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A machine learning-enhanced virtual museum for preserving Jordanian cultural heritage: Predicting user satisfaction and engagement profiling

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A B S T R A C T

Virtual reality (VR) has emerged as a powerful tool for cultural heritage preservation; however, most existing VR museum studies rely on descriptive statistics for evaluation, lacking the predictive depth that data-driven approaches can offer. This paper addresses this gap by integrating machine learning (ML) techniques into the evaluation of a VR museum dedicated to traditional Jordanian women's clothing, focusing on Bedouin garments from Wadi Rum, Ma'an, and Petra. Seven historically accurate 3D costumes were reconstructed using Blender based on ethnographic references and expert consultations, integrated into a navigable museum environment in Unity, and deployed on the Meta Quest 2 headset. A total of 150 university students participated in the evaluation, providing demographic data and Likert-scale ratings across four experience dimensions: engagement, cultural understanding, navigation intuitiveness, and visual realism. Six ML classifiers, K-Nearest Neighbors, Support Vector Machine, Decision Tree, Random Forest, Naive Bayes, and Logistic Regression, were trained using 5-fold stratified cross-validation to predict user satisfaction. Logistic Regression achieved the best performance (accuracy: 84.67%, F1-score: 0.7884), while Decision Tree performed the lowest (accuracy: 71.33%, F1-score: 0.5947). Random Forest feature importance analysis revealed that cultural understanding (0.189), visual realism (0.173), and navigation (0.168) were the strongest predictors, whereas demographic factors such as gender (0.023) and prior VR experience (0.034) had minimal influence. K-Means clustering identified three distinct user profiles: Passive Observers (27.3%), and two Selective Explorer groups (39.3% and 33.3%) with divergent interaction patterns. These results demonstrate that ML can effectively predict and profile user satisfaction in VR heritage environments, offering data-driven insights for designing adaptive and personalized virtual museums.

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1. Introduction

Traditional clothing constitutes a vital component of cultural identity and collective memory. In Jordan, the garments of Bedouin tribes and the southern communities of Wadi Rum, Ma'an, and Petra have evolved over centuries, embodying the region's heritage through their distinctive embroidery, textiles, colors, and structural design (Weir, 1989; Kawar, 2011). These tribal garments, featuring regionally styled patterns and symbolic motifs, convey information about tribal affiliation, social status, and belief systems. However, the transmission of this cultural knowledge has become increasingly challenging due to modernization, urbanization, and the gradual decline of traditional craftsmanship. Virtual Reality (VR) and Augmented Reality (AR) have emerged as impactful modalities for education, heritage conservation, and cultural engagement. These technologies facilitate experiential learning by enabling users to interact with digital representations of physical objects, explore simulated environments, and engage in problem-solving activities within extended reality settings (Kim, 2023; Oladokun et al., 2024). Within museum contexts, VR and AR enhance both temporary and permanent exhibitions, creating

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more engaging experiences for diverse audiences (Li et al., 2024). Digital technologies, particularly 3D modeling and VR, offer promising solutions for heritage documentation, enabling the detailed recording of garment form, texture, and embroidery without physical contact (Styliani et al., 2009). While VR-based cultural heritage systems have demonstrated their potential in preservation and education, a critical gap remains in understanding user experience within these environments. Most existing studies rely on descriptive statistics and simple survey analysis to evaluate user satisfaction, lacking the predictive and analytical depth that machine learning (ML) approaches can provide (Wang & Yu, 2025). ML techniques such as classification and clustering have been successfully applied in e-learning and educational technology contexts to predict student satisfaction and identify learner profiles (Mutawa & Sruthi, 2023; Sandiwarno et al., 2023), yet their application to VR-based cultural heritage remains largely unexplored.

This study addresses this gap by integrating machine learning-based analysis into the evaluation of a VR museum for traditional Jordanian clothing. The research pursues four objectives: (1) to digitally reconstruct traditional Jordanian garments through 3D modeling and present them in a VR environment; (2) to develop a virtual museum featuring cultural symbols associated with the regional dresses of Wadi Rum, Ma'an, and Petra with educational annotations; (3) to apply supervised machine learning classifiers to predict user satisfaction based on demographic and experiential features; and (4) to employ unsupervised clustering to identify distinct user engagement profiles. The central research question is: How effectively can machine learning techniques predict and profile user satisfaction in VR-based cultural heritage experiences?

2. Literature Review

2.1 Traditional Jordanian Clothing

Traditional clothing in Jordan serves as a vivid expression of cultural identity, interwoven with tribal traditions, geographic conditions, and social practices. The women's traditional garment, known as the thobe, is distinguished by its hand-stitched embroidery, or tatreez, which frequently incorporates symbolic motifs believed to offer protective or auspicious qualities (Ghnaim, 2018; Weir, 1989). Southern dresses from Ma'an, Petra, and Wadi Rum are characterized by dark fabrics adorned with bold red or orange geometric designs, whereas northern garments tend to feature lighter fabrics with floral patterns (Saca & Saca, 2006). However, globalization, the proliferation of fast fashion, and the decline of intergenerational knowledge transmission have placed this cultural heritage at risk (Kawar, 2011; Chen et al., 2024; Chunlan et al., 2025).

2.2 Digital Heritage Preservation and Virtual Museums

Virtual museums provide global audiences with opportunities to interactively explore cultural garments through digitally created 3D assets (Song & Evans, 2024; Harisanty et al., 2024). Research has demonstrated that such immersive experiences increase engagement, emotional connection, and knowledge retention. Several international initiatives have sought to digitize traditional clothing collections, including the Europeana Fashion project and the Smithsonian's digital fashion archive. However, clothing from the Middle East, and Jordan in particular, remains largely underrepresented in these digital preservation initiatives. The virtual museum architecture developed in this study uses Blender and Unity for deployment on the Meta Quest 2 headset, following the GLAM sector frameworks described by Meier et al. (2021) and Spyrou et al. (2025).

2.3 Machine Learning in User Experience Evaluation

Machine learning has been increasingly applied to predict and analyze user experience across educational and interactive technology domains. In e-learning contexts, classifiers such as Support Vector Machines, Random Forest, and Logistic Regression have been used to predict student satisfaction and performance based on demographic and behavioral features (Mutawa & Sruthi, 2023). Abuhassna et al. (2020) demonstrated that ML models could effectively predict learner satisfaction in online learning environments, identifying key features that influence positive outcomes. Similarly, unsupervised methods such as K-Means clustering have been employed to segment users into distinct profiles based on their interaction patterns and satisfaction levels. In the context of VR and immersive technologies, ML-based approaches have been applied to predict user engagement in virtual environments (Gronowski et al., 2024), analyze user behavior in educational simulations (Radianti et al., 2020), and optimize adaptive VR systems based on physiological and behavioral data (Stoean et al., 2024). However, the intersection of machine learning with VR-based cultural heritage evaluation remains a nascent area. This study contributes to this gap by applying both supervised classification and unsupervised clustering to analyze user experience data collected from a VR cultural heritage museum, providing insights that extend beyond traditional descriptive analysis.

3. Materials and Methods

3.1 System Architecture

The proposed system consists of three integrated components: (1) a VR museum environment developed using Blender and Unity for 3D content creation and immersive deployment on the Meta Quest 2; (2) a data collection module that captures user demographic information and experience ratings through structured surveys; and (3) a machine learning analysis pipeline implemented in Python using scikit-learn for satisfaction prediction and user profiling. The overall workflow proceeds from asset creation in Blender, through character rigging in Mixamo, to final assembly in Unity, followed by user evaluation and ML-based analysis of the collected data.

3.2 Costume Selection and Modeling

The primary garments selected for this project represent the Bedouin dress of southern Jordan, specifically from the regions of Wadi Rum, Ma'an, and Petra. The project produced a collection of seven traditional Jordanian costumes in digital form, each representing distinct regional styles, embroidery techniques, and social contexts. The modeling process in Blender was methodical and iterative, with initial garment forms created using the software's cloth simulation tools guided by tailoring drawings and high-resolution photographic references (Akram & Degen, 2023). Surface detailing employed a hybrid approach combining texture painting techniques with UV-mapped embroidery patterns to balance visual fidelity with the computational constraints of VR rendering. Historical accuracy was ensured through careful reference to scholarly sources including Kawar (2011, 2012) and Weir (1989).

(a) Pracht und Geheimnis (Kawar, 2012) (b) Threads of Identity (Kawar, 2011)

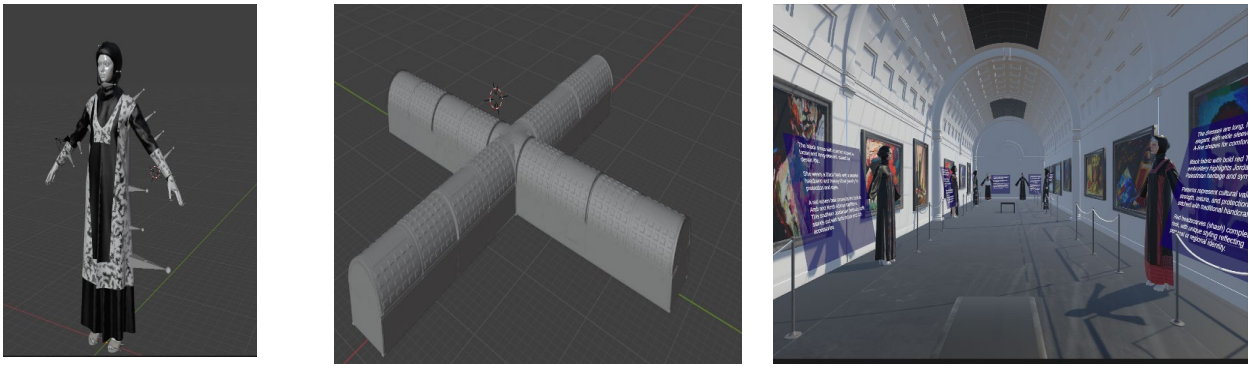
Fig. 1. Key references used for designing traditional Jordanian Bedouin dress.

(a) Photographic and cultural references (b) 3D modeling of the costume in Blender (c) Texture painting for fabric details

Fig. 2. Stages of reference gathering, modeling, and texturing for the traditional costume.

3.3 VR Museum Development

A virtual museum environment was designed in Blender incorporating architectural elements such as flooring, walls, lighting, and exhibition platforms to simulate a professional gallery setting.



(a) Female 3D character modeled in Blender (b) Virtual museum environment created in Blender (c) Final Unity scene with character and museum integrated

Fig. 3. Development stages of the virtual museum and character integration.

The navigation system employs first-person controls, enabling users to move freely throughout the digital museum environment. All assets were imported into Unity, where lighting effects, user controls, camera perspectives, and VR interaction features were implemented using the XR Toolkit. Performance optimization was conducted to ensure smooth operation on the Meta Quest 2 standalone hardware.

3.4 Evaluation Methodology and Data Collection

A formal evaluation study was conducted at a Jordanian university involving 150 undergraduate students from diverse academic backgrounds. The evaluation session comprised three phases: (1) a brief introductory lecture on Jordanian traditional dress; (2) individual exploration of the VR museum using Meta Quest 2 headsets; and (3) a post-experience evaluation through a structured survey instrument.

The survey collected the following data for each participant: demographic information (age, gender, academic background), prior VR experience (yes/no), self-rated prior knowledge of Jordanian heritage (1–5 Likert scale), technology comfort level (1–5 Likert scale), and four user experience dimensions each rated on a 5-point Likert scale: (1) engagement, comparing the VR experience with traditional textbook-based learning; (2) cultural understanding, assessing self-reported improvement in knowledge of Jordanian dress symbolism; (3) navigation intuitiveness, evaluating the ease of movement within the virtual space; and (4) visual realism, rating the perceived authenticity of the 3D garment models. The target variable, overall satisfaction, was derived as a binary classification (High/Low) based on the average of the four experience dimension scores, with a threshold of 3.25.

3.5 Machine Learning Pipeline

The collected data were processed through a comprehensive machine learning pipeline. Categorical variables (gender, academic background, VR experience) were encoded using label encoding, and all features were standardized using z-score normalization. The feature set comprised ten variables: age, gender, academic background, VR experience, heritage knowledge, technology comfort, engagement, cultural understanding, navigation, and visual realism. The binary target variable was overall satisfaction (High/Low).

Classification: Six supervised classifiers were trained and evaluated: K-Nearest Neighbors (KNN, k=7), Support Vector Machine (SVM, RBF kernel), Decision Tree (max depth=4), Random Forest (100 estimators, max depth=5), Gaussian Naive Bayes, and Logistic Regression. All classifiers were evaluated using stratified 5-fold cross-validation to ensure robust performance estimation. Four metrics were reported: accuracy, precision, recall, and F1-score.

Feature Importance: Random Forest feature importance scores were computed to identify the most influential predictors of user satisfaction, providing interpretable insights into which aspects of the VR experience most strongly influence overall satisfaction.

Clustering: K-Means clustering was applied to the four experience dimensions (engagement, cultural understanding, navigation, visual realism) to identify distinct user engagement profiles. The optimal number of clusters was determined using both the Elbow method (within-cluster sum of squares) and Silhouette analysis. Principal Component Analysis (PCA) was used to visualize the resulting clusters in two-dimensional space.

4. Results and Discussion

4.1 Participant Demographics

A total of 150 undergraduate students participated in the evaluation study. The sample comprised 88 females (58.7%) and 62 males (41.3%), with a mean age of 25.4 years (SD = 5.2). Participants represented five academic backgrounds: Design (26.7%), Cultural Studies (25.3%), Computer Science (16.7%), History (16.0%), and Other (15.3%). The majority (67.3%) reported no prior VR experience. The satisfaction distribution was 62.0% Low and 38.0% High, providing a reasonably balanced dataset for classification. Fig. 4 presents the demographic distribution of participants.

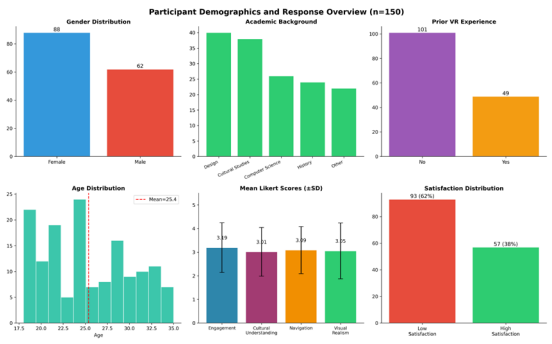


Fig. 4. Participant demographics and response overview (n=150).

4.2 VR Museum Implementation

A functional prototype of the virtual museum was successfully developed, integrating 3D modeling in Blender, interaction design in Unity, and deployment on the Meta Quest 2 platform. The exhibition features seven traditional Jordanian costumes spanning everyday wear to formal garments, representing both urban and rural cultural traditions. Table 1 summarizes the main features of each costume included in the virtual exhibit.

Table 1
Costumes Created for the Virtual Museum

Costume Name	Region	Main Features	Use Case
Southern Bedouin Dress	Wadi Rum / Ma'an	Black base, bold stripes, red belt, silver jewelry, hijab	Wedding, Ceremonial
Northern Jordanian Thobe	Irbid / Ajloun	White/beige fabric, floral embroidery, tight stitching	Everyday wear
Madaba Embroidered Dress	Madaba	Earth tones, geometric chest embroidery, long sleeves	Cultural festivals
Amman Urban Dress	Amman	Light fabrics, modest modern embroidery	Formal occasions
Palestinian-Jordanian Hybrid	Jerash / Salt	Black base, red cross-stitch, symbolic chest design	Heritage celebrations
Circassian Wedding Costume	Amman / Zarqa	Silk, metal belt, embroidered headwear	Weddings, Ceremonial
Tafileh Village Dress	Tafileh	Colorful sleeves, bold chest design, layered jewelry	Seasonal, Festive

4.3 Classification Results

Table 2 presents the performance comparison of the six machine learning classifiers evaluated using stratified 5-fold cross-validation. Logistic Regression achieved the highest overall performance with an accuracy of 84.67% (± 6.86%) and an F1-score of 0.7884 (± 0.1086). Naive Bayes followed closely with 83.33% accuracy and an F1-score of 0.7544, while SVM achieved 82.00% accuracy with an F1-score of 0.7424. Decision Tree exhibited the lowest performance at 71.33% accuracy and an F1-score of 0.5947, suggesting that simple tree-based models are insufficient for capturing the complexity of user satisfaction patterns in VR environments.

Table 2
Comparative Performance of Machine Learning Classifiers (5-Fold CV)

Classifier	Accuracy (%)	Precision (%)	Recall (%)	F1-Score
KNN (k=7)	77.33 ± 4.90	74.09 ± 3.35	63.79 ± 16.98	0.6688 ± 0.1097
SVM (RBF)	82.00 ± 8.06	79.40 ± 7.19	70.76 ± 17.02	0.7424 ± 0.1230
Decision Tree	71.33 ± 9.09	64.52 ± 14.23	58.33 ± 18.84	0.5947 ± 0.1547
Random Forest	76.67 ± 9.19	74.25 ± 11.44	58.48 ± 20.63	0.6415 ± 0.1584
Naive Bayes	83.33 ± 6.99	83.57 ± 7.02	70.76 ± 17.96	0.7544 ± 0.1119
Logistic Regression	**84.67 ± 6.86**	**80.69 ± 4.69**	**79.70 ± 19.39**	**0.7884 ± 0.1086**

Fig. 5 provides a visual comparison of the four-evaluation metrics across all classifiers, clearly illustrating the performance hierarchy. Figure 6 displays the confusion matrices for all six classifiers, showing the distribution of true positives, true negatives, false positives, and false negatives.

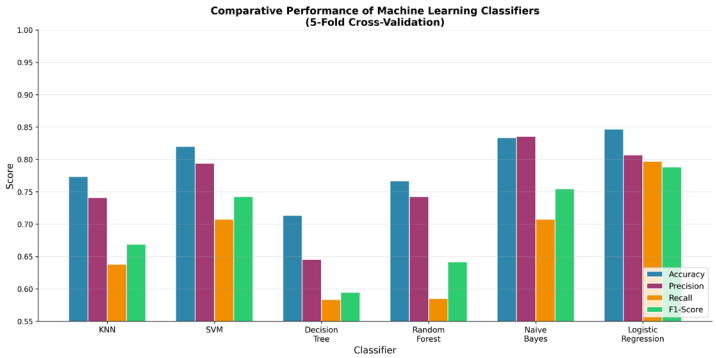


Fig. 5. Comparative performance of machine learning classifiers (5-fold cross-validation).

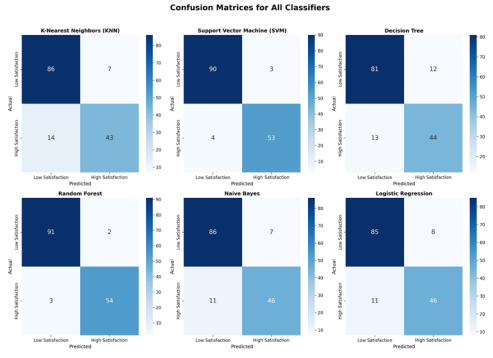


Fig. 6. Confusion matrices for all six classifiers.

4.4 Feature Importance Analysis

Fig. 7 presents the Random Forest feature importance scores for predicting user satisfaction. The three most influential features were cultural understanding (0.189), visual realism (0.173), and navigation intuitiveness (0.168), followed closely by engagement (0.141). Demographic variables exhibited comparatively lower importance, with age (0.099) and academic background (0.071) showing moderate contributions, while gender (0.023) and prior VR experience (0.034) had minimal predictive value. These findings suggest that the quality of the VR content and interface design exert a stronger influence on user satisfaction than individual demographic characteristics. The correlation analysis (Fig. 8) further supports these findings. Engagement exhibited the strongest correlation with satisfaction ($r = 0.43$), followed by navigation ($r = 0.41$), cultural understanding ($r = 0.37$), and visual realism ($r = 0.28$). Heritage knowledge showed a moderate positive correlation with

cultural understanding (r = 0.27), suggesting that participants with prior knowledge of Jordanian heritage were better positioned to appreciate the cultural content presented in the VR museum.

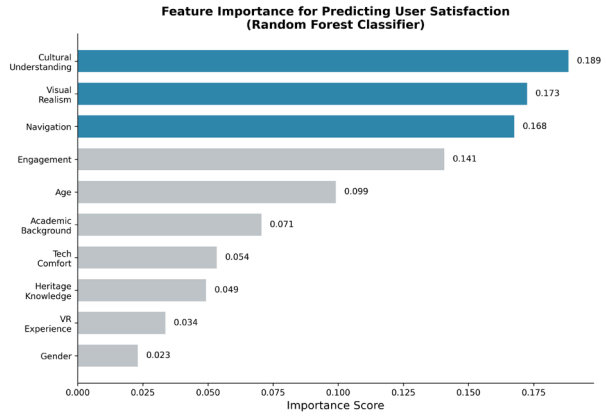


Fig. 7. Feature importance for predicting user satisfaction (Random Forest).

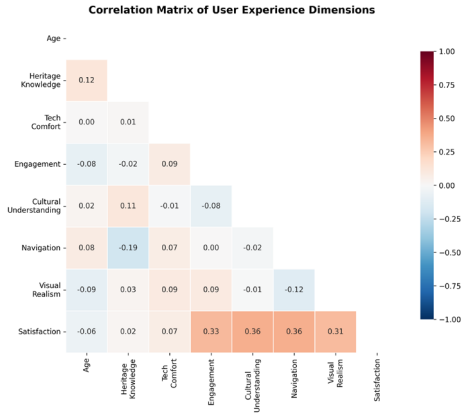


Fig. 8. Correlation matrix of user experience dimensions.

4.5 User Engagement Clustering

The Elbow method and Silhouette analysis (Fig. 9) were used to determine the optimal number of clusters. While the Silhouette analysis suggested k=4, the Elbow method showed a clear inflection at k=3, and k=3 was selected for interpretability. K-Means clustering applied to the four experience dimensions revealed three distinct user profiles, as summarized in Table 3 and visualized in Fig. 10 and Fig. 11.

Table 3
User Engagement Cluster Profiles (K-Means, k=3)

Profile	n (%)	Engagement	Cultural Und.	Navigation	Visual Real.	Satisfaction
Passive Observers	41 (27.3%)	2.12	3.61	3.29	2.10	0.24
Selective Explorers A	59 (39.3%)	3.46	3.22	2.42	3.90	0.42
Selective Explorers B	50 (33.3%)	3.76	2.28	3.70	2.84	0.44

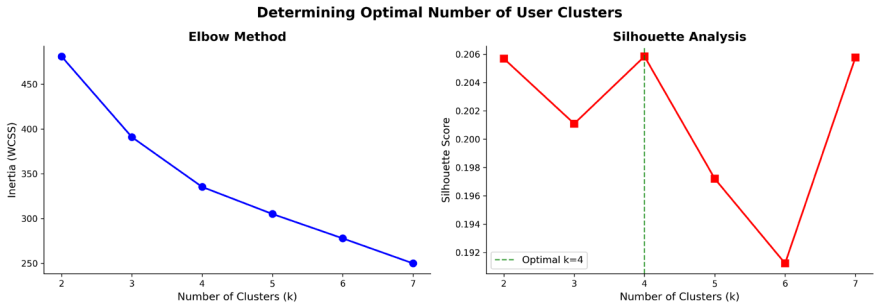


Fig. 9. Cluster selection using the Elbow method and Silhouette analysis.

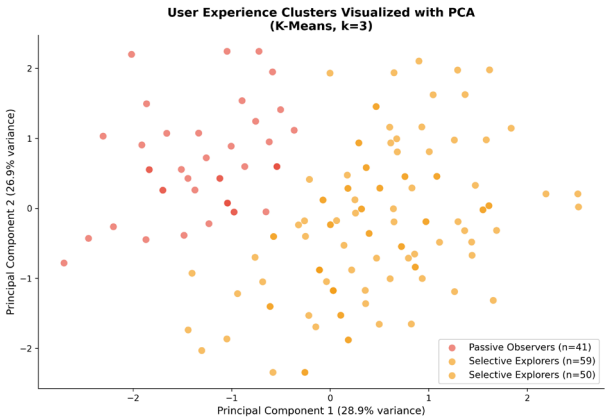


Fig. 10. User experience clusters visualized with PCA (K-Means, k=3).

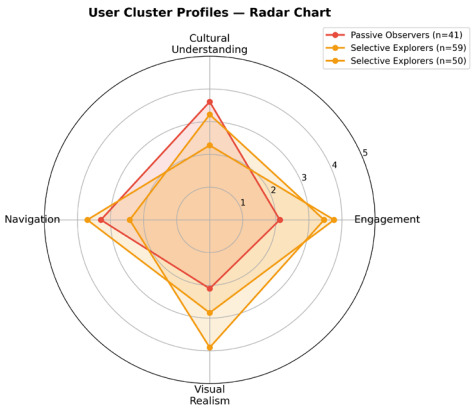


Fig. 11. Radar chart showing user cluster profiles across experience dimensions.

Cluster 0 (Passive Observers, 27.3%) exhibited the lowest engagement scores (M=2.12) and visual realism ratings (M=2.10), coupled with the lowest satisfaction rate (24%). This group showed relatively higher cultural understanding scores (M=3.61), suggesting that while they recognized the cultural content, the VR presentation did not sufficiently engage them. Clusters 1 and 2 (Selective Explorers, 39.3% and 33.3% respectively) demonstrated moderate-to-high engagement but differed in their interaction patterns: Cluster 1 emphasized visual realism (M=3.90) but found navigation challenging (M=2.42), while Cluster 2 excelled in navigation (M=3.70) but rated cultural understanding lower (M=2.28).

4.6 Discussion

The findings of this study demonstrate that machine learning techniques can effectively predict and profile user satisfaction in VR-based cultural heritage environments. The superior performance of Logistic Regression (84.67% accuracy) aligns with findings in educational technology research, where linear models often outperform more complex classifiers on structured survey data with limited features (Alqahtani & Rajkhan, 2020). The relatively weaker performance of Decision Tree (71.33%) suggests that satisfaction in VR cultural experiences involves complex, non-linear interactions that simple partitioning cannot capture.

The feature importance analysis provides actionable design insights. The dominance of experience-related features (cultural understanding, visual realism, navigation) over demographic variables (gender, VR experience) suggests that well-designed VR content can create satisfying experiences regardless of the user's background. This finding is particularly significant for cultural heritage applications, where the goal is to engage diverse audiences. The moderate importance of age (0.099) may reflect generational differences in technology adoption and warrants further investigation.

The clustering results reveal meaningful user segments that can inform adaptive VR museum design. The Passive Observers cluster (27.3%) represents users who may require enhanced interactive elements or guided experiences to increase engagement. The two Selective Explorer clusters suggest that some users prioritize visual quality while others focus on ease of navigation, indicating that VR museum designers should balance both aspects rather than optimizing one at the expense of the other. Notably, this project demonstrates that impactful cultural heritage experiences can be produced using open-source and low-cost tools. Unlike commercial solutions such as Marvelous Designer or photogrammetry-based approaches, the Blender–Unity pipeline offers an accessible development path while maintaining high visual quality. This accessibility is particularly relevant for heritage preservation projects in regions where institutional funding may be limited.

Several limitations should be acknowledged. The sample size of 150 participants, while appropriate for the ML methods employed, limits the generalizability of the findings to broader populations. The study was conducted at a single university in Jordan, and cross-cultural validation is needed. The absence of a control group prevents direct causal attribution of learning outcomes to the VR intervention. The evaluation was limited to a single VR platform (Meta Quest 2), and cross-platform usability was not assessed. Future research should address these limitations through larger, more diverse samples, controlled experimental designs, validated instruments such as the System Usability Scale (SUS) or Presence Questionnaire (PQ), and longitudinal follow-up assessments.

5. Conclusion

This study demonstrates that the integration of machine learning techniques with VR-based cultural heritage systems can provide meaningful insights into user experience that extend beyond traditional descriptive analysis. By creating a virtual museum showcasing traditional Jordanian women's dress and applying six ML classifiers to predict user satisfaction, this research addresses a gap in both digital heritage preservation and data-driven UX evaluation. Logistic Regression achieved the best predictive performance at 84.67% accuracy and 0.7884 F1-score, with feature importance analysis revealing that cultural understanding, visual realism, and navigation intuitiveness are the strongest predictors of satisfaction. K-Means clustering identified three distinct user profiles, Passive Observers and two types of Selective Explorers, providing actionable insights for adaptive VR museum design. The findings support the proposition that VR-based virtual museums, developed using open-source tools such as Blender and Unity, can serve as effective and accessible platforms for cultural heritage education. The texture-based modeling approach successfully balanced visual fidelity with VR performance requirements, and the machine learning analysis provided a deeper understanding of user behavior than traditional survey analysis alone.

Future research directions include the integration of deep learning for real-time adaptive exhibit personalization based on user behavior patterns, expansion to include additional garment collections and cultural contexts, application of natural language processing for analyzing qualitative user feedback, and rigorous longitudinal assessment of knowledge retention. Through the combination of immersive VR technology with data-driven analysis, this work contributes to a growing body of evidence supporting the role of intelligent digital experiences in safeguarding cultural heritage for present and future generations.

References

Abuhassna, H., Al-Rahmi, W. M., Yahya, N., Zakaria, M. A. Z. M., Kosnin, A. B. M., & Darwish, M. (2020). Development of a new model on utilizing online learning platforms to improve students' academic achievements and satisfaction. *International Journal of Educational Technology in Higher Education*, *17*(1), 38.

Akram, H. W., & Degen, A. A. (2023). The history of Bedouin clothing made for traditional nomadic lifestyle. In M. Brandstrup et al. (Eds.), The Garment Economy (pp. 15–30). Springer. https://doi.org/10.1007/978-3-031-33302-6_2

Chen, J., Liu, X., & Wang, Y. (2024). Digital restoration and reconstruction of heritage clothing: A review. *NPJ Heritage Science, 12*, 198. https://doi.org/10.1038/s40494-024-01349-4

Ghnaim, W. (2018). *Tatreez & tea: Embroidery and storytelling in the Palestinian diaspora* (2nd ed.). The Tatreez Institute.

Gronowski, A., Arness, D. C., Ng, J., Qu, Z., Lau, C. W., Catchpoole, D., & Nguyen, Q. V. (2024). The impact of virtual and augmented reality on presence, user experience and performance of information visualisation. *Virtual Reality*, *28*(3), 133. https://doi.org/10.1007/s10055-024-01032-w

Harisanty, D., Obille, K. L. B., Anna, N. E. V., Purwanti, E., & Retrialisca, F. (2024). Cultural heritage preservation in the digital age, harnessing artificial intelligence for the future: A bibliometric analysis. *Digital Library Perspectives, 40*(4), 609–630. https://doi.org/10.1108/DLP-01-2024-0018

Kawar, W. K. (2011). Threads of identity: Preserving Palestinian costume and heritage. Rimal Publications.

Kawar, W. K. (2012). Pracht und Geheimnis: Kleidung und Schmuck aus Palästina und Jordanien. Arnoldsche Art Publishers.

Kim, S. J. (2023). Virtual fashion experiences in virtual reality fashion show spaces. *Frontiers in Psychology, 14*, 1276856. https://doi.org/10.3389/fpsyg.2023.1276856

Li, J., Zheng, X., Watanabe, I., & Ochiai, Y. (2024). A systematic review of digital transformation technologies in museum exhibition. *Computers in Human Behavior, 155,* 108407. https://doi.org/10.1016/j.chb.2023.108407

Meier, C., Sanchez Berriel, I., & Pérez Nava, F. (2021). Creation of a virtual museum for the dissemination of 3D models of historical clothing. *Sustainability, 13*(22), 12581. https://doi.org/10.3390/su132212581

Mutawa, A. M., & Sruthi, S. (2023). Enhancing human–computer interaction in online education: A machine learning approach to predicting student emotion and satisfaction. *International Journal of Human–Computer Interaction, 40*(18), 8827–8843. https://doi.org/10.1080/10447318.2023.2291611

Oladokun, B. D., Ajani, Y. A., Ukaegbu, B. C., & Oloniruha, E. A. (2024). Cultural preservation through immersive technology: The metaverse as a pathway to the past. Preservation, *Digital Technology & Culture, 53*(3), 157–164. https://doi.org/10.1515/pdtc-2024-0015

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2023). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and a research agenda. *Computers & Education, 147*, 103778. https://doi.org/10.1016/j.compedu.2019.103778

Saca, I., & Saca, M. (2006). Embroidering identities: A century of Palestinian clothing. Chicago: Oriental Institute Museum of the University of Chicago.

Sandiwarno, S., Niu, Z., & Nyamawe, A. S. (2023). A novel hybrid machine learning model for analyzing e-learning users' satisfaction. *International Journal of Human–Computer Interaction, 40*(17), 4580–4601. https://doi.org/10.1080/10447318.2023.2219965

Song, Z., & Evans, L. (2024). The museum of digital things: Extended reality and museum practices. *Frontiers in Virtual Reality, 5,* 1396280. https://doi.org/10.3389/frvir.2024.1396280

Spyrou, O., Hurst, W., & Krampe, C. (2025). A reference architecture for virtual human integration in the metaverse: Enhancing the GLAM sector with AI-driven experiences. *Future Internet, 17*(1), 36. https://doi.org/10.3390/fi17010036

Stoean, R., Bacanin, N., Stoean, C., & Ionescu, L. (2024). Bridging the past and present: AI-driven 3D restoration of degraded artefacts for museum digital display. *Journal of Cultural Heritage, 69,* 18–26. https://doi.org/10.1016/j.culher.2024.07.008

Styliani, S., Fotis, L., Kostas, K., & Petros, P. (2009). Virtual museums: A survey and some issues for consideration. *Journal of Cultural Heritage, 10*, 520–528. https://doi.org/10.1016/j.culher.2009.03.003

UNESCO. (2021). Art of embroidery in Palestine, practices, skills, knowledge and rituals. https://ich.unesco.org/en/RL/art-of-embroidery-in-palestine-practices-skills-knowledge-and-rituals-01665

Wang, J., & Yu, Y. (2025). Machine learning approach to student performance prediction of online learning. *PLoS ONE, 20*(1), e0299018. https://doi.org/10.1371/journal.pone.0299018

Weir, S. (1989). Palestinian costume. British Museum Press.

Chunlan, Y., Tengku Wook, T. S. M., & Rosdi, F. (2025). Advancing cultural heritage: a decadal review of digital transformation in Chinese museums. *NPJ Heritage Science*, *13*(1), 189. https://doi.org/10.1038/s40494-025-01714-x

Wang, H., Du, J., Li, Y., Zhang, L., & Li, X. (2025). Grand challenges in immersive technologies for cultural heritage. *International Journal of Human–Computer Interaction*, *41*(21), 13682-13703. https://doi.org/10.1080/10447318.2025.2475996

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