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ORIGINAL RESEARCH ARTICLE

Virtual space experience design of grand canal cultural heritage landscape: Panoramic interaction and guided tour algorithm

Qing Li

Thanon Ram Intra, Khwaeng Anusawari, Khet Bang Khen, Krung Thep, Maha Nakhon10220, Thailand; m13785875266@163.com

ABSTRACT

This work presents the application of interactive virtual reality (IVR) technology in the preservation and presentation of cultural heritage (CH) for China's Grand Canal. The Grand Canal is a historical engineering marvel and an icon in Chinese cultural and economic development. This work addresses the need for the enhancement of traditional methods for CH education and preservation through immersive and interactive experiences. In this study, an IVR system is developed that is tailored to represent China's Grand Canal with the objective of providing users with historical accuracy and better engagement. The IVR experience is designed based on core user experience (UX) principles to maintain usability, accessibility, and engagement. Key features of the model include panoramic interactions, higher participation, and realistic representations through better graphic rendering and 3-D modelling. A guided tour algorithm was employed for personalized and adaptive UX to increase user satisfaction. The findings found after the IVR implementation through the sourced feedback reveal that the IVR system has improved user engagement, comprehension, satisfaction, and immersion compared to traditional touring methods. The statistical analysis, including comparative analysis, cross-tabulation, and correlation tests, supported these conclusions.

Keywords: cultural heritage education; interactive virtual reality; user experience; grand canal

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1. Introduction

The preservation and presentation of cultural heritage (CH) sites are crucial to the maintenance of historical awareness and the provision of cultural identity. As technology evolves, new methods emerge for enhancing the experience and understanding of these invaluable sites[1–5]. This study uses virtual reality (VR) technology to represent and interact with the CH site, which is the Grand Canal in China. The Grand Canal is a UNESCO World Heritage Site that is a vast waterway system in the eastern plains of China, extending from Beijing in the north to Zhejiang Province in the south[6–8]. Historically, the Grand Canal has played a significant role in China's history, serving as a means of communication and trade and also as a symbol of cultural and technological advancement. However, like many CH sites, the Grand Canal also faces challenges in terms of accessibility, preservation, and public engagement[9,10].

The integration of VR technology in CH gives a chance to overcome these challenges. By utilizing VR, we can provide an immersive experience that overcomes geographical and temporal barriers, thereby allowing individuals to explore and learn about the site in ways that are not possible through traditional methods[11,12]. Despite its potential applications, the application of VR in CH is not without challenges. Challenges such as technical limitations, user accessibility, and the authenticity of the experience are some of the concerns that must be handled. Also, there is a need to understand how VR experiences impact user engagement and knowledge acquisition compared to that of the traditional methods of CH presentation[13–15].

This project aims to develop an IVR experience for the Grand Canal that enables users to explore its rich history and cultural significance virtually. This work involved creating a realistic IVR environment that, by incorporating historical data together with architectural elements and cultural narratives, is aimed to offer an engaging and educational experience. Initial findings from the implementation of this IVR experience suggest a positive impact on user engagement and knowledge. Users also reported a deeper understanding of the Grand Canal's history and significance by mentioning the immersive nature of the IVR experience as a critical factor in their enhanced learning.

The paper is structured as follows: section 2 presents the knowledge about the Grand Canal, section 3 presents virtual space design, section 4 presents the algorithm, section 5 presents system evaluation, and section 6 concludes the work.

2. The Grand Canal CH landscape

2.1. Historical overview

The Grand Canal was a magnificent feat of engineering that stands as one of the most astounding historical accomplishments in China, with a history that stretches over more than 2500 years. This canal extends approximately more than 1700 km and is the longest and oldest artificial waterway in the world, surpassing even the Suez and Panama Canals in both age and length. Its construction began in the 5th century BC during the Spring and Autumn period and was expanded during the Sui Dynasty (581–618 AD). The Grand Canal was not a singular construction project but rather an amalgamation of various waterways that was undertaken across several dynasties, focusing primarily on the purpose of connecting the Yellow River and Yangtze River basins. The canal served as a vital conduit for the transport of grain, troops, and cultural exchange between the northern and southern regions of China. Historically, the canal played a crucial role in ensuring ancient China's economic prosperity and political stability, provided through the movement of goods and resources that were critical for the survival and growth of various dynasties. The court painter Xu Yang, a native of Suzhou, was commissioned by the Qianlong emperor (r. 1736–95) to record in twelve monumental handscrolls the emperor's historic 1751 tour of south China. He had painted the early images of the Grand Canal, as shown in **Figure 1**.

(a) (b)

Figure 1. (a) and **(b)** Grand Canal early painting by Xu yang.

2.2. Cultural significance

The Grand Canal is a repository of rich CH of diverse Chinese cultures, dialects, and traditions as it passes through several provinces, each with its unique cultural identity. The canal has long been celebrated in Chinese literature, art, and folklore and has inspired numerous poets, painters, and musicians. Along the canal, there are countless historical sites and landmarks covering cities, bridges, temples, and traditional villages. Each has a story of its own in the evolution of China's history. Today, the Grand Canal is considered a living museum that showcases the evolution of Chinese architectural styles and urban planning. It is recognized by UNESCO as a World Heritage Site for its role in shaping the cultural landscape of China.

2.3. Current digital representations

In this digital era, several initiatives have been undertaken to digitize aspects of the Grand Canal for educational, preservation, and touristic purposes (**Figure 2a,b**). These include i) virtual reality (VR) experiences that have allowed users to navigate through the canal's historical routes, ii) augmented reality (AR) apps that overlay historical information on real-world sites, and iii) interactive online platforms offering virtual tours and detailed historical narratives. These digital representations provide the following purposes: as tools for preservation, as educational resources and as solutions for promoting tourism. However, there are challenges that remain to accurately capture the essence of the canal's CH in these digital formats that ensure it resonates with the historical and cultural depth of the Grand Canal.

(a) **(b)**

Figure 2. (a) and **(b)** digital images of Grand Canal.

3. Designing the virtual space

3.1. User experience (UX) principles

The design of the virtual space for the proposed IVR model is based on core UX principles for the application's usability, accessibility and engagement. To ensure a seamless interface, the model presents consistency in navigation controls and visual elements. Accessibility is provided by implementing voice narration for the visually impaired. Engagement is enhanced through interactive elements that allow users to participate actively in the experience. The design also incorporates feedback mechanisms to adapt and improve. **Figure 3** shows the 3D rendered image of the grand canal of its digital image counterpart.

Figure 3. 3D rendered image of Grand Canal.

3.2. Panoramic interaction

Panoramic interaction provides users with a 360-degree view of the Grand Canal through high-resolution panoramic photography and 3D modelling. Users can navigate these panoramic views, thereby giving a sense of real-world exploration. Hotspots are placed within the panorama for users to interact with specific locations and learn more about them. To enhance the understanding of presence, the ambient sounds recorded from the actual locations are integrated to provide an audio backdrop that complements the visual experience.

3.3. Immersiveness and realism

Advanced graphic rendering techniques and realistic 3D modelling were employed to ensure immersive realism. The virtual environment uses high-definition textures and accurate lighting models to replicate day and night or different weather scenarios. Realism is enhanced through the use of VR technology. When experienced through a VR headset, the virtual space offers a fully immersive experience where users can feel as if they are actually navigating along the Grand Canal. Additionally, the use of spatial audio technology helps in creating a 3D soundscape that dynamically changes with the user's interactions and movements within the virtual space.

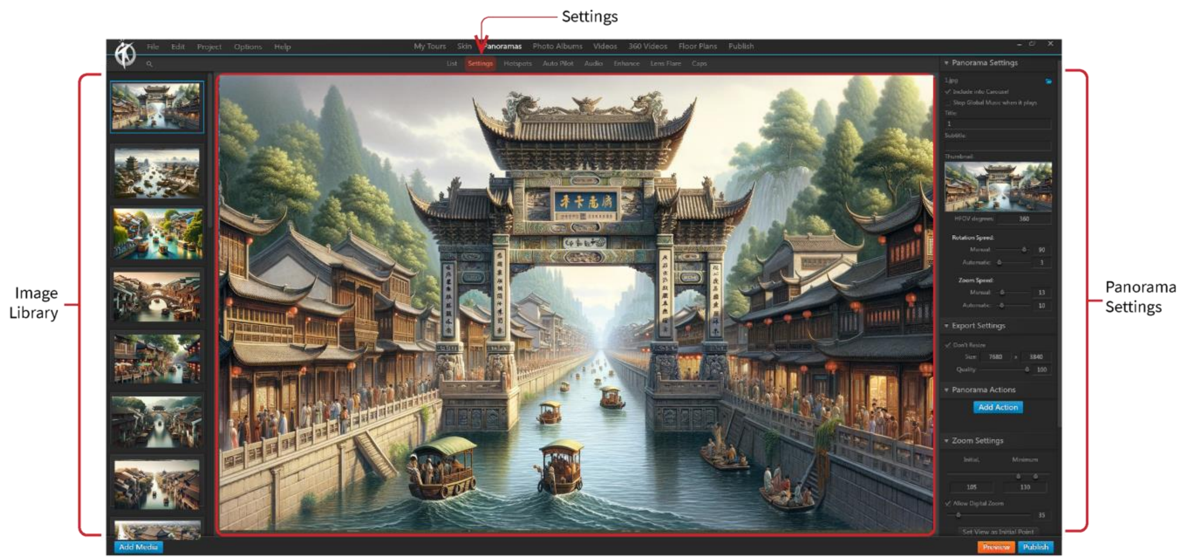


Figure 4. Proposed IVR for the Grand Canal.

4. Guided tour algorithm

Algorithm design

The IVR model of the Grand Canal is presented in **Figure 4**. The algorithm guiding the virtual tour of the Grand Canal creates an adaptive, user-centred experience. It integrates a rule-based decision tree to provide a dynamic and engaging tour.

1) Initialization: The tour begins by loading an existing user profile (UP) or creating a new one for first-time users. The profile tracks user preferences, interaction history, and engagement metrics.
2) Theme selection: Users were presented with thematic options for their tour. The user's choice guides the initial content and route.
3) Tour loop: The algorithm next guides the users through the series of points of interest (POIs) based on the selected theme, and introductory content is presented for each POI. The user interactions are monitored to adjust the type of content offered.
4) Adaptive suggestions: The system analyzes the UP to adjust forthcoming POIs and content dynamically.
5) User-controlled navigation: Users have the control to override the chosen path at any point.
6) Dynamic path adjustment: At the end of each POI, the algorithm decides the next step using the user's choices.

7) Tour conclusion: The tour concludes with a summary of highlights and provides options for further exploration.
8) Profile update: Post-tour, the UP is updated with new data from the session for future personalization.

Algorithm: Guided virtual tour of the Grand Canal

Definitions:

- User profile (UP): Stores user preferences, interaction history, and engagement metrics.
- Point of interest (POI): Specific locations or topics within the tour, each with associated content.
- Content pool (CP): A database of all available content categorized by theme, type, and complexity.
- User input (UI): Real-time input from the user during the tour.

Algorithm structure:

1) Initialize tour
   - Load the user profile (UP) for returning users; otherwise, create a new UP.
   - Present initial tour options based on general themes (e.g., history, architecture).
2) User selection
   - Capture the user's choice of initial theme.
   - Load relevant POIs from CP based on the selected theme.
3) Begin tour loop
   - For each POI in the chosen theme:
     - Navigate to POI.
     - Present introductory content.
     - Monitor UI for interest level (e.g., time spent, interactions).
     - Offer deeper content based on UI signals.
     - Log interaction in UP.
4) Adaptive content suggestion
   - Analyze UP for emerging preferences and interests.
   - Adjust upcoming POIs and content suggestions dynamically.
   - If a new interest is detected, offer a thematic branch switch (e.g., from history to architecture).
5) User-controlled navigation
   - Allow users to select POIs manually at any point.
   - Update tour path dynamically based on user selections.
6) End-of-POI Decision Making
   - After each POI, decide the next step based on:
     - User's direct choice.
     - Suggestions based on UP analysis.
     - If near the end of a theme, suggest a new theme.
7) Tour conclusion
   - Summarize tour highlights based on UP.
   - Provide options for further exploration or repeated themes.
   - Offer a feedback mechanism to improve future tour experiences.
8) Update user profile
   - Log final interactions and preferences from the current session.
   - Store for use in future sessions.

5. System evolution and participant study

Developing the IVR experience involved iterative design and testing phases to refine the system based on user feedback and technical evaluations. This section details the system's evolution, focusing on participant involvement, study design, measurement techniques, and data collection methodologies.

(i) Participant recruitment and demographics

Participants were recruited from a diverse demographic, encompassing 50 individuals, to ensure a wide range of perspectives and experiences. The group, varying in age from 18 to 65, included historians, students, tourists, and technology enthusiasts. **Table 1** presents the characteristics of the participants in the study.

Table 1. Participant characteristics distribution.

Characteristic	**Distribution**
Age group	18–24: 20%, 25–34: 25%, 35–44: 15%, 45–54: 20%, 55–64: 10%, 65+: 10%
Gender	Male: 50%, female: 50%
Occupation	Students: 20%, historians: 15%, technology experts: 20%, tour guides: 10%, retired: 15%, others: 20%
Prior VR experience	Yes: 40%, no: 60%
Interest in history/culture	Low: 10%, moderate: 30%, high: 40%, very high: 20%

(ii) Study design

For our investigation into the IVR experience, we structured a between-subjects experiment comprising two distinct conditions: this system specialized IVR narrative system and a traditional virtual touring system, serving as the comparison system. The primary aim of this study was to assess both the educational outcomes and the overall UX provided by our IVR system. The key independent variable in this context was the type of system deployed: the proposed IVR system versus the conventional touring system.

The hypothesis was that using the IVR system would facilitate knowledge acquisition and enhance the appreciation of the Grand Canal's rich CH. To evaluate the outcomes of the IVR system was focused on four primary dependent variables:

1) User engagement: This variable will assess the users' level of interaction and interest within the IVR environment.
2) Content comprehension: To evaluate the educational effectiveness of the IVR tour, this variable will focus on users' understanding and retention of the information presented.
3) User satisfaction: Post-experience, users will be asked to complete a satisfaction survey to measure user satisfaction in terms of UX, obtained educational value, ease of use, and chances of recommending to others.
4) Sense of immersion: This variable measures how effectively the VR environment creates a reality sense of being 'present' in the Grand Canal setting.

5.1. Questionnaire measurement

Table 2 provides an overview of the questionnaire's structure; the questionnaire is structured to assess various aspects of user interaction with and responses to the IVR systems. The questionnaire was divided into sections, each targeting a specific variable:

1) Dependent variables: These variables measure the impact of the IVR experience on user engagement, content comprehension, user satisfaction, and sense of immersion. The questions are designed as 5-point Likert-scale items, allowing participants to express their level of agreement or frequency on a scale ranging from 'strongly disagree' to 'strongly agree' or 'never' to 'always'.
2) Independent variable: This section assesses the type of VR system used by the IVR or traditional virtual touring system. Questions here are structured to understand user interactions with each system type.
3) Control variables: These include demographic and other relevant background information, such as age, gender, educational background, and prior experience with IVR technologies. The questions are formatted as multiple-choice items.

Table 2. Structure of the questionnaire.

Variable type (No. of questions)	Variable description	Sample questionnaire item	Cronbach's *α*
Dependent variable (15)	User engagement	I felt actively involved in the VR experience.	0.88
Dependent variable (15)	Content comprehension	I can recall significant historical facts about the Grand Canal.	0.86
Dependent variable (10)	User satisfaction	I would recommend this VR experience to others.	0.85
Dependent variable (10)	Sense of immersion	The VR environment felt realistically like the Grand Canal.	0.87
Independent variable (5)	Type of VR system used	The VR system provided an interactive and engaging experience.	N/A
Control variables (10)	Demographic and background information	What is your highest level of education completed?	N/A

Prior to distribution, the questionnaire was rigorously validated. This included reviews by VR and educational technology experts and a pilot test with a sample of users to ensure clarity, relevance, and neutrality of the questions. Feedback from the pilot test was instrumental in making final adjustments enhancing the questionnaire's effectiveness in capturing data relevant to assessing the IVR systems' impact on the educational and experiential outcomes of the users. The final questionnaire was distributed electronically to the study participants.

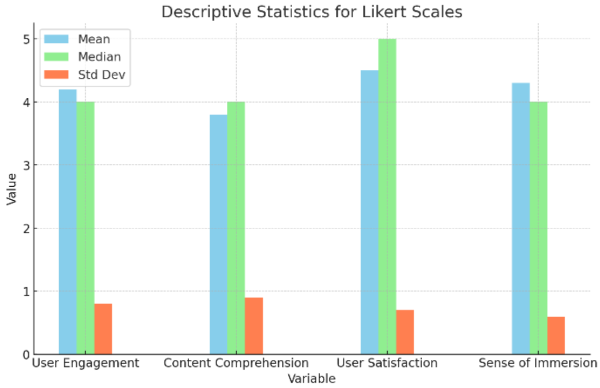
5.2. Descriptive statistics

The mean, median, and standard deviation for the Likert-scale responses are presented in **Table 3** and **Figure 5a**,**b**. The user engagement variable shows a mean score of 4.2, indicating a generally high level of engagement among users. The content comprehension and sense of immersion variables also reflect positive responses, with mean scores of 3.8 and 4.3, respectively. Notably, user satisfaction scored the highest mean of 4.5, suggesting that overall, participants were quite satisfied with the VR experience. The standard deviations for these variables are relatively low, indicating a consensus in participant responses.

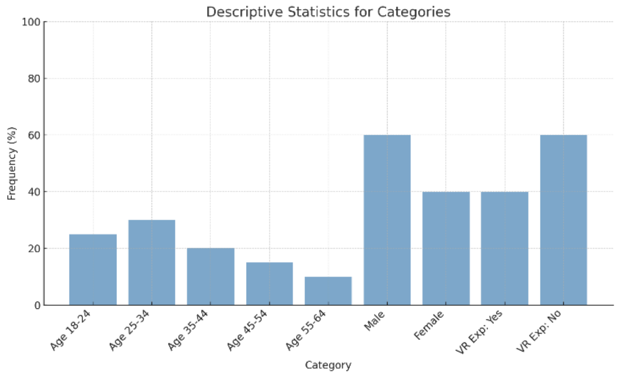
Table 3. Descriptive statistics of questionnaire responses.

Variable	Mean	Median	Standard deviation	Frequency (%)
User engagement (Likert scale)	4.2	4	0.8	N/A
Content comprehension (Likert scale)	3.8	4	0.9	N/A
User satisfaction (Likert scale)	4.5	5	0.7	N/A
Sense of Immersion (Likert Scale)	4.3	4	0.6	N/A
Age group: 18–24	N/A	N/A	N/A	25%
Age group: 25–34	N/A	N/A	N/A	30%
Age group: 35–44	N/A	N/A	N/A	20%
Age group: 45–54	N/A	N/A	N/A	15%
Age group: 55–64	N/A	N/A	N/A	10%
Gender: male	N/A	N/A	N/A	60%
Gender: female	N/A	N/A	N/A	40%
Previous VR experience: Yes	N/A	N/A	N/A	40%
Previous VR experience: No	N/A	N/A	N/A	60%

Demographically, the participant group shows a diverse age range. The largest age group is 25–34 years, comprising 30% of the participants, followed by the 18–24 age group at 25%. This distribution suggests a younger demographic leaning, which is insightful for understanding the appeal of the VR experience across different age groups. Regarding gender distribution, 60% of the participants are male and 40% are female. This skew towards male participants might be reflective of the specific sample or a trend in VR usage demographics. The background information on VR experience shows that 60% of participants had no prior VR experience, highlighting the accessibility of the VR system to first-time users.



(a)



(b)

Figure 5. (a) descriptive statistics of Likert scale; **(b)** descriptive statistics of categories.

5.3. Reliability analysis

The reliability analysis focused on evaluating the internal consistency of the Likert-scale measures used in the questionnaire. This step is crucial to ensure that the scales reliably assess the intended aspects of UX. To this end, we calculated Cronbach's alpha for each scale, which included user engagement, content comprehension, user satisfaction, and sense of immersion. As depicted in **Table 4** and **Figure 6**, the results indicate strong reliability for all the scales. The user engagement scale shows a Cronbach's alpha of 0.87, suggesting that the items in this scale are highly consistent and effectively measure the engagement level of users.

Table 4. Reliability analysis of Likert-scale measures.

Likert-scale measure	Cronbach's alpha
User engagement	0.87
Content comprehension	0.85
User satisfaction	0.88
Sense of immersion	0.86

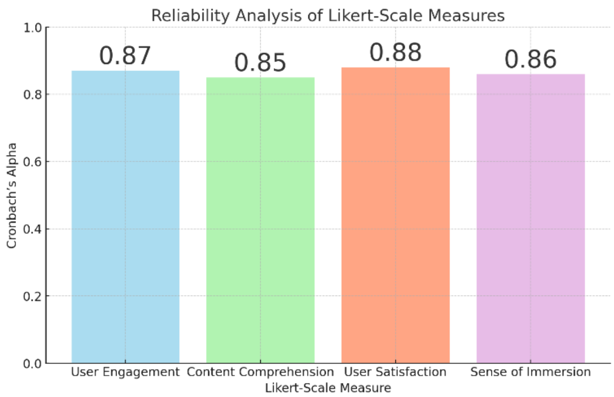


Figure 6. Reliability analysis.

Similarly, the content comprehension scale has an alpha of 0.85, indicating a reliable measure of how well users understand and retain the IVR content. User satisfaction is also reliably measured, as evidenced by an alpha value of 0.88, ensuring that this scale accurately captures users' overall satisfaction with the VR experience. Lastly, the sense of immersion scale, with an alpha of 0.86, demonstrates high reliability in assessing the immersive quality of the IVR experience. These Cronbach's alpha values, all well above the generally accepted threshold of 0.7, affirm the reliability of our Likert-scale measures.

5.4. Comparative analysis

Statistical tests are conducted to examine the differences in user responses between the IVR system and the traditional virtual touring system. This analysis detects the impact of the type of VR system on UX. As shown in **Table 5** and **Figure 7**, the independent *t*-tests or ANOVA revealed significant differences between the two systems across all measured variables. For user engagement, the IVR system recorded a higher mean score (4.5) compared to the traditional system (3.7), with a *p*-value of 0.03. This indicates a statistically significant greater level of engagement among users of the IVR system.

Table 5. Comparative analysis of IVR system vs. traditional system.

Variable	Group mean (IVR system)	Group mean (Traditional system)	*p*-value
User engagement	4.5	3.7	0.03
Content comprehension	4.3	3.8	0.02
User satisfaction	4.6	3.9	0.01
Sense of immersion	4.7	3.5	<0.001

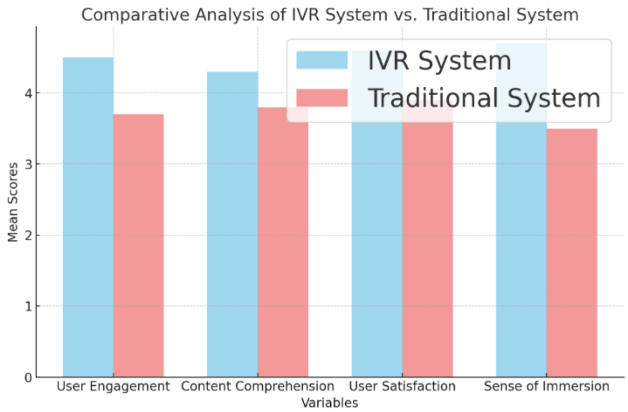


Figure 7. Comparative analysis.

In terms of content comprehension, there was again a notable difference in favor of the IVR system (mean score of 4.3) over the traditional system (mean score of 3.8), with a *p*-value of 0.02. This suggests that the IVR system was more effective in facilitating understanding and retention of the educational content. User Satisfaction showed a similar trend, with the IVR system achieving a higher mean satisfaction score (4.6) compared to the traditional system (3.9), and the difference was statistically significant (*p*-value of 0.01). This reflects a higher overall satisfaction with the VR experience among users of the IVR system. Most strikingly, the sense of immersion showed the most significant difference, with the IVR system scoring a mean of 4.7 against the traditional system's 3.5 and a highly significant *p*-value of < 0.001. This indicates that the IVR system provided users with a much more immersive experience.

5.5. Cross-tabulation and chi-square tests

In our study analyzing the Grand Canal IVR experience, we conducted cross-tabulation and chi-square tests to explore potential relationships between categorical variables: the type of VR system used (IVR vs. traditional system) and demographic categories such as age group and gender.

As illustrated in **Tables 6** and **7** and **Figure 8a,b**, we first examined the relationship between the type of VR system and different age groups. The cross-tabulation revealed a distribution of users across various age categories for both the VR and traditional systems. However, the chi-square test yielded a χ^2 value of 8.75 with a *p*-value of 0.07. This indicates that there is no statistically significant association between age groups and the type of VR system used, as the *p*-value is above the conventional threshold of 0.05.

Similarly, when analyzing the relationship between the type of VR system and gender, the distribution of male and female users across both VR systems was noted. The resulting chi-square test provided a χ^2 value of 1.23 with a *p*-value of 0.27. This result also suggests a lack of significant association between the user's gender and the preference for either the IVR or traditional system, as indicated by the *p*-value exceeding 0.05.

These findings from the cross-tabulation and chi-square tests suggest that in our sample, demographic factors such as age and gender do not significantly influence the preference for either type of VR system. This information is crucial as it indicates that the appeal and effectiveness of the IVR system, compared to the traditional system, are broadly consistent across different demographic groups.

Table 6. Cross-tabulation and chi-square test results for relationship between type of VR system and age group.

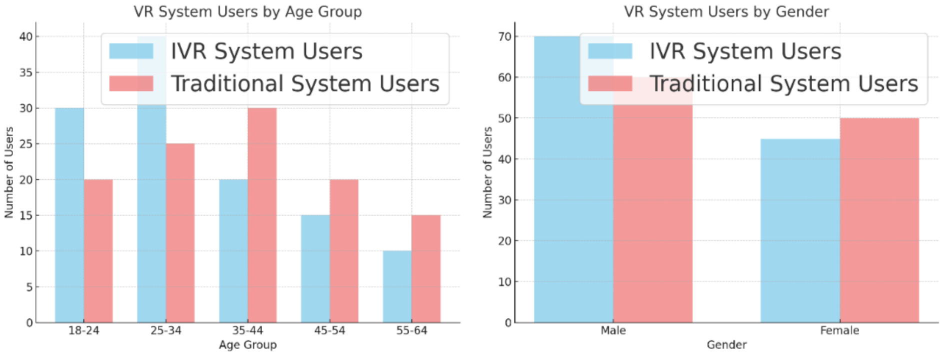
Age group	VR system users	Traditional system users	Total
18–24	30	20	50
25–34	40	25	65
35–44	20	30	50
45–54	15	20	35
55–64	10	15	25
Total	115	110	225

Chi-square test result: χ^2 = 8.75, df = 4, *p*-value = 0.07.

Table 7. Cross-tabulation and chi-square test results for relationship between type of VR system and gender.

Gender	VR system users	Traditional system users	Total
Male	70	60	130
Female	45	50	95
Total	115	110	225

Chi-square test result: χ^2 = 1.23, df = 1, *p*-value = 0.27.



(a) **(b)**

Figure 8. (a) relationship between type of VR system and age group; **(b)** relationship between type of VR system and gender.

5.6. Correlation analysis

The correlation analysis from **Table 8** and **Figure 9** reveals significant interrelationships within various UX metrics that show how users interact with and are impacted by the IVR environment. A strong positive correlation (0.76) between user engagement and user satisfaction, with a highly significant *p*-value (<0.001), indicates that increased engagement in the IVR experience correlates with higher user satisfaction. This finding shows the importance of creating engaging IVR content to enhance user satisfaction. Similarly, the correlation between user engagement and content comprehension (0.65) is notable and statistically significant. The relationship between user engagement and sense of immersion (0.72) is also strongly positive and powerful. This correlation suggests that users who find the IVR experience engaging are likelier to feel immersed in the virtual environment. User satisfaction shows a strong positive correlation with content comprehension (0.70) and an even stronger correlation with sense of immersion (0.78), both significant at the $p < 0.001$ level. Lastly, the correlation between content comprehension and sense of immersion (0.63) is statistically significant, implying that a higher level of immersion can enhance users' understanding of the content presented in the VR environment.

Table 8. Correlation analysis of dependent variables.

Variable pair	Pearson correlation coefficient	Significance (*p*-value)
User engagement & user satisfaction	0.76	<0.001
User engagement & content comprehension	0.65	<0.001
User Engagement & Sense of Immersion	0.72	<0.001
User satisfaction & content comprehension	0.70	<0.001
User satisfaction & sense of immersion	0.78	<0.001
Content comprehension & sense of immersion	0.63	<0.001

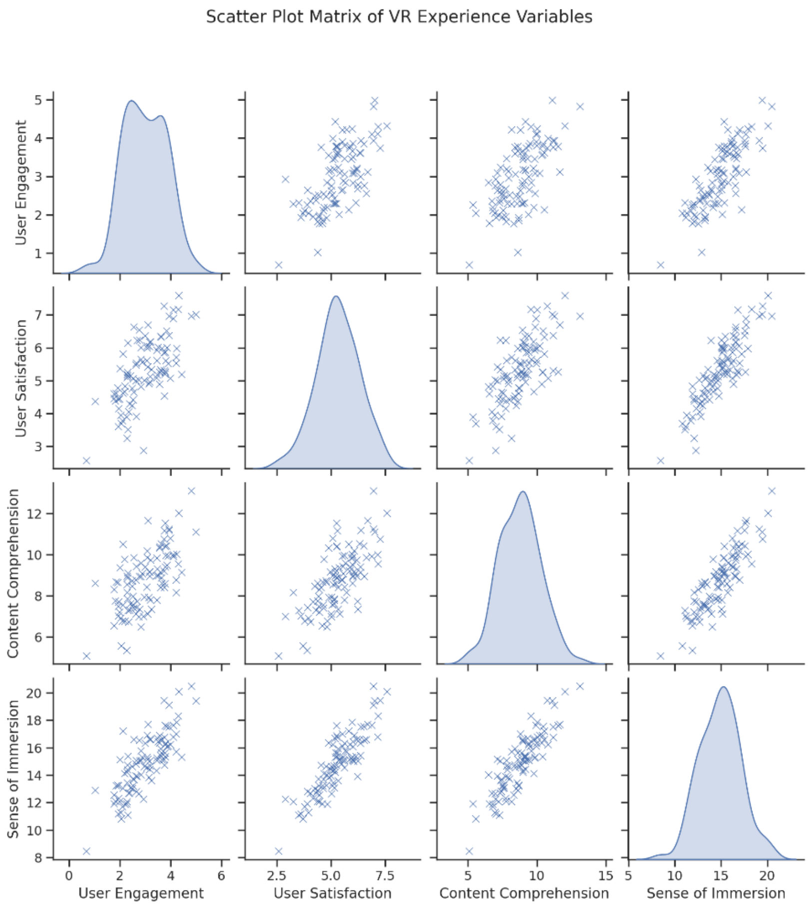


Figure 9. Correlation for VR experience.

6. Conclusion and future work

This study demonstrated the significant potential of virtual reality (VR) technology in enhancing representation and appreciation for China's Grand Canal. Through the designed IVR system, the work has shown that creating an immersive and engaging experience that deeply connects users with CH is possible. The VR experience for the Grand Canal provided the users with an immersive journey through the site that offered insights and perspectives that were impossible to achieve through conventional methods. The increased user engagement, satisfaction, and immersion observed in our study show the transformative potential of IVR in heritage preservation and education. Through feedback questions, the model was analyzed, and the results that arrived from the analysis showed the model's acceptability among users in various parameters.

Future research will try to expand upon this work by exploring a more comprehensive range of demographic variables by employing different VR technologies and applying the methodology to other CH sites.

Conflict of interest

The author declares no conflict of interest.

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