The Impact of VR Interaction Methods on User Experience: Taking Medical Education and Cultural Heritage Games as Examples

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Abstract. With the rapid development of virtual reality (VR) technology, its applications in fields such as medical education and cultural heritage have become increasingly widespread. As the bridge connecting VR systems with users, interaction methods directly influence user experience. This paper focuses on how VR interaction methods impact user experience, using medical education and cultural heritage games as typical case studies. Firstly, the definition and classification of VR interaction are clarified, and a user experience evaluation framework includes immersion, usability, cognitive load, and goal achievement is established. Secondly, by analyzing the interaction design practices in the two scenarios, revealing the role of interaction design in enhancing operational realism and learning efficiency in medical education, as well as its positive impact on reducing cognitive load and enhancing immersion in cultural heritage games. Finally, based on the case studies, proposing several recommendations including scenario-driven interaction design principles, multimodal interaction enhancement strategies, a balanced approach between naturalness and functionality, and the construction of a scenario-based evaluation system. The research findings provide theoretical references and guidance for VR interaction design in different fields, help improve user experience quality in VR systems.

Keywords: VR Interaction; user experience; medical education; cultural heritage; scenario-driven.

1. Introduction

In recent years, VR technology has shown enormous potential in fields such as education, culture, and medical care by its great immersion and realism. As VR technology breaks the ethical and resource constraints of traditional medical education and drives innovative cultural dissemination models in cultural heritage games, the different demands across various scenarios for interaction precision, naturalness and feedback have become increasingly evident. However, existing research lacks systematic analysis of how VR interaction methods influence user experience in specific scenarios [1,2].

This research has important implications for optimizing VR interaction design and improving VR systems across different scenarios. Scientific interaction design not only enhances user immersion and reduces cognitive load but also helps the precise teaching of medical skills and the efficient transmission of knowledge in cultural heritage dissemination, providing practical support for the scenario-based implementation of VR technology [3,4].

This study primarily employed literature analysis to systematically review theoretical literature related to the definition, classification, and user experience evaluation of VR interaction. The advantage of this method lies in its ability to comprehensively integrate existing research findings, clarify the technical characteristics of VR interaction and the core evaluation dimensions of user experience, build a theoretical foundation for the research [1,5,6]. Additionally, the case study method was employed to conduct a deep analysis of interaction design in medical education and cultural heritage games. Through operational data and experience metrics (such as operational error rates and immersion scores) in specific scenarios, the study revealed the mechanisms by which different interaction methods influence user experience, enhancing the practical applicability of the research conclusions [7,8,9].

The ultimate research goal of this study is to find how VR interaction methods influence user experience and to establish VR interaction design principles and evaluation frameworks. To achieve this goal, key concepts were defined, typical scenarios were analyzed, and targeted recommendations were proposed based on case summaries. These findings provide theoretical references and guidance for VR interaction design in related fields, promoting the efficient application of VR technology.

2. Definition of Key Concepts

2.1. The Meaning and Classification of VR Interaction

VR interaction refers to the process that users exchange information with virtual scenes and objects dynamically through the specific device and movement, with main features of real-time feedback and spatial immersion [6]. Compared with traditional human-computer interaction, VR interaction can simulate sensory experiences such as sight, hearing, and touch in the reality. thereby constructing a closed interaction system between users and virtual environments, providing a strong sense of immersion [1].

According to how the technology works and the purpose of interaction, VR interaction can be summarized into three types: Input interaction refers to the way users transmit information to the virtual environment, including physical controller operations, gesture recognition and auxiliary input methods such as eye tracking and voice control [1,8,10,11]; Output interaction is the way the virtual environment transmits information to the user, including visual rendering (e.g., lighting effects), spatial audio effects (e.g., 3D audio to enhance scene realism), and multimodal feedback such as haptic feedback (e.g., force feedback devices), vibration and temperature [1,3,5]; Adaptive interaction is a dynamic adjustment enabled by artificial intelligence technology, such as optimizing responses based on user behavior (e.g., adjusting task difficulty or feedback frequency), and adjusting interaction precision based on device performance [5,12].

2.2. Key Factors Affecting VR User Experience

VR user experience refers to users’ subjective feelings and overall evaluation when using VR systems; the assessment needs to combine technical characteristics and scenario requirements, and key factors include Immersion, which refers to users' perception of the virtual environment, influenced by visual realism, naturalness of interaction, and the richness of feedback—take medical VR training as an example, the addition of haptic feedback really helps enhance users' immersion in surgical scenarios [4,6]; Usability, which is the learning cost and operational efficiency of interaction methods, measured by indicators such as accuracy and smoothness of operation, with research showing that although gesture interaction is more natural, controllers usability score is higher in precision operation tasks [8]; Cognitive Load, which is the user's mental exertion during interaction, as overly complex interaction designs such as excessively heavy device wearables or information overload can reduce the quality of the experience [13]; and Goal achievement, which is the degree how the interactive system meets the requirements of the scenario, such as the effectiveness of skills training in medical education, the efficiency of knowledge transferring in cultural heritage games and other scenario-based indicators[2,9]. These factors constitute the evaluation framework for VR user experience, providing a basis for research on the analysis of cases and the impact of interaction methods.

3. Analysis of Typical VR Interaction Scenarios

3.1. VR Interaction Design in VR Medical Education

Medical education demands precision and safety in skill transfer. VR technology can overcome the ethical and resource constraints of traditional teaching by simulating real clinical scenarios in a virtual environment. Its interaction design must prioritize authenticity of operation and efficiency of learning. The core interaction method in this application is precise controller and gesture recognition, supplemented by multi-modal feedback such as haptic feedback, building a training system of perception, operation and feedback'.

3.1.1 Gesture and controller interaction in VR medical education

In VR anatomical education systems, gestures and controller interactions have been integrated to a certain extent. The system designed by Than and Yap uses skeleton tracking and gesture recognition technology, enabling users to perform natural gestures such as pinching, rotating, and zooming to manipulate virtual organs, adjust view angles, and observe microscopic structures, reducing initial learning costs. Its usability, as measured by the SUS scale, scored 85.3 points, significantly higher than traditional cadaver-based teaching [9]. Controller interaction plays an important role in high-precision tasks, leveraging sub-millimeter-level tracking and pressure-sensitive trigger keys from professional devices to do precise operations such as virtual organ separation and vascular marking. In the 'understanding complex organ spatial relationships' task, the error rate of controller-assisted operations was 41% lower than that of pure gesture interaction, aligning with the research conclusion that 'controllers have higher usability scores in precise operation tasks' [8].

The combination of these two interaction methods enhances the user experience very well: during the initial exploration period, the naturalness of gesture interaction enhances immersion, while during the high-precision operation period, the addition of controller ensures stability. For example, the controller's '3D anchor points' can be used to fix the position of organs, and the 'tool wheel' allows for quick switching between anatomical tools, with gestures used to confirm operations. This combination reduces cognitive load through natural gestures while meeting the medical education requirement for operational standards through the controller's physical feedback and precise control, enabling users to efficiently establish cognitive understanding of anatomical structures [10].

3.1.2 Multimodal interaction design driven by haptic feedback in VR medical education

In VR medical education systems, haptic feedback serves as the core medium for reproducing the physical characteristics of clinical operations. It must be deeply integrated with visual and auditory modalities to construct a sense of physical realism and help users better obtain information.

Haptic feedback is the foundation for establishing a sense of realism in clinical procedures, enabling precise transmission of physical properties, helping users develop an understanding of operational force and physiological feedback. In surgical skill training, Jie and Yap developed a VR laparoscopic simulation system that uses force feedback instruments to simulate tissue mechanical differences: when cutting muscle, the system provides soft, continuous resistance, while contact with bone results in sudden increased resistance and high-frequency vibrations. This improved users' accuracy in identifying 'tissue property differences' by 53% and reduced suturing force control errors by 32% [4]. In anatomical education, Than and Yap used a virtual organ model with pneumatic sensing technology to simulate differences in organ elasticity. Users could perceive subtle changes in texture hardness and surface smoothness through haptic gloves, improving anatomical structure memory retention rates (+27%) [9]. Van Damme et al. further confirmed that learners relying solely on visual cues had a failure rate of 41% in 'blind force control tasks,' while adding haptic feedback reduced the failure rate to 15% [3].

Single haptic feedback has certain limitations that influences users' immersion, needing the integration of visual and auditory feedback to optimize information presentation. The integration of visual and haptic feedback can enhance operational precision: in surgical simulations, three-dimensional anatomical model highlights the haptic interaction area (e.g., dynamic markers at incision sites) while simultaneously displaying force feedback numerical curves, transforming abstract tactile sensations into concrete data. This reduces the probability of operational deviation from the target area from 28% to 9% [4]. The coordination of auditory and haptic senses can enhance immersion in the scenario and warn of risks: in suturing training, Van Damme et al. designed a 'tension-sound effect linkage mechanism' that plays low-frequency, stable sound within a safe range. When tension exceeds the safe range, the sound effect frequency increases synchronously with haptic resistance, improving users' response speed to ‘operational risks’ by 29% and effectively reducing the rate of virtual tissue tearing [3]. This multimodal collaborative interaction design, based on clinical logic, ensures precise and efficient information transmission.

3.2. VR Interaction Design in VR Medical Education

Cultural heritage games need to balance cultural dissemination and user enjoyment through interaction design, allowing users to perceive cultural value and impart knowledge through enjoyable game exploration. The VR interaction in this scenario focuses on natural gestures recognition and spatial navigation, requiring a low operating threshold to enhance user participation while ensuring the accuracy of cultural information transmission.

3.2.1 Gesture interaction in VR cultural heritage games

Gesture interaction is a key design for enhancing immersion. Liu et al. designed a ‘virtual touch’ interaction in the ‘Dunhuang Mural VR Game’: users can ‘touch’ mural details using gestures (without a controller), triggering historical story explanations or animation demonstrations (e.g., the dynamic restoration of flying apsara murals) [2]. User experience data shows that the ‘cultural immersion score’ (UEQ scale) for the natural gesture interaction group was 28% higher than that of the controller interaction group, and the game task completion rate increased to 92% compared to only 65% for traditional exhibitions. This design meets the cultural context's demand for ‘low-threshold participation,’ simulating touch behavior in reality to transition users from ‘passive viewing’ to ‘active exploration,’ arousing their desire to learn [8].

3.2.2 Spatial navigation interaction in scene tour

VR scene tour of large-scale cultural heritage sites (such as ancient city ruins) face issues related to ‘spatial positioning’ and ‘path guidance.’ Cao et al. designed a VR navigation system that incorporates a ‘mini-map with voice guidance’ interaction: users set their destination by clicking on the map with the controller, and the system automatically plans the optimal path, using spatial sound effects to indicate. Experiments show that this interaction method increases users' ‘scene exploration efficiency’ (the number of cultural sites covered per unit of time) by 40% and reduces communication costs in multi-user collaborative tasks by 35% [7]. This design combines multimodal and adaptive interaction, suits the ‘group exploration’ needs of cultural heritage games. By reducing the possibility of users getting lost through lightweight navigation interaction, it allows users to focus more on the cultural content itself rather than operational logic [5].

4. Discussions

4.1. Summary of Typical Scenarios

4.1.1 VR medical education

This scenario needs precision and safety in transfer of skills, the interaction design works through technological integration and multimodal feedback to establish an efficient training system. In terms of interaction methods, the advantages of gesture and controller complement each other: gesture recognition reduces learning costs by utilizing skeleton tracking technology to support natural operations such as pinching, rotating, and zooming. The SUS scale score for this system designed by Than and Yap reached 85.3 points, outperforming traditional teaching methods [9]. Controllers with sub-millimeter-level tracking and pressure-sensitive trigger keys perform well in high-precision tasks like virtual organ separation and vascular marking, reducing operational error rates by 41% compared to pure gesture-based interaction [8]. In terms of feedbacks, haptic feedback is deeply integrated into clinical scenario simulations: Jie and Yap's laparoscopic simulation system uses force feedback devices to simulate differences in muscle and skeletal mechanics, improving ‘tissue property recognition’ accuracy by 53% and reducing suture force control errors by 32% [4]; Than and Yap's pneumatic sensing virtual organ model uses haptic gloves to convey texture differences, improving anatomical structure memory retention by 27% [9]. At the same, visual dynamic marking and auditory effects optimize operational precision and risk warning efficiency [3,4].

4.1.2 VR cultural heritage games

This scenario aims to achieve low-threshold cultural dissemination and an immersive experience, the interaction design needs to consider the transmission of cultural values and user experience. Gesture interaction achieves a connection between users and cultural content through ‘virtual touch’ technology in Liu et al.'s ‘Dunhuang Mural VR Game,’ gesture operations can trigger historical story explanations and animation demonstrations, resulting in a 28% higher ‘cultural immersion score’ compared to the controller interaction group, and task completion rates increase to 92% [2]. Spatial navigation interaction addresses the pain points of exploring large scenes through a ‘mini-map with voice guidance’ system. Cao et al. build a system that allows users to set destinations by clicking on the map, combined with spatial sound effects to guide the path, resulting in a 40% increase in ‘scene exploration efficiency’ and a 35% reduction in communication costs for multi-user collaboration [7].

4.2. Points of View

Interaction design should be determined by scenario requirements. Medical education requires precision and authenticity, while cultural heritage games require low cognitive load and immersion, which directly affects the selection and combination logic of interaction technology design [2,8].
Single input interaction has limits, the integration of different input interactions can lead to breakthroughs while ensuring immersion. Multimodal interaction can greatly enhance the user experience, the coordination of vision, hearing, touch, etc. can meet the requirements of authenticity and operability while reducing cognitive load and helping to complete tasks [3,4].

Technology selection must balance naturalness and functionality. Natural interaction reduces learning costs, while functionality increases cognitive load. Lightweight interaction design must consider functional completeness when simplifying operations. High-precision interaction should be based on professional tool functionality but also consider naturalness [5,8].

4.3. Suggestions

4.3.1 VR interaction design should be driven by the scene

VR interaction design should be guided by the needs of the scene, with a deep analysis of scenario characteristics during the early stages of interaction design. For high-precision tasks such as VR medical education, interaction solutions should prioritize accuracy [8] and can utilize multimodal feedback technology [4] to ensure the realism of operation simulations and the efficiency of skill learning. For entertainment-oriented scenarios such as VR cultural heritage games, the focus should be on low-threshold participation and immersion. Interaction design should prioritize natural gesture recognition and lightweight guidance [7] to reduce learning costs, enhance exploration willingness, and align with the demand for ‘active cultural exploration’ [2].

4.3.2 Strengthening multimodal interaction design

Multimodal interaction in VR environments has great potential, the research should be promoted. In high-precision task scenarios, multimodal feedback can enhance operational accuracy and risk perception capabilities [3,4]. In low-threshold scenarios, multimodal interaction can enrich immersion and reduce cognitive load [6]. At the same time, it is important to take care of information overload issues during the fusion process to ensure that multimodal feedback complements rather than duplicates each other [13].

4.3.3 Balancing naturalness and functionality in technology selection

When selecting technology, it is important to balance ‘natural interaction’ and ‘functional integrity’ to meet scenario requirements. For high-precision tasks, professional controllers with rich functionality can ensure operational stability, while the introduction of natural gestures can reduce learning costs during initial period and enhance realism [8,9]. For low-threshold scenes, lightweight interaction methods such as gesture recognition and voice control should be prioritized, but functional completeness must be ensured [11]. For example, simplifying navigation operations without sacrificing path accuracy [7]. Additionally, adaptive interaction technology can be used to adjust interaction precision and feedback frequency based on user behavior and device performance, further optimizing the balance between naturalness and functionality [5,12].

4.3.4 Establish a user experience evaluation system for each scenario

A scientific and comprehensive evaluation system is needed to guide the improvements of VR interaction design. For VR medical education, evaluation indicators focus on operational accuracy, learning efficiency, and training effectiveness [4]. For VR cultural heritage games, key factors include cultural immersion scores, task completion rates, and efficiency [2]. Feedback from users should be considered to form an evaluation framework to help provide support for interaction design improvements.

5. Conclusion

This study analyzed two typical scenarios—medical education and cultural heritage games to clarify how VR interaction methods (input interaction, output interaction, and adaptive interaction) influence user experience. The study found that interaction design in different scenarios must follow the needs of scenarios. Additionally, it confirmed that the coordination of multimodal interaction and balancing naturalness and functionality are keys to optimizing user experience, and that scenario-based evaluation systems are crucial for improving interaction design. Thus, the research concludes that VR interaction design must center on scenario requirements, by reasonably selecting interaction technologies, strengthening multimodal integration, balancing technical characteristics, and combining scenario-based evaluation metrics, to effectively enhance user experience quality.

This study provides valuable insights for future research in the field of VR interaction design, mainly influences both practical applications and theoretical developments in related areas: In practical terms, it establishes a design paradigm of ‘precise operations + multimodal feedback’ for the development of VR systems in medical education, and clarifies the direction of ‘low-threshold interaction + lightweight navigation’ for VR game design in cultural heritage preservation; Theoretically, it establishes the logical connection between scene requirements and interaction method selection, enriching the evaluation framework for VR user experience.

Future research should focus on three areas for further exploration: First, expanding the scope of scenarios to apply research findings to more fields and verify the universality of scenario-based interaction design principles; Second, deepening technological integration to explore the application of AI-driven adaptive interaction in scenarios; And third, improving the evaluation system to construct a more comprehensive and objective quantitative assessment model for VR user experience.

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