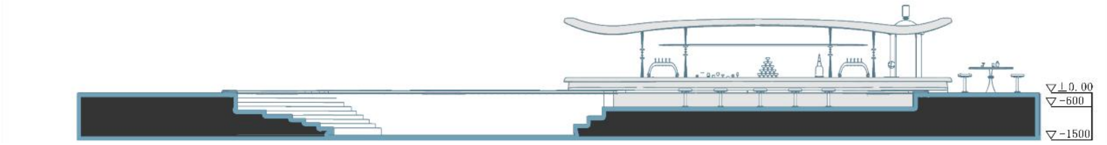

Figure 19. Sectional View of Swimming Pool Bar Scene
(Source: Self-drawn by the author)

(III)Large space star orbit court: Large space scenes are very suitable for designing surreal scenes, which is exactly what VR virtual spaces are good at. Every star that streaks across leaves a winding light mark on the sea surface, as if the entire universe is slowly dissolving on this liquid mirror; the trajectories of these star trails finally converge to the center of the scene, where there is a temple composed of a semi-transparent water curtain (Figure 20). This kind of interaction between entity and illusion makes the boundary between the body and space vague and poetic. The entire scene is shrouded in a quiet atmosphere of mysticism. When users wade in water, the ripples caused by their steps will temporarily break these celestial projections - this is not only a surreal visual spectacle but also an embodied cognitive theater constructed through fluid simulation and light and shadow algorithms.

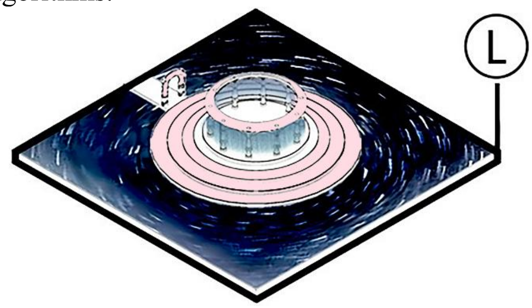

Figure 20. Star Trail Court
(Source: Self-drawn by the author)

4. Conclusion

The study adopts a logical framework of "theoretical framework - experimental verification - data analysis - application transformation". By analyzing users' reliance behavior on mirrors in VR social spaces and experimental data, it proposes a set of design schemes with "window mirrors" as the core, aiming to enhance users' sense of embodiment and alleviate virtual cybersickness. The experimental part explores the impact of embodiment on cybersickness in virtual environments. The research results show that mirror exposure may be an effective method to enhance embodiment, and embodiment can alleviate cybersickness symptoms. The design starts from two aspects: spatial integration and interaction optimization. It verifies the feasibility of the scheme in indoor and outdoor scenes by adjusting the layout and introducing dynamic adjustment functions. The "window mirror" composite interface design has both universality and expansibility - it can not only be used as a basic window to adapt to various scenes, but also can be flexibly expanded at the interaction level: indoors, it can be extended to a multi-functional combination of "TV + mirror", and outdoors, it can evolve into a water reflection system, which can be flexibly integrated into multiple scenes. It can not only enhance the sense of spatial immersion, but also balance performance and user experience, providing new ideas for the design of VR social environments.

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