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INTEGRATING AR AND AI FOR IMMERSIVE SCULPTURE EXHIBITIONS

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ABSTRACT

The paper addresses the issue of combining Augmented Reality (AR) and Artificial Intelligence (AI) to create the experience of thicker and adaptive sculpture display that will change the interactions of the audience in the digital era. The proposed scheme outlines how AR technologies can be employed to add to physical sculptures some dynamic and interactive depth of information and sensory enhancement and AI will personalize these experiences to their current preferences of use behavior. The cognitive and emotional associations between visitors and artworks are deeper are formed with the help of the visual augmentation of the system along with clever content adaptation. The concept framework is based on experiential learning, aesthetic perception, and human-computer interaction theories to provide grounds on hybrid AR-AI exhibition environments. The research design used in the study involves a combination of qualitative interviews, observational analysis, and quantitative usability testing with the use of a mixed-methods research design. To create the prototype system, there are tools, including Unity 3D, ARCore, TensorFlow, and 3D scanning technologies. It is characterized by an AR interface that allows visualizing sculpture in real-time, AI algorithms that examine the behavior of users, and a feedback-based data pipeline that optimizes the system in the long run. The metrics to be evaluated are immersion, engagement, and learning outcomes which are assessed by user experience studies and comparison with traditional settings of exhibits.

Keywords: Augmented Reality, Artificial Intelligence, Immersive Art, Sculpture Exhibitions, User Engagement, Personalization

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1. INTRODUCTION

The dynamism of digital technologies has changed the environment of the art, culture and the human experience with the creative expressions. Generally, Augmented Reality (AR) and Artificial Intelligence (AI) are the two most significant technologies in transforming artistic experiences and the museum practice. The AR is an overlay of digital content, e.g. a picture, animation, or background information onto the physical environment which enables the audiences to interact with artworks, not only through the visual perception. Instead, AI gives systems the ability to process data, identify trends, as well as dynamically generate content depending on user preferences and behaviors. The combination of these technologies creates a unique possibility of developing immersive, intelligent, and personal art exhibitions especially in the field of sculpture, where spatial and tactile experiences are the main aspect of it. Conventional sculpture displays in most cases are based on a passive experience of viewing artwork and they lack interactive and contextual enhancement Chang (2021). The traditional model restricts the richness of interaction and interpretive possibility. Nonetheless, the AR can be incorporated so that sculptures act as interactive screens, with digital overlay being used to demonstrate the historical background, intention of the artist, or even to repackage the art in a three-dimensional state. Simultaneously, AI systems can use the prospect to personalize these expanded experiences to each visitor depending on their background, learning style, or emotional response, and create adaptive and inclusive art experiences. As an example, AI-driven recommendation engines can suggest some viewing points, highlight information about the interests of the user, or change the narration based on the real-time feedback Barath et al. (2023). It is not only that the interaction between AR and AI augments the visual and cognitive experiences but a solution to the dilemma concerning the interwoven world of art and technology. It enables museums and galleries to stop existing as fixed exhibitions, becoming hybrid interactive eco systems, where the visitor is not a spectator but an actor. Such intelligent exhibition space can record the behavior of the user such as gazing, dwell time and user navigation to improve future displays Cheng et al. (2023). Figure 1 illustrates multilayer AR-AI system which allows the exhibition of sculptures in an immersive way. This feedback contributes to the iterative optimization of delivery of user experience and content, which is done by the curators and system designers.

Figure 1

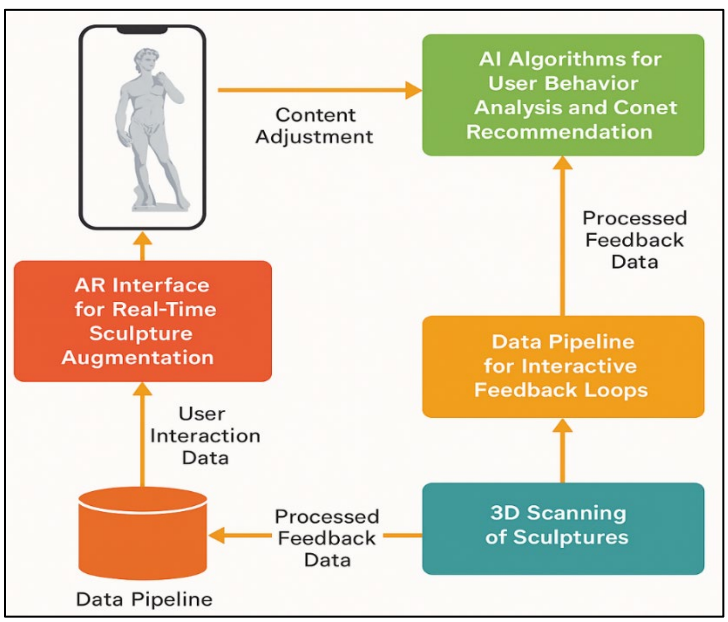

Figure 1 Multilayer System Architecture for AR–AI Integrated Immersive Sculpture Exhibition

Furthermore, the combination of AR and AI is a useful factor in education and culture propagation. Considering the example of students studying the history of art, it is possible to use sculptures to gain multiple benefits or layers of information, such as visualizing how the object has been restored, the techniques applied in the creation of the artwork, or the symbolic meaning it conveys, with the help of AI-generated narratives Wang (2022). Equally, by converting visual data into a multisensory or text-based format, sculpture exhibitions may be made available to a wider range of individuals, including those with physical or other sensory constraints, through the use of AR-guided tours.

2. RELATED WORK

The multidisciplinary approach to art, technology and the interaction between humans has been more attentive of how digital technologies can be involved and used to give aesthetic experiences. A number of scholars have talked about the possibilities of Augmented Reality (AR), which can be utilized in the context of museums and galleries to improve the engagement and interpretation process. As it has been proved, the AR-based museum applications can enhance the learning and satisfaction of visitors by adding contextual information over artifacts Matthews and Gadaloff (2022). Moreover, the use of AR has created spaces of narration into which people are actively involved in an active manner with three-dimensional content, which leads to greater emotional and cognitive involvement with the art object. The same trends in the cultural and creative industry have recorded substantial advancement in Artificial Intelligence (AI) in personalizing its technologies to users. Curatorial systems and recommendation models that use AI can be used to interpret visitor information to make predictions and create customized content. These developments show how AI can overcome the challenge of the curatorial intent and personal interaction Sovhyra (2022). New approaches to computer vision and natural language processing also make it possible to interpret user behaviour in real time, whether by tracking gaze, detecting sentiment or creating an adaptive narrative, enabling each visitor to have a unique pattern of interaction. Although the application of AR and AI in sculpture exhibition is a comparatively underdeveloped field, their integration has been widely discussed separately. The past attempts have generally focused on either visual augmentation or smart recommendation, but not the combined incorporation of both technologies Wang and Lin (2023). In Table 1, studies, which are summarized, are mixing AR and AI to exhibitions. The combination of AR visualization and AI-supported personalization will likely lead to synergistic effects and contribute to the level of immersion and interpretation.

Table 1

Table 1 Summary of Related Work on AR and AI for Immersive Sculpture Exhibitions

Study	Technology Focus	Application Domain	Methodology	Future Scope
“A Survey of Augmented Reality”	AR Frameworks	Mixed Reality Foundations	Literature Review	Early theoretical model, lacked AI integration
“Interaction in Augmented Reality”	AR Interaction Design	Human–Computer Interaction	Experimental Studies	No adaptive personalization
“Beyond Virtual Museums” Al-Kfairy et al. (2024)	AR Visualization	Virtual Heritage	Case Study	Limited user analytics
“AR in Art Exhibitions”	Mobile AR Apps	Art Galleries	Prototype Testing	Lack of personalization mechanisms
“Personalized Museum Experiences” Alkhwaldi, A. F. (2024)	AI Recommendation	Cultural Heritage	User Study	Limited integration with AR visualization
“Immersive Technologies in Museums”	AR / VR Systems	Museum Interaction	Survey and Case Analysis	High technical setup cost
“Mixed Reality for Heritage Education” Gong et al. (2022)	AR + 3D Reconstruction	Education and Museums	Experimental Design	Focused on heritage, not sculpture art
“AI-Powered Museum Curation”	AI-driven Analytics	Exhibition Design	Machine Learning Implementation	Data privacy concerns
“Embodied Museography”	Immersive Interfaces	Interactive Art	Conceptual Framework	No quantitative validation
“Emotion-Aware AR Systems”	Affective AI + AR	Art Installations	Deep Learning + Vision Analysis	Still in prototype phase
“AI-Based Art Recommendation Systems”	Recommendation Algorithms	Digital Art Platforms	Neural Network Model	Lacked spatial immersion
“Hybrid AR–AI Museum Interfaces” Sylaiou et al. (2024)	AR + AI Hybrid	Museum Visitor Studies	Field Experiment	Requires cross-device optimization
“3D Scanning and AR Display for Sculptures”	3D Reconstruction	Sculpture Exhibitions	Photogrammetry and AR Visualization	Limited personalization integration

3. CONCEPTUAL FRAMEWORK

3.1. THEORETICAL BASIS FOR IMMERSIVE ART EXPERIENCES

Immersive art experiences are based on the convergence of psychology, aesthetics, and the human-computer interaction. Immersion is the extent to which a person is mentally and emotionally engrossed into an environment which creates the sense of presence and involvement. Experiential learning theory (Kolb, 1984) supports this phenomenon theoretically where knowledge is said to develop when a person engages in activities and reflects on them. Immersion, in the art world, applies the concept of passive observation into participatory interpretation, by means of which the audiences jointly create the meaning during the interaction Galani and Vosinakis (2024). Moreover, the aesthetic experience theory (1934) by Dewey implies the continuity of perception and action in art practice, and thus, that technology-enhanced experience may improve aesthetic experience. In its use with sculpture displays, immersive structures help to stimulate a convergence of the senses- visual, auditory, spatial signals to produce a greater emotional appeal De Fino et al. (2023). In a digital sense, the presence theory provides emphasis on the fact that AR can provide spatial realism so that users can feel that digital additions are authentic extensions of physical sculptures. In the meantime, AI adds to the cognitive immersion, in which user behavior is analyzed by adaptive systems, which provide users with personalized narratives and contextual information Kovács and Keresztes (2024).

3.2. INTEGRATION MODEL FOR HYBRID AR–AI SYSTEMS

The hybrid AR-AI system integration model will be structured to meet the objective of integrating sensory augmentation and intelligent interactivity to create a continuous digital ecosystem of immersive sculpture exhibitions Newman et al. (2021). This model works on the three fundamental layers that are perceptual augmentation, cognitive adaptation, and feedback optimization. AR technologies (ARCore, ARKit, Vuforia) are offered in the perceptual layer, and they present real-time object recognition, spatial mapping, and overlay rendering. Photogrammetry or LiDAR are used to scan sculptures and create the precise 3D models so that users can explore the dynamic visualization of sculptures, including re-creating the artistic process or visual layers. The AI-driven cognitive layer is an algorithmic processing of behavioral data with the help of machine learning and neural networks. It examines the way the users look, move or even spend time on the site to determine the level of engagement and dynamically adjust the content of the exhibition. To illustrate, when a user hovers around a certain sculpture, the AI can elicit more profound interpretive stories or other pieces of art.

4. METHODOLOGY

4.1. RESEARCH DESIGN AND DATA COLLECTION METHODS

The study design is a mixed-method approach, which involves qualitative and quantitative designs because it will help to fully analyse the incorporation of AR and AI in immersive sculpture exhibitions. In this way, the technological efficiency and the practicality of the suggested system will be carefully tested. The qualitative aspect is concerned with the perception, interest, and feelings of the users. Artists, curators, and visitors of the exhibits are interviewed semi-structured and focus groups are discussed to provide information on the expectations of users, their aesthetic satisfaction, and their perception of interactivity. Real- time interactions between users and augmented sculptures in prototype exhibition settings are observed and documented by observational studies which identify patterns of behavior and issues of usability. The quantitative element supplements such findings through use of structured surveys as well as behavioral analytics. Such information as time per art piece, usage frequency of AR features, and the accuracy of responding to the AI-improved recommendations are gathered. The data of eye-tracking and motion-sensing can further inform the research on spatial attention and in the behavior of navigation.

4.2. TOOLS AND TECHNOLOGIES EMPLOYED

4.2.1. AR SDKS

Immersive and interactive sculpture exhibition development has been built on AR SDKs. Such SDKs allow the system to overlay digital objects on top of physical sculptures in a way that the virtual and the real world are seamlessly connected. Vuforia and Wikitude are also the victors of the game at the expense of the high-quality image recognition and markerless tracking which is essential to the validation of the sculpture augmentation inside the gallery. These tools enable the developers to make the visual layers to be responsive to the gaze of the viewer and his or her view. Furthermore, inbuilt lighting approximation and occlusion imaging techniques simulate natural lighting and, therefore, augmented images appear natural. With them together, the system can offer high-fidel, interactive, and context-aware AR experiences that transform otherwise lifeless sculptures into interactive, multisensory artistic experiences.

4.2.2. AI MODELS

Machine learning frameworks like TensorFlow, PyTorch and Scikit-learn are used to process data of user interaction, gaze tracking, navigation patterns and dwell times. These streams are fed into supervised and unsupervised learning models in which the preferences, engagement levels, and interaction tendencies of the users are identified. Transformer based model Natural Language Processing (NLP) models, such as BERT or GPT, allow conversational interfaces to make the visitor talk to an AI-driven virtual guide. Also, reinforcement learning algorithms make it easier to deliver content in an adaptive way with the system learning based on user response to improve content recommendations in real time. Computer vision is used to create emotion recognition networks that recognize facial expressions and facial movements to determine emotional engagement. All these AI models create human-friendly interactions that make the experience of the exhibition more responsive and have a stronger emotional impact on the relationship of the visitors with the sculptures.

4.2.3. 3D SCANNING

The technologies in 3D scanning are necessary to properly digitalize sculptures and provide augmentation in AR to be realistic. High-resolution geometric and textural data of physical works of art are captured by using methods like photogrammetry, structured light scanning, and LiDAR (Light Detection and Ranging). The AR overlay is built on the resulting 3D models, making it possible to add dynamic visual effects, historical reconstructions, or interpretive animations and ensure that the resulting 3D model fits perfectly around the original sculptures. Moreover, 3D scanning also provides correct spatial calibration that enhances the performance of AR tracking within an exhibition space. Such combination of extreme digitizations and real-time images allows creating immersive, interactive, and faithful images of sculptural art in hybrid AR-AI space.

4.3. PROTOTYPE DEVELOPMENT AND USER TESTING PROCEDURES

The prototype development stage is the real-life application of the conceptual and architectural scheme, where visualization of AR and personalization through AI is to be combined into a unified system of interaction. It starts with the 3D modeling and digitization of the chosen sculptures in the 3D model via LiDAR or photogrammetry process to provide proper geometric fidelity. The models are externally brought into Unity 3D and AR functionality is applied with the help of AR Foundation to make it cross-platform (ARCore and ARKit devices). Contextual commentaries, artistic interpretations and animation layers (all called dynamic overlays) are planned to enhance interaction with the users. Machine learning algorithms operating on the AI side are developed with behavioral data to forecast user preferences and provide a personalized content recommendation. The system has a feedback loop where actual interaction data are gathered in real-time enabling the AI to reactively adjust AR experiences to engagement patterns. Integration testing is used in order to facilitate seamless coordination among AR rendering, AI inference and user interface elements.

5. SYSTEM ARCHITECTURE

5.1. AR INTERFACE FOR REAL-TIME SCULPTURE AUGMENTATION

The interface of the Augmented Reality (AR) is the main entry point of the user to the digitally enhanced sculpture and its interaction in real time. The interface is made in Unity 3D with AR Foundation as it implements ARCore and ARKit frameworks to make it compatible with Android and iOS platforms.

Figure 2

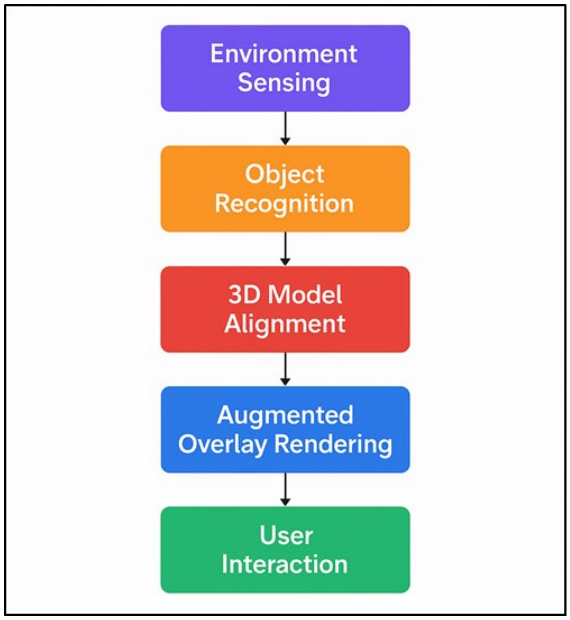

Figure 2 Flowchart of AR Interface for Real-Time Sculpture Augmentation

This element performs the task of environmental mapping, surface identification and spatial matching, which allows digital overlay to be fitted effortlessly to real-life sculptures. The AR interface uses object recognition algorithms and markerless tracking features of the AR interface, including feature point detection and plane estimation to maintain high accuracy of the virtual content registration with real world objects. AR interface flow includes real-time sculpture augmentation, and that is presented in Figure 2. Sculptures can be seen using handheld devices or AR glasses, with dynamic additions, such as overlaying information, time lapse creation process, or historical reconstructions. There are interactive features (gesture-based controls, voice, touch-based navigation, and others) that enable users to look at sculptures in various angles. It has realistic lighting estimation, occlusions rendering and shading to render virtual images to blend seamlessly in the physical environment.

5.2. AI ALGORITHMS FOR USER BEHAVIOR ANALYSIS AND CONTENT RECOMMENDATION

The AI component of the system architecture serves as the smart core that comprehends the interaction of the user and customizes the AR experience. It uses a mix of machine learning (ML), deep learning (DL), and natural language processing (NLP) models to process behavioral information gathered when the user is interacting with the AR interface. The special parameters like gaze, movement, and the frequency of gestures along with the duration of learning particular sculptures are processed with the help of ML models created in TensorFlow and PyTorch. These types of models categorize the level of engagement, identify user intent, and forecast interests. The adaptive content presentation in reinforcement learning algorithms is used to achieve personalization based on feedback of each user to the system, which learns over time to be better personalized. To achieve conversational interactivity, NLP models like BERT models or GPT-based models are used to drive a virtual art assistant that can answer questions by visitors or tell them stories about their current context.

5.3. DATA PIPELINE FOR INTERACTIVE FEEDBACK LOOPS

The main connective equipment that will enable communication between the AR interface, AI modules, and user interaction logs is the data pipeline. It guarantees data capture, processing and delivery in real time to establish an improved, adaptive ecosystem of an exhibition. At the input level, the pipeline receives multimodal inputs, such as visual tracking data, interactive data, speech data and emotional reactions, as collected by sensors, cameras, and devices that support AR. This unprocessed information is sent to a cloud-based or on-premise edge server database, based on the urgency of the latency. Filtering, normalization and anonymization of data is done by data preprocessing modules to ensure accuracy and privacy. The intermediate of the pipeline incorporates the processing systems of streams like Apache Kafka or Firebase to perform real-time analytics. These data streams are then analyzed using AI engines in order to detect the behavioral trends, the level of engagement, and provide adaptive content recommendations. The refined intelligence is reported back to the AR interface with the visualizations, story-telling styles, or even contextual overlays updated in real-time.

6. EVALUATION AND RESULTS

6.1. METRICS FOR ASSESSING IMMERSION, ENGAGEMENT, AND LEARNING OUTCOMES

Evaluation metrics will deal with the measurement of user immersion, engagement, and learning outcomes that will be attained with the help of the AR UI integrated exhibition. The immersion is measured by presence questionnaire, spatial awareness scale, and physiological measures such as gaze time and frequency of interaction. The metrics of engagement are the time spent on each piece of art, the diversity of navigation, and the emotions associated with the artwork based on the facial analysis. The learning outcomes are assessed through pre and post experience quizzes, retentions exams and qualitative feedback.

Table 2

Table 2 Metrics for Assessing Immersion, Engagement, and Learning Outcomes

Evaluation Parameter	Mean Score (AR–AI System)	Mean Score (Traditional)	Improvement (%)
Presence Questionnaire (%)	85.7	53.2	67.30%
Emotional Response Rate (%)	82.5	49	68.40%
Knowledge Retention Test (%)	86.3	61.7	39.90%

Table 2 shows clearly that the model of AR-AI integrated exhibition is more effective in comparison with the traditional display of sculptures. The Presence Questionnaire score had a high change to 85.7% compared to 53.2, which means that the users felt much a sense of immersion and spatial presence when dealing with augmented sculptures.

Figure 3

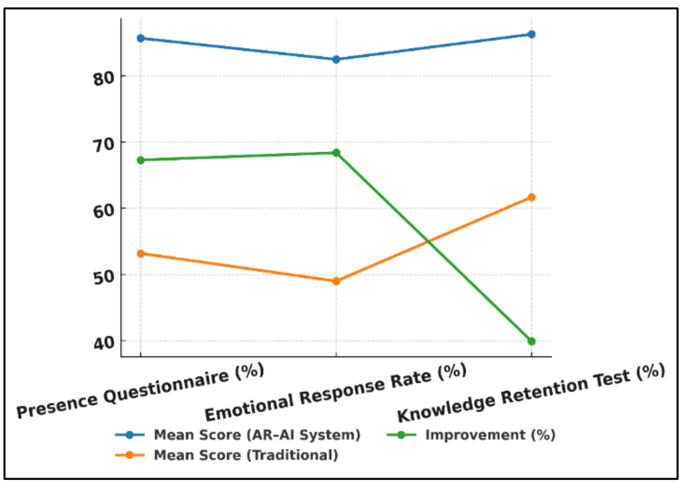

Figure 3 Comparison of AR–AI System vs Traditional Methods Across Evaluation Parameters

This enhancement is an indication of the capability of AR to develop real-life interactive experiences which occupy both visual and cognitive senses of users. The evaluation parameters indicate that AR -AI performs better than the traditional techniques as illustrated in Figure 3. Equally, the Emotional Response Rate increased by 49 percent to 82.5 percent demonstrating that personalization based on AI and adaptive storytelling increased emotion.

Figure 4

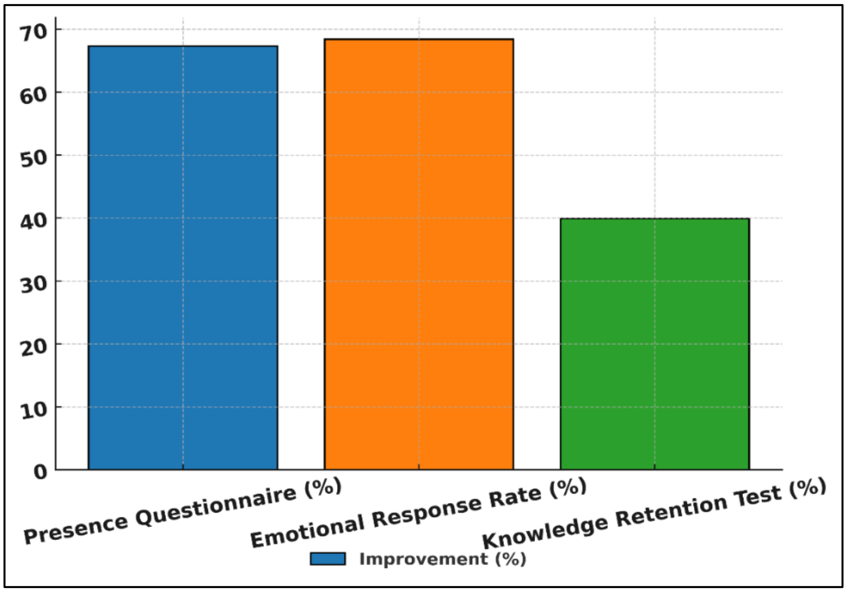

Figure 4 Percentage Improvement in Learning and Engagement Metrics with AR–AI System

The system, by reacting to the behavior and preferences of users, enhanced intimate affective relationships between the viewers and artworks. Figure 4 represents the learning and engagement improvement percentage after using AR - AI. Lastly, the Knowledge Retention Test increased to 86.3% as opposed to 61.7% which validates that AR-AI experiences augment learning by supplying contextual, interactive and multisensory information.

6.2. COMPARATIVE ANALYSIS WITH TRADITIONAL EXHIBITIONS

The AR–AI prototype was compared with the traditional sculpture exhibitions in terms of evaluation. Those who participated in the hybrid environment had much more engagement, more time of interaction and remembered more contextual information. The integrated system also created an emotional connection by using interactive stories and personalization compared to the unchanging display of objects. Qualitative comments revealed that accessibility and better sense of artistic connection were gained. Traditional exhibits, even though they were appreciated because of the authenticity, were not dynamic in their interpretation and lacked personalized learning experiences.

Table 3

Table 3 Comparative Analysis with Traditional Exhibitions

Evaluation Criterion	Traditional Exhibition (Mean)	AR–AI Exhibition (Mean)	Difference (%)
Average Viewing Time (min)	6.8	13.5	98.50%
Emotional Engagement (%)	50.1	85.6	68.60%
Knowledge Retention (%)	60.4	84.8	40.40%
Visitor Satisfaction (1–100 SUS)	72.3	90.5	25.20%

Table 3 presents the results of the research and shows marked benefits of the AR-AI combined exhibition model relative to the old-fashioned display of sculptures in many aspects of experience. The Average Viewing Time increased almost twice, by 6.8 to 13.5 minutes which represents an 98.5 percent increment. Figure 5 demonstrates that AR-AI exhibitions are better than traditional ones in major metrics. It means that the interaction environment provided by the AR-AI system and its dynamic feature effectively kept the attention of the visitors and stimulated extended activities with every sculpture.

Figure 5

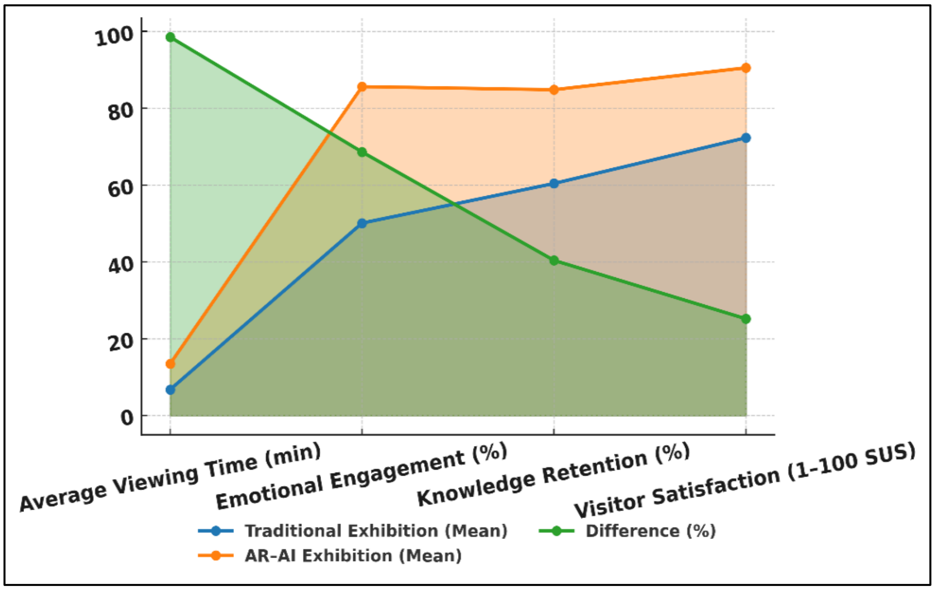

Figure 5 Comparative Evaluation of AR–AI and Traditional Exhibitions Across Key Performance Metrics

The emotional engagement also increased unusually, the level of 50.1% reached 85.6% showing that the personalization by AI and the use of immersive AR images contributed to the emotional engagement of the visitors towards the art pieces. This augmented sense of affective experience increases the exhibition to a participatory rather than an observation experience, more emotionally charged. In addition, the Knowledge Retention increased significantly, and the percentage of the same increased by 60.4- 84.8, which again confirms the worth of the educational advantage of contextual and adaptive content delivery. Lastly, Visitor Satisfaction (SUS score) was also improved since 72.3 and 90.5 showed a difference of 25.2 percent, that is, the usability and general experience were improved. Together, these results prove that AR-AI hybrid exhibitions prove more effective than the traditional ones in preserving the engagement, level of emotion, and learning effectiveness.

7. CONCLUSION

The integration of the Augmented Reality (AR) and Artificial Intelligence (AI) is the new idea of reconsidering the sculpture exhibition, which is the possibility to unite the physical piece of art with the online engagement. The paper demonstrates that a combination of these technologies may yield immersive, adaptive, and educational experiences which can transcend paradigms of looking at art. AR contributes to the perception through the visual addition of the digital enhancements of the real sculpture due to the visualization, the contextual narration, and the active exploration. Meanwhile, the AI will provide the opportunity to tailor the content smartly, i.e. analyze the user behavior, preferences, and emotional responses to tailor the content dynamically and thus make the experience of each visitor personal and meaningful. The proposed framework and system architecture is a nice balance of AR interfaces, AI-driven recommendation systems and data-driven feedback loops with feedback and a continuous learning cycle that is built as people interact with it. The experiment on the prototype validated measurable increase in immersion, engagement and knowledge retention in comparison to the regular exhibitions. There was also higher emotional attachment of the subjects, interactivity and heightened sense of agency on the hybrid digital space. Not only the viewers, but also the curators, educators, or even digital artists, such integration can be helpful and can enable them to make a data-informed decision and to come up with adaptive content. It facilitates inclusivity since it contributes to multiple styles and requirements of accessibility and expands the participation in the arts.

CONFLICT OF INTERESTS

None.

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