MUSEUM IMMERSION: COMPARING VR HEADSETS AND TOUR FORMATS

IMERSÃO EM MUSEUS: COMPARANDO HEADSETS DE REALIDADE VIRTUAL E FORMATOS DE VISITA GUIADA

INMERSIÓN EN MUSEOS: COMPARACIÓN DE GAFAS DE REALIDAD VIRTUAL Y FORMATOS DE RECORRIDO

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DOI: 10.54899/dcs.v22i85.4091
Recibido: 21/11/2025 | Aceptado: 15/12/2025 | Publicación en línea: 22/12/2025.

ABSTRACT

This research investigates the effectiveness of different approaches for presenting cultural experiences in virtual environments, using a digitized museum as a case study. Two Virtual Reality (VR) tour formats were developed from a 360◦ recording of the museum space: an interactive tour allowing free navigation and information selection, and a guided tour featuring an AI-driven narrative, resembling a 360◦ video. The study's primary focus is to evaluate which tour format provides greater user immersion and retention time, and to investigate the influence of the headset type (Meta Quest 2, Meta Quest 3, Meta Quest Pro, and Pico 4) on usability and user experience. The methodology employed a mixed-methods approach, includingtheadaptedMV-SUSscale,ThinkingAloud technique, A/B testing, and Recall Tests with five participants. The findings indicate a strong user preference for the Free Tour (80%), emphasizing the value of user autonomy. Furthermore, the preference for newer generation headsets (Quest 3 and Pico 4) highlights the significance of hardware quality. Crucially, the perfect performance (100% accuracy) in the recall test validates the significant educational potential of VR in cultural mediation. The study contributes valuable insights for implementing VR technologies in museological contexts, seeking to enhance cultural experience and accessibility.

Keywords: Virtual Reality. User Experience. Digital Museums.

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RESUMO

Esta pesquisa investiga a eficácia de diferentes abordagens para apresentar experiências culturais em ambientes virtuais, utilizando um museu digitalizado como estudo de caso. Dois formatos de visita virtual em realidade virtual (RV) foram desenvolvidos a partir de uma gravação em 360° do espaço do museu: uma visita interativa que permite navegação livre e seleção de informações, e uma visita guiada com narrativa conduzida por inteligência artificial, semelhante a um vídeo em 360°. O foco principal do estudo é avaliar qual formato de visita proporciona maior imersão e tempo de retenção do usuário, e investigar a influência do tipo de headset (Meta Quest 2, Meta Quest 3, Meta Quest Pro e Pico 4) na usabilidade e na experiência do usuário. A metodologia empregou uma abordagem mista, incluindo a escala MV-SUS adaptada, a técnica de pensamento em voz alta, testes A/B e testes de recordação com cinco participantes. Os resultados indicam uma forte preferência dos usuários pela Visita Livre (80%), enfatizando o valor da autonomia do usuário. Além disso, a preferência por headsets de nova geração (Quest 3 e Pico 4) destaca a importância da qualidade do hardware. Fundamentalmente, o desempenho perfeito (100% de precisão) no teste de memorização valida o significativo potencial educacional da realidade virtual na mediação cultural. O estudo contribui com informações valiosas para a implementação de tecnologias de realidade virtual em contextos museológicos, buscando aprimorar a experiência cultural e a acessibilidade.

Palavras-chave: Realidade Virtual. Experiência do Usuário. Museus Digitais.

RESUMEN

Esta investigación analiza la eficacia de diferentes enfoques para presentar experiencias culturales en entornos virtuales, utilizando un museo digitalizado como caso de estudio. Se desarrollaron dos formatos de recorrido de Realidad Virtual (RV) a partir de una grabación de 360° del espacio museístico: un recorrido interactivo que permite la navegación libre y la selección de información, y un recorrido guiado con una narrativa impulsada por IA, similar a un vídeo de 360°. El estudio se centra principalmente en evaluar qué formato de recorrido proporciona mayor inmersión y tiempo de retención del usuario, e investigar la influencia del tipo de visor (Meta Quest 2, Meta Quest 3, Meta Quest Pro y Pico 4) en la usabilidad y la experiencia del usuario. La metodología empleó un enfoque de métodos mixtos, que incluyó la escala MV-SUS adaptada, la técnica de Pensamiento en Voz Alta, pruebas A/B y pruebas de recuerdo con cinco participantes. Los resultados indican una fuerte preferencia de los usuarios por el Recorrido Libre (80%), lo que enfatiza el valor de la autonomía del usuario. Además, la preferencia por las nuevas generaciones de gafas (Quest 3 y Pico 4) destaca la importancia de la calidad del hardware. Fundamentalmente, el rendimiento perfecto (100 % de precisión) en la prueba de recuerdo valida el importante potencial educativo de la RV en la mediación cultural. El estudio aporta información valiosa para la implementación de tecnologías de RV en contextos museológicos, buscando mejorar la experiencia cultural y la accesibilidad.

Palabras clave: Realidad Virtual. Experiencia del Usuario. Museos Digitales.

INTRODUCTION

The emergence of the Metaverse and immersive technologies is revolutionizing cultural access, transforming the relationship between users and heritage institutions. Over the past decade, the use of Virtual Reality (VR) has moved beyond entertainment to become a critical tool for cultural preservation and dissemination. A notable example is Tuvalu's pioneering initiative to digitize its national heritage against the threat of climate change, demonstrating the strategic importance of immersive preservation.

Museums, in particular, are exploring VR to overcome physical barriers, offering visitors unique, interactive, and personalized experiences that transcend geographical limitations. This research systematically investigates the efficacy of different approaches for presenting cultural content in virtual environments, usingadigitizedmuseumasitscasestudy. The core research question is: **"Which combination of tour format and visualization technology provides the most immersive and satisfactory experience for visitors to virtual museums?"**

The main objectives of this study are:

1. To investigate the effectiveness of the **Interactive Free Tour** versus the **AI-Narrated Guided Tour** on user experience metrics.
2. To evaluate the impact of four distinct VR headsets (Meta Quest 2, Meta Quest 3, Meta Quest Pro, and Pico 4) on usability, comfort, and immersion.
3. To utilize a multidimensional methodological approach, including the adapted MV-SUS scale, Thinking Aloud technique, A/B Testing, and Recall Tests, to gather both quantitative and qualitative data.

The findings are intended to contribute to the formulation of innovative practices for cultural content presentation and serve as a guide for institutions considering large-scale VR implementation.

THEORETICAL FRAMEWORK AND RELATED WORK

Virtual Reality and Cultural Heritage

VR technology facilitates experiences where users feel present in a virtual space, achieving a sense of *telepresence*. In the context of museums, VR offers opportunities for

reconstruction, visualization of inaccessible artifacts, and enriched educational interaction. The 360° image-based virtual tour, the methodology adopted here, is a common and accessible technique for digitizing physical spaces, ensuring visual quality and an immediate sense of immersion (Peteva, 2022).

Usability in VR Environments

Usability is crucial for the success of any technological interface, particularly in VR where poor design can lead to motion sickness (*cinetose*) or cognitive overload. The concept of usability encompasses not onlyefficiencyandeffectivenessbutalsousersatisfaction and comfort (Nielsen, 2000). The specific challenges in VR include intuitive navigation, minimizing latency, and ensuring ergonomic comfort across different hardware.

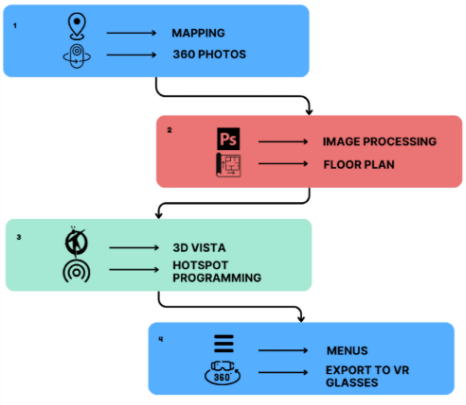
The MV-SUS Scale

The System Usability Scale (SUS) is a globally recognized tool for measuring usability. For this research, the MV-SUS (Museu Virtual - System Usability Scale) scale was adapted. This adaptation broadens the focus beyond standard usability to include dimensions specific to immersive cultural experiences, such as Immersion, Presence, Educational Value, and Comfort (Febiharsa *et al*., 2025). The scale allows for a standardized assessment, yielding a single score from 0 to 100, facilitating comparison and benchmarking.

METHODOLOGY

The study employed a **mixed-methods approach** utilizing a **within-subjects experimental design**. Five participants (N=5) experienced both the Free Tour and the Guided Tour, each across four different VR headsets, following a counterbalanced order to mitigate learning and fatigue effects.

Figure 1: ”Flowchart for Agile Development in Virtual Reality”



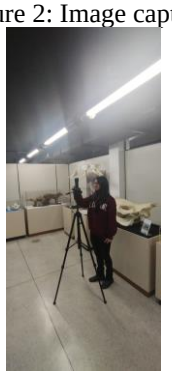
Source: Authors

Virtual Environment Development

The virtual environment was based on a traditional museum space, digitized through a four-phase protocol:

1. **Mapping and Image Capture:** A predefined path was established within the museum. Highresolution 360° images were captured using the **Insta360 One RS** camera mounted on a tripod at a height of 1.6 meters, simulating an average adult’s line of sight.

Figure 2: Image capture

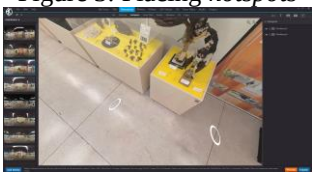


Source: Authors

2. **Image Processing:** Captured stereoscopic images were converted to the standard **equirectangular format**. The images were processed to correct distortions and optimize for VR rendering.
3. **Virtual Tour Creation:** The environment was built using the **3DVista suite**. Navigation was implemented via interconnected hotspots (teleportation), and interactive information

points (text/image/video) were embedded. The audio narration for the Guided Tour was generated

Figure 3: Placing *hotspots*



Source: Authors

using the **ElevenLabs** AI voice synthesis platform (ElevenLabs, 2025), configured for clear and professional narration.

4. **UI Design and Export:** An intuitive User Interface (UI) was designed, emphasizing visual comfort to minimize motion sickness. The final application was exported as web files (HTML5, CSS,andJavaScript)toberundirectlyontheVR headsets' native browser (Meta Quest Browser).

Hardware and Participants

Visualization Devices

Materials and Equipment for User Testing

Hardware (Display Devices

The developed virtual environment was tested on four distinct models of Virtual Reality (VR) headsets, selected because they represent different generations and price categories in the market, allowing for a comprehensive evaluation:

Meta Quest 2

Entry-level, widely adopted model, featuring an LCD screen and a resolution of 1832×1920 pixels per eye. Palusova (2023)

Meta Quest 3

Latest-generation model, with pancake lenses for greater visual clarity, a superior resolution of 2064 × 2208 pixels per eye, and color depth tracking. Palusova (2023)

Meta Quest Pro

Focused on professional users, it features pancake lenses, a resolution of 1800×1920 pixels per eye, face andeyetracking, andcontrollerswithhapticfeedback.

Palusova (2023)

Pico 4

Direct competitor to the Quest 2, equipped with pancake lenses, a resolution of 2160×2160 pixels per eye, and a balanced design for comfort. Palusova (2023)

The choice of these devices allowed us to evaluate how factors such as ergonomic comfort, which impact immersion and usability in a cultural context, influence the experience.

Participants

User Sample and Recruitment Criteria

According to Nielsen (2000), and the NN Group guidelines for usability testing, which indicate that 5 users are sufficient to identify more than 80 percent of the usability problems in a design, the sample for this study was composed of 5 participants, intentionally recruited to represent a diverse profile of potential end-users of virtual museums. The recruitment criteria prioritized variety in technological experience, age ranges, and relationships with the academic and cultural universe. The sample consisted of:

- Undergraduate Student – 18 years old
- Undergraduate Student (from another field) – 38 years old
- University Education Professor – 34 years old
- Civil Servant Interested in Culture – 54 years old
- User with no prior VR experience – 23 years old

The general inclusion criteria were: being over 18 years old and having a general interest

in culture and technology. Prior experience with VR was not a requirement, in order to capture perspectives from both novices and experienced users, reflecting the actual target audience of a cultural institution.

Data Collection Instruments

Data Analysis

Quantitative Data: The MV-SUS scores was calculated (if we call the score p and the answered value r, we can use the following calculations for each item i: for positive items $p_i = r - 1$; and for negative items $p_i = 5 - r$; then, for the overall score, we sum the items as follows 10

$$2.5\sum_{i=1} p_i = P_f \qquad (1)$$

where P_f is the final score, from 0 − 100). The accuracy data from the $_{recall\ test}$ and the SUS will be statistically analyzed (Repeated Measures ANOVA) Samadi *et al*. (2021) using the *SPSS software* to compare the conditions.

Qualitative Data: Open-ended responses and *Thinking Aloud* transcriptions will be submitted to Thematic Content Analysis for the identification of themes and patterns.

Triangulation: Quantitativeandqualitativeresults will be integrated to provide a comprehensive understanding of the findings.

- **MV-SUS (Museu Virtual - System Usability Scale):** An adapted 10-item, 5-point Likert scale used to quantitatively measure usability, immersion, comfort, and educational value.

MV-SUS

(Virtual Museum - System Usability Scale) Adapted scale with 10 items on a 5-point Likert scale (1: Strongly Disagree to 5: Strongly Agree):

1. I found the virtual museum experience immersive and engaging.
2. I had difficulty navigating the virtual environment (e.g., getting lost or not understanding how to move). [N]
3. The interaction controls (e.g., picking up objects, zoom) were intuitive and easy to use.
4. I felt physical discomfort (e.g., dizziness, nausea) during the experience. [N]
5. The museum content (e.g., information, narratives) was clear and interesting.

6. I found the technology unnecessarily complex for the educational purpose. [N]
7. I felt present in the virtual environment, as if I were in the physical museum.
8. I experienced technical problems (e.g., freezing, delays) that hindered the experience. [N]
9. I learned something new more effectively than I would in a traditional museum.
10. I would need technical help to repeat the experience on my own. [N]

Note: N = Negative item, for score reversal.

Objective behind each MV-SUS question (Virtual Museum - System Usability Scale):

Engagement and Immersion: "I found the virtualmuseumexperienceimmersiveandengaging."

Usability (Navigation): "I had difficulty navigating the virtual environment..."

Usability (Interaction): "The interaction controls... were intuitive and easy to use."

Comfort (Cybersickness): "I felt physical discomfort... during the experience."

Content Quality: "The museum content... was clear and interesting."

Perceived Complexity: "I found the technology unnecessarily complex..."

Presence: "I felt present in the virtual environment..."

Technical Reliability: "I experienced technical problems... that hindered the experience."

Educational Value: "I learned something new more effectively..."

Autonomy: "I would need technical help to repeat the experience..."

- **Thinking Aloud Technique (TAT):** Participants were encouraged to verbalize their thoughts, feelings, and difficulties spontaneously during the interaction, providing rich qualitative data (Caroline *et al*., 2017).
- **A/B Test:** After experiencing both formats, participants explicitly chose their preferred tour (Free vs. Guided), with justification.
- **Recall Test:** A three-question multiple-choice test administered post-experience to assess knowledge retention and the effectiveness of cultural mediation.

RESULTS AND DISCUSSION

Tables

The tables correspond to the individual MV-SUS scores of the participants represented as P[Participant Age]:

Table 1: Table 1: P38

Question	Response	Calculation
1	2	1
2	3	2
3	4	3
4	5	0
5	4	3
6	5	0
7	1	0
8	1	4
9	1	0
10	1	4
Sum		17
Total Score		42.5

Author's elaboration (2025)

Table 2: Table 2: P54

Question	Response	Calculation
1	4	3
2	2	3
3	4	3
4	2	3
5	3	2
6	3	2
7	3	2
8	3	2
9	1	0
10	2	3
Sum		23
Total Score		57.5

Source: Author's elaboration (2025)

Overall Usability Performance (MVSUS)

The MV-SUS analysis revealed a mean score of **62.5** for the Free Tour experience across

all headsets, with a standard deviation (σ) of 13.02. Individual scores ranged from 42.5 to 77.5.

Table 3: Table 3: P34

Question	Response	Calculation
1	5	4
2	1	4
3	4	3
4	3	2
5	4	3
6	1	4
7	4	3
8	4	1
9	1	0
10	3	2
Sum	26	
Total Score	65	

Source: Author's elaboration (2025)

Table 4: Table 4: P23

Question	Response	Calculation
1	5	4
2	4	1
3	5	4
4	3	2
5	5	4
6	1	4
7	4	3
8	1	4
9	3	2
10	2	3
Sum	31	
Total Score	77.5	

Author's elaboration (2025)

Table 5: Table 5: P18

Question	**Response**	**Calculation**
1	5	4
2	1	4
3	5	4
4	4	1
5	5	4
6	1	4
7	4	3
8	3	2
9	3	2
10	5	0
Sum		28

Total Score	70

Author's elaboration (2025)

Table 6: Resumo dos Escores MV-SUS por Participante

participant	Sum	Escore SUS
1	17	42,5
2	23	57,5
3	26	65,0
4	31	77,5
5	28	70,0
average	**25,0**	**62,5**
standard deviation	**5,34**	**13,02**

Prepared by the author (2025)

MV-SUS Score Interpretation

According to the Bangor scale, a score of 62.5 falls within the **acceptable usability range**. This suggests that while the system is functional, there is significant room for improvement to achieve a "Good" or "Excellent" rating (scores above 70 and 80, respectively). The high standard deviation indicates that the experience was not uniformly perceived, highlighting the need to address specific issues impacting certain users.

Dimensional Analysis of MV-SUS

The analysis of specific dimensions provided targeted insights:

- **Strengths (High Scores):** Immersion, Engagement, and Control Intuitiveness received mean scores above 4.0 (on a 5-point scale), indicating that the core experience is highly captivating and easy to interact with.
- **Areas for Improvement (Low Scores):** The lowest score was recorded for **Educational Effectiveness**(1.8), suggestingthatdespitethehigh level of engagement, the perceived learning process was weak. Additionally, **Perceived Complexity** and **Physical Discomfort** (related to motion sickness/ergonomics) were critical areas.

Tour Format Preference

TheA/Btestingyieldedaclearpreferenceforthe**Free Tour** format:

- **Free Tour:** 4 out of 5 participants (**80%**) preferred this format.
- **Guided Tour:** 1 participant (20%) preferred this format.

This result strongly supports the hypothesis that, even for first-time VR users, the **autonomy of exploration and the freedom to choose information** are paramount values in a virtual cultural experience (Moura, 2025; Yang, 2023). Participants emphasized the flexibility to pause, revisit, and selectively engage with content, which the linear Guided Tour restricts.

Headset Preference

The preference for hardware clustered around the newer models:

- **Meta Quest 3:** Preferred by 2 participants.
- **Pico 4:** Preferred by 2 participants.
- **Meta Quest Pro:** Preferred by 1 participant.
- **Meta Quest 2:** Not preferred by any participant.

The Quest 2, being the oldest model tested, was consistently noted for its lower resolution and heavier bulk compared to the others. This reinforces the finding that **technological advancements**, especially in visual fidelity (higher resolution and Pancake lenses) and ergonomics, are non-negotiable factors for a premium and comfortable immersive experience (Palusova, 2023).

Recall Test Results and Educational Impact

Despite the low score in the MV-SUS dimension for perceived educational effectiveness, the objective measure of knowledge retention was outstanding:

- **Recall Test Performance:** All five participants (**100%** of the sample) achieved the maximum score (3 out of 3 questions correct).

This perfect recall rate is a critical finding. It suggests that while users *perceived* the educational process as weak (low MV-SUS score), the immersive nature of VR led to a highly effective transfer and retention of information (Cohen *et al*., 2017). The discrepancy between perceived learning and objective retention highlights a limitation in the MV-SUS scale's ability to accurately capture cognitive impact, even in its adapted form.

Qualitative Analysis (Thinking Aloud)

The qualitative data collected via the Thinking Aloud technique identified primary usability bottlenecks:

- **Motion Sickness and Navigation:** Although implemented, the teleportation method caused discomfort for one participant. Issues with spatialorientation, suchasa"lackofnotionofwhich part of the museum I was in" and difficulties with the navigation markers, were frequently reported.
- **Interface Complexity:** Novice users found the initial interaction flow slightly confusing, particularly regarding the simultaneous display of information points and navigation hotspots.
- **Ergonomics:** Complaints were related to the fixed viewing height, suggesting the need for avatar height adjustment to match individual physical characteristics.

Key suggestions for improvement included: implementing alternative comfort options (e.g., smooth locomotion alongside teleportation), simplifying the interface for first-time use, and incorporating more interactive and personalized educational elements (e.g., closer interaction with artifacts).

CONCLUSIONS AND FUTURE WORK

This study successfully investigated the usability and user experience in a virtual museum, comparing navigationmodalitiesandevaluatingtheinfluenceofmodern VR hardware.

The primary conclusions drawn are:

1. **Autonomy is Key:** The strong preference for the Free Tour (80%) affirms that providing visitors with **autonomy of exploration** is fundamental to designing engaging and satisfactory immersive cultural experiences.
2. **Hardware is Critical:** The concentration of preference on the Quest 3 and Pico 4 demonstrates that continued investment in high-quality hardware is essential, as visual fidelity and comfort significantly enhance the user experience.
3. **EducationalEffectivenessvs. Perception:** The overall acceptable MV-SUS score (62.5) indicates good usability, but the 100% accuracy in the Recall Test is the most compelling

result, validating the significant **educational potential** of VR for effective information retention, despite the users' low self-assessment of learning.

Practical Implications

Cultural institutions should prioritize the development of non-linear, exploratory experiences and invest in VR hardware featuring Pancake lens technology. Future implementations should focus on addressing identified usability pain points, specifically by refining navigation mechanisms (e.g., offering varied locomotion options) and simplifying the interface to achieve an "Excellent" usability rating (SUS score > 80).

Limitations and Future Work

The primary limitation of this study is the **small sample size (**N = 5**)**. While adequate for identifying core usability problems, it restricts broad generalization. Future work should expand the sample size, include longitudinal studies to assess long-term retention, and investigate the impact of full-room scale VR (versus 360° images) on presence and immersion metrics.

In summary, this research confirms the transformative potential of immersive technologies to democratize access to culture and enhance museological experiencesbyintegratinguserautonomy, technological quality, and strong educational efficacy.

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