International Journal of Human–Computer Interaction

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/hihc20

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To cite this article: Christos Troussas, Christos Papakostas, Akrivi Krouska, Phivos Mylonas & Cleo Sgouropoulou (27 Dec 2024): Fuzzy-Based Virtual Reality System for Cultural Heritage: Enhancing User Interaction and Experience Through Contextual Assistive Messaging, International Journal of Human–Computer Interaction, DOI: 10.1080/10447318.2024.2443801

To link to this article: https://doi.org/10.1080/10447318.2024.2443801

Published online: 27 Dec 2024.

INTERNATIONAL JOURNAL OF HUMAN–COMPUTER INTERACTION
https://doi.org/10.1080/10447318.2024.2443801

Fuzzy-Based Virtual Reality System for Cultural Heritage: Enhancing User Interaction and Experience Through Contextual Assistive Messaging

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ABSTRACT

The article highlights the need for enhanced user interaction and personalization in virtual reality (VR) systems for cultural heritage. As cultural sites become accessible through VR, delivering meaningful and tailored user experiences is crucial for effective learning and engagement. Traditional VR systems often fail to address varying levels of user expertise, limiting the accessibility of cultural content. To solve this, the study introduces SculptMate, a fuzzy logic-based VR system that estimates user proficiency in computers and VR, delivering context-sensitive assistive messages. In a study with 64 participants, SculptMate was compared to a standard VR system. Results demonstrated significantly higher engagement and comprehension of cultural artifacts with SculptMate, offering a personalized, immersive experience. The study emphasizes the potential of integrating fuzzy logic into VR to improve educational outcomes and user satisfaction. Future enhancements include dynamic machine learning, multisensory components, and platform optimization for broader accessibility and better user experiences.

KEYWORDS

Virtual reality; cultural heritage; virtual museums; fuzzy weights; user experience; personalization; feedback; assistive messages; rule-based system; user expertise modeling

1. Introduction

The evolution of virtual reality (VR) technology in the last years has been tremendous, thus creating endless opportunities for experiencing and engaging entertainment. But the potential of it go much beyond entertainment to a realm like cultural heritage or virtual museums. Historical places, artifacts, and artworks can be accessed or visited virtually in such environments (Lee et al., 2023). VR reproducing realistic 3D models of ancient monuments or artifacts allows users to "travel" back in time and appreciate the cultural significance behind sculptures. Besides, this technology can also bridge geographical distances and limited access to physical heritage sites making it easier for individuals from different parts of the world to connect with and learn about cultural heritage that would have otherwise remained inaccessible. Thus, through interactive storytelling and immersiveness, VR is another way of revitalizing cultural heritage while offering a unique educational platform for preserving as well as sharing our common history (Wang & Hu, 2020).

However, the content showcased in VR experiences can sometimes pose challenges for users who have limited prior experience with such systems or possess low knowledge/skills in interacting with VR environments (Verma et al., 2023). This can hinder their ability to fully engage with and navigate the virtual exhibits, potentially impacting their overall experience. Recognizing the importance of supporting users in their interaction with VR exhibits, it becomes crucial to understand their skills and provide appropriate assistance. Various techniques exist to assess and model users' knowledge/skills, such as user profiling, machine learning, etc. One of the most popular methods is fuzzy logic, which enables modeling of imprecise or uncertain knowledge and allows the system to provide individualized support regarding the peculiarities of each particular user (Gomathi & Rajamani, 2018; Krouska et al., 2019).

As to the application domain of VR applications in cultural heritage, investigations into this area are at a sufficient level, as is the creation of virtual museums (Bachiller et al., 2023; Farella et al., 2022; Liu, 2022; Medrano et al., 2021; Plasencia et al., 2021; Plecher et al., 2019; Prazina et al., 2020; Rambaree et al., 2023; Shih & Chen, 2020; Sun et al., 2021; Xie et al., 2022; Yiyi & Lingxuan, 2022; Yuan & Zhou, 2023), in terms of technological platforms and infrastructure (Farella et al., 2022; Sun et al., 2021; Xie et al., 2022; Yuan & Zhou, 2023), design and user experience (Bachiller et al., 2023; Medrano et al., 2021; Plasencia et al., 2021; Plecher et al., 2019; Yiyi & Lingxuan, 2022) as well as cultural preservation and heritage representation (Liu, 2022; Prazina et al., 2020; Rambaree et al., 2023; Shih & Chen, 2020). All the aforementioned works present important insights into the utilization of VR in cultural heritage. There was already present research on the use of VR technology, which has been tested to offer people vivid and interactive experiences in getting to know historical sites, objects, and pieces of art virtually. Studies have found out that the usage of VR has a positive effect on increasing engagement, giving people a

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sense of presence, and letting them experience cultural material in new, exciting ways. For example, in Rambaree et al. (2023), the authors investigate how head-mounted display (HMD) VR can enhance intercultural empathy among students in the context of international social work education. Attention is paid to the experiences of the students while engaging in a school-based bullying scenario. In Bachiller et al. (2023), the authors give the use case about the application of VR in a technological heritage museum to improve visitors' experience and online access. Even with such promising results, there is still a major gap with respect to the integration of intelligent techniques for personalization of the experience within cultural heritage VR applications. In fact, this lack of personalization within VR in education has also been identified by a recent review study by Marougkas et al. (2023).

Some of the work has focused on using fuzzy logic to model user knowledge in certain application domains (Chandrashekara et al., 2018; Doz et al., 2022; Fernández-Blanco Martín et al., 2023; Fil et al., 2020; Hegazi et al., 2023; Leon-Garza et al., 2020; Pena-Rios et al., 2016, 2017; Sihotang et al., 2022; Strousopoulos et al., 2023), such as information retrieval (Chandrashekara et al., 2018; Leon-Garza et al., 2020), educational and cultural domain (Doz et al., 2022; Hegazi et al., 2023; Sihotang et al., 2022; Strousopoulos et al., 2023), engineering and industrial applications (Chandrashekara et al., 2018; Fil et al., 2020; Pena-Rios et al., 2016, 2017), etc. The outcomes of these studies have shown promising results in accurately capturing and representing users' knowledge levels. Notwithstanding these advancements, its application specifically in the context of VR cultural heritage settings remains relatively unexplored.

Recent applications, including those by Plecher et al. (2019) and Shih and Chen (2020), in which VR systems for increasing user engagement with cultural heritage, were developed through an immersive experience. Usually, within such systems, less consideration has been given to the issue of the different levels of users' expertise while interacting with VR technology, which may lower the effectiveness of using VR in this regard. There are a considerable number of applications of VR in cultural heritage; most are based on static or generic messaging that does not change according to the user's background or his/her skill level. This causes an underlying gap in personalization, which is crucial for maximizing engagement and learning in diverse user populations.

The article addresses a persistent challenge in personalizing museum experiences despite recent advancements. Drawing from several articles in the pertinent literature (Teeng et al., 2022; Ibañez-Etxeberria et al., 2020; Marougkas et al., 2023; Javdani Rikhtehgar et al., 2023; Shehade & Stylianou-Lambert, 2020; Theodoropoulos & Antoniou, 2022), it becomes evident that despite rapid progress in digitization and related technologies, virtual museum exhibition experiences remain limited in their capabilities. While existing literature offers valuable insights into user experiences, there exists a conspicuous gap in research focusing on AI technologies for personalization of such experiences, indicating ample opportunity for future exploration. Specifically, in the work of Ibañez-Etxeberria et al. (2020), it is noted that the availability of adapted content is almost non-existent, highlighting an area requiring immediate improvement. Furthermore, the article of Teeng et al. (2022) underscores the necessity of tailored experiences for users in the context of applied VR in cultural heritage, signaling a pathway toward heightened personalization, thereby underlining the novelty of the research presented in our article. Thus, the article contributes novel perspectives and fills a critical void in the literature.

This article introduces an intelligent approach that combines fuzzy-based knowledge modeling and rule-based contextual assistive messaging strategy to enhance the overall user experience and interaction within VR cultural heritage environments. It considers the level of knowledge of the users, which differentiates with five distinct fuzzy weights in an effort to realize their computer experience more effectively and, therefore, their skill levels. This makes the experience of each user personalized and tailor-made. Also, the rule-based mechanism of 19 rules, which concern how the assistive messages will be delivered, works in combination with the fuzzy-based technique. The proposed approach has been implemented in the SculptMate VR system (Strousopoulos et al., 2023), a VR cultural heritage application allowing for personalized user interactions depending on their expertise in computer skills and VR, as well as experience and interests in the artistic domain. At the core of the system lies the evaluation of users at different knowledge levels by fuzzy weights and delivery in context of assistive messages through a rule-based system. SculptMate brings together the fusion of mobile technology, 3D modeling, and artificial intelligence (AI) to provide a new dimension to art appreciation. It would have within its architecture a 3D model viewer wherein the user can explore a large collection of virtual sculptures across many historical periods and styles from global museums and galleries. It would also have a rule-based engine for enhancement of personalization while analyzing user interaction data like likes, dislikes, and behavioral data. This will be powered by an engine that integrates with a preference-based filtering system, allowing the user to be able to personalize recommendations for active engagement and new discoveries. SculptMate further goes on to innovate interaction with diverse 3D sculpture models across various eras. The uniqueness of the platform features the curation of experiences around users' technology, culture, and tastes. In particular, evaluation findings well demonstrate the proposed approach's effectiveness in ensuring that different levels of knowledge among users are taken into consideration and support is applicable.

The novelty of our proposed fuzzy-based VR system, SculptMate, lies in its ability to dynamically adapt to users by modeling expertise in both computer skills and VR interaction. Contrary to previous systems that focused either on improving visual fidelity or user interaction without personalization, SculptMate employs fuzzy logic to deliver personalized, context-sensitive messages that assist users. This system also provides personalized feedback depending on the level of expertise a user has, hence closing the gap between novice and expert users in such a way that engagement and understanding of the cultural artifact are increased. Therefore, our system contributes uniquely to this developing area of VR applications in cultural heritage in order to make most of these experiences more accessible and effective for a greater number of people (Teeng et al., 2022; Marougkas et al., 2023).

The article is organized as follows. First, it starts with an overview of the system's architecture and the user study in Section 2. Then, it introduces fuzzy weights for modeling user's computer and VR skills, enabling graduation in expertise. After, it proposes a mechanism of the rule-based assistive messaging and explains how messages can be adapted according to the user's skill estimates. Finally, it evaluates this approach with several tests and analyses. The article concludes by summarizing the findings and suggestions for future work on enhancing user interaction through adaptive messaging systems.

2. Materials and methods

2.1. System overview

Herein, the architecture of the SculptMate system is proposed, which enhances users' interaction with cultural heritage artifacts through personalized assistive messaging based on users' expertise in computer and VR skills. The workflow of the system starts by assessing users' skills, which will then feed into the fuzzy engine for classification into different levels of expertise. The resultant classifications feed into a rule-based mechanism that will provide personalized assistive messages through the VR environment. Figure 1 illustrates the high-level system overview.

2.2. Key components

The crucial modules forming the SculptMate system, which are discussed in some detail in what follows, are the User Expertise Evaluation – a questionnaire-based evaluation of the user's expertise with computers and VR, yielding as output a test score, which is passed on to the fuzzy logic engine (Section 3) – and the Fuzzy Weight Engine, whose task is the classification of a user into one of several levels of perceived expertise, based on trapezoidal membership functions, as discussed in detail in Section 3. The rule-based mechanism (Section 4) consists of 19 predefined rules that vary system behavior as a function of the skill level of the user. In this system, using tailored assistive messaging, messages are delivered to the user in respect of interaction options adapted to the expertise of a user.

2.3. User study design

To assess the effectiveness of SculptMate (Section 5), a user study involving 64 participants was conducted. The participants were split into two groups: an experimental group that used the personalized assistive messaging system and a control group that used a standard VR interface. Behavioral data, such as interaction time and the number of assistive message triggers, were gathered along with subjective feedback from post-interaction surveys.

3. Fuzzy weights for modeling user computer/VR skills

It is essential to evaluate users' level of computer and VR proficiency in order to provide them with effective assistance for VR systems, which is a difficult and uncertain undertaking. The system employs fuzzy weights to classify users into different levels of expertise based on their proficiency in both computer skills and VR. This classification is derived from a comprehensive questionnaire that evaluates general computer skills, experience with VR systems, and familiarity with virtual environments. As there is not a standardized skills practice test specifically designed to evaluate VR cultural heritage experiences, we developed a bespoke questionnaire designed to gauge general computer skills, tailored to assess users' engagement, immersion, personalization, and understanding within the virtual cultural heritage environment. This questionnaire was meticulously crafted by a team of 15 experts in the field of cultural informatics, ensuring its relevance and appropriateness for evaluating the effectiveness of our system. By leveraging the expertise of professionals in cultural informatics, we ensured that the questionnaire accurately captured the nuances of the cultural heritage experience, providing valuable insights into user perceptions and interactions within the virtual environment. The questionnaire consisted of 10 questions, each of which was given a score ranging from lower grade to greater grade. For each question, participants were encouraged to pick one of the options, each of which represented a different grade. For example, selecting option A

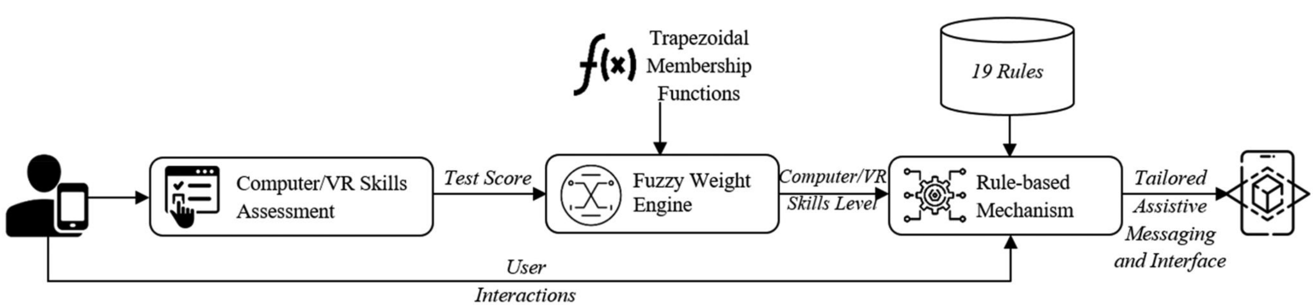

Figure 1. High-level system overview.

would result in a score of 1, while selecting option B would result in a score of 2, and so on. The maximum score attainable for each participant was set at 44, reflecting the overall proficiency in utilizing VR systems. Table 1 presents the list of questionnaire items.

The questions presented in Table 1 are designed to assess a user's experience and comfort level with both general computer skills and VR-specific interactions, providing a comprehensive understanding of their overall digital proficiency. Classifying a user with a computer/VR skills test score of 39/44 as either very good or excellent presents a challenge, as both classifications hold a certain degree of validity. To overcome this challenge, fuzzy weights provide an appropriate solution. This method uses five fuzzy weights to describe learners' computer skills: Fundamental (F), Basic (B), Intermediate (I), Advanced (A), and Expert (E). Trapezoidal membership functions are used to represent these fuzzy weights, as shown in Figure 2 and described in Table 2. Four boundary values (a_1, a_2, a_3, a_4) make up the trapezoidal membership functions. The degree of membership steadily rises from 0 to 1 between a_1 and a_2. Between a_2 and a_3, it remains at 1, and between a_3 and a_4, it shifts from 1 to 0. Trapezoidal membership functions were chosen for their ability to accurately capture the interval where students' scores align with a specific skills category. This choice ensures a more precise representation of learners' computer skills within the fuzzy-based model.

As mentioned earlier, the current level of a user's computer/VR skills in VR interactions is represented using the membership functions discussed previously. These membership functions define the values of the fuzzy weights within a range of 0 to 1. A skills level value of 1 indicates that the user is familiar with the use of computers and VR technology, demonstrating a deep and comprehensive understanding of their functions and applications. Therefore, the sum

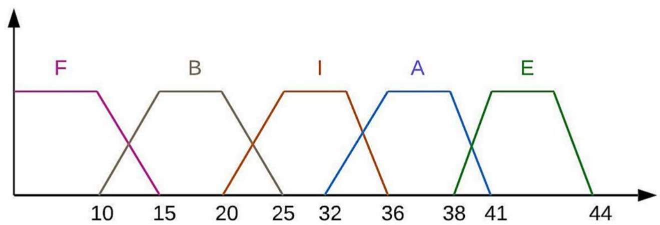

Figure 2. Fuzzy weights of computer/VR skills level.

Table 1. Computer/VR skills assessment.

Questions	Responses
General computer skills: 1. How familiar are you with basic computer tasks such as creating folders, saving files, and navigating a file system?	a. Not familiar at all b. Somewhat familiar c. Moderately familiar d. Very familiar e. Extremely familiar
Internet and online navigation: 2. How proficient are you in using web browsers to search for information and navigate websites?	a. Not proficient at all b. Somewhat proficient c. Moderately proficient d. Very proficient
Software usage: 3. How familiar are you with using different types of software applications (e.g., word processors, spreadsheets, and graphic design tools)?	a. Not familiar at all b. Somewhat familiar c. Moderately familiar d. Very familiar e. Extremely familiar
Troubleshooting: 4. How confident are you in your ability to troubleshoot and solve common computer problems (e.g., software crashes, connectivity issues)?	a. Not confident b. Somewhat confident c. Moderately confident d. Very confident
Data management: 5. How often do you back up important data and use cloud storage services?	a. Never b. Rarely c. Occasionally d. Frequently
VR experience: 6. How often do you use VR systems (e.g., VR headsets, VR applications)?	a. Never b. Rarely c. Occasionally d. Frequently
VR navigation: 7. How comfortable are you with navigating virtual environments using VR controllers or hand gestures?	a. Not comfortable at all b. Somewhat comfortable c. Moderately comfortable d. Very comfortable e. Extremely comfortable
VR applications: 8. How familiar are you with using VR applications for entertainment, education, or professional purposes?	a. Not familiar at all b. Somewhat familiar c. Moderately familiar d. Very familiar e. Extremely familiar
VR interaction: 9. How proficient are you in interacting with virtual objects and menus in VR?	a. Not proficient at all b. Somewhat proficient c. Moderately proficient d. Very proficient
VR system knowledge: 10. How knowledgeable are you about the setup and maintenance of VR hardware and software (e.g., calibrating VR systems, updating software)?	a. Not at all b. Somewhat c. Moderately d. Very much

Table 2. Membership functions of computer/VR skills level.

Computer/VR skills level	Membership functions
Fundamental (F)	$\mu_F(x) = \begin{cases} 1 & x \leq 10 \\ 1 - \frac{x-10}{5} & 10 < x < 15 \\ 0 & x \geq 15 \end{cases}$
Basic (B)	$\mu_B(x) = \begin{cases} \frac{x-10}{5} & 10 < x < 15 \\ 1 & 15 \leq x \leq 20 \\ 1 - \frac{x-20}{5} & 20 < x < 25 \\ 0 & x \leq 10 \text{ or } x \geq 25 \end{cases}$
Intermediate (I)	$\mu_I(x) = \begin{cases} \frac{x-20}{5} & 20 < x < 25 \\ 1 & 25 \leq x \leq 32 \\ 1 - \frac{x-32}{4} & 32 < x < 36 \\ 0 & x \leq 20 \text{ or } x \geq 36 \end{cases}$
Advanced (A)	$\mu_A(x) = \begin{cases} \frac{x-32}{4} & 32 < x < 36 \\ 1 & 36 \leq x \leq 38 \\ 1 - \frac{x-38}{3} & 38 < x < 41 \\ 0 & x \leq 32 \text{ or } x \geq 36 \end{cases}$
Expert (E)	$\mu_E(x) = \begin{cases} \frac{x-38}{3} & 38 < x < 41 \\ 1 & 41 \leq x \leq 44 \\ 0 & x > 44 \end{cases}$

of the values of the divided fuzzy sets, as described by Equation (1) (Zadeh, 1996), represents the skills level of computer/VR technologies:

$$\mu_F(x) + \mu_B(x) + \mu_I(x) + \mu_A(x) + \mu_E(x) = 1 \quad (1)$$

The determination of the fuzzy weights and the establishment of thresholds for their membership functions were conducted by a panel of 15 informatics faculty members from public universities. These experts were tasked with providing detailed descriptions of computer/VR skills levels, along with the corresponding ranges that define each skills level. It is endowed with the kind of experience needed in the truthful portrayal of computer/VR skills of users, with more than 12 years of faculty experience within university settings. Their contributions guarantee the reliability and validity of the fuzzy-based model in the representation of the levels of users' computer and VR skills in system interactions.

4. Rule-based mechanism for assistive messaging and tailored user experience

The personalized assistive messages and user interface are generated using a rule-based system that considers the user's expertise in computer and VR skills. The system first classifies users based on their technical expertise in computer skills and VR technology, using the fuzzy weights. The computer/VR skills are categorized into five levels: Fundamental, Basic, Intermediate, Advanced, and Expert. This technical classification informs the complexity and style of the assistive messages and of the components used for delivering them, ensuring they are accessible and appropriate for the user's demonstrated skills. This ensures that fundamental and basic users receive more guidance and simplified interactions, while intermediate, advanced, and expert users experience increasingly complex and detailed support, tailored to their growing familiarity and proficiency with the virtual environment.

The main purpose of the SculptMate system is for mobile VR platforms, which use devices like smartphones or tablets. It enables users to investigate, in a 3D virtual environment, how to observe sculptures from all sides by moving devices or using touch gestures like swiping and pinching on screen. Here, "touching" means the tapping, swiping, and pinching on the screen to manipulate the view of the sculptures. No sophisticated VR hardware such as VR glasses, haptic gloves, or any kind of device providing physical feedback is part of the system. The sculptures are rigid, non-deformable models without tactile sensations, like hardness or texture, are felt by the user. This setup is visually immersive but without physical haptic feedback, clear and consistent in terms of user interactions.

The implementation of the rule-based system, totaling 19 rules, is presented in Table 3 and then analyzed as follows.

Following, the rules are analyzed in terms of their adaptability to users' varying levels of expertise and their alignment with the fuzzy logic model presented in Section 2.

```
# Rule 1: if user_approaches_sculpture_for_first_time:
provide_brief_introduction()
```

The authors implemented a rule in the virtual environment for interacting with sculptures so that when a user approaches a sculpture for the first time, a short introduction is given. This is in order to ensure maximum engagement and understanding of the artworks in the first instance by the user with appropriate contextual information. Analyzing the user's interactions with the feature revealed its positive effects on the user experience. The short introduction could give users the core background information about the sculpture, such as the inspiration of the artist, the historical context, or artistic meaning. User feedback indicated that the introduction served to deepen the relation with the artwork and enhance an appreciation for the cultural and historical content values associated with the work. This rule was also very immersive, but educational for those who might not have known the particular sculpture or even the world of art in general. It is our aspiration to engage users by offering an educational environment that makes it both interesting and informative for any novice or seasoned art enthusiast, increasing user satisfaction and enriching the virtual journey across the spectrum of sculptures.

This would be the case when considering the rule and its consequences regarding the system behavior adaptation to

Table 3. Summary of rule-based mechanism.

Rule	Trigger	System response
Rule 1	User approaches sculpture for first time	Provides a brief introduction about the sculpture.
Rule 2	User selects specific sculpture	Provides additional information about the selected sculpture.
Rule 3	User interacts with sculpture in a specific way	Provides guidance on interaction (e.g., zoom, rotate).
Rule 4	User expresses confusion or asks a question	Offers explanations to clarify confusion.
Rule 5	User spends significant time exploring sculpture	Recommends similar sculptures based on user interest.
Rule 6	User completes interactions with multiple sculptures	Offers a summary or quiz to reinforce learning.
Rule 7	User demonstrates advanced knowledge or interest	Suggests educational resources for further learning.
Rule 8	User is inactive for a period	Provides a gentle reminder or suggestion to re-engage.
Rule 9	User explores sculptures from specific artist	Offers information about the artist.
Rule 10	User interacts with sculptures from specific art movement	Explains characteristics of the art movement.
Rule 11	User expresses admiration for specific sculpture	Provides background stories or anecdotes related to the sculpture.
Rule 12	User shows interest in sculpture symbolism	Explains the symbolic meaning of the sculpture.
Rule 13	User asks for recommendations based on preferences	Suggests sculptures from relevant genres or styles.
Rule 14	User expresses desire to learn sculpting techniques	Provides learning resources for sculpting.
Rule 15	User interacts with sculptures depicting historical event	Provides contextual historical information.
Rule 16	User indicates interest in specific sculpture materials	Offers information about the materials used in sculptures.
Rule 17	User shows curiosity about sculptor's creative process	Explains the artist's approach and techniques.
Rule 18	User provides ratings for sculpture	Expresses gratitude and offers related suggestions.
Rule 19	User demonstrates interest in sculpture restoration	Provides information on conservation techniques.

user technical skills: in the case of users with computer/VR skills at fundamental level, this rule involves the fact that the system will provide a short and introductory explanation about the sculpture, its historical importance, and maybe part of the contextual background. This approach is tailored to users who are new to the VR environment, since they may require more guidance and a simplified introduction to fully engage with the content. This ensures they are not overwhelmed by complex details and can easily navigate the experience, gradually building their understanding of both the VR interface and the subject matter. However, when the system identifies a user as an expert, the response is likely to be more in-depth information that discusses intricate details, lesser-known facts, and scholarly insights, since they are expected to have a higher level of familiarity with the technology. As such, they can handle more complex information without the need for basic guidance.

# Rule 2: if user_selects_specific_sculpture:
provide_additional_information()

A rule was built into the constructed virtual environment for interaction with sculptures that, upon the event of a user selecting a particular sculpture, triggered the display of additional information. This rule implemented the goal of enhancing the user's experience with additional information about the artifact selected by the user.

It is this implemented rule that gives users at different technical skills levels a highly adaptive experience. For users with basic computer/VR skills, the subject matter is introduced in a very gentle way: building foundational knowledge one step at a time. The system guides and orients them through the content without them getting lost. For expert users, it ensures an intellectually engaging and rewarding interaction. By providing advanced information, the system respects the user's expertise and his wish to deep dive into the subject. This kind of design gives the impression of being inside the scenario and motivates experts to further engage in VR experience.

By analyzing user interactions, we found that this feature highly contributed to increasing the level of engagement and knowledge the users gained. Users liked the descriptive details included in the extended description, such as what materials were used, dimensions of the sculpture, background information on the artist, and inspiration behind the piece. Moreover, this additional information empowered the user to deal more deeply with the artistic nuances of the selected sculpture, letting them see the fineness of the workmanship and the creative element involved in the making of such an art piece. In addition, the rule dealt with users' interest and desire to learn more about the sculptures, promoting exploration and discovery within the virtual environment. Positive user feedback and increased times of interaction with some sculptures proved the efficiency of this rule, enhancing the overall educational and immersive experience. By providing detailed information, allowing a closer relationship between users and sculptures, we aimed to foster long-lasting appreciation of the art and to activate users in order to engage more actively with the varied sculpture collection of the virtual environment.

# Rule 3: if user_interacts_with_sculpture_in_specific_way:
provide_guidance()

This is a rule triggering the sending of guidance once a user has in some way interacted with a sculpture. Interacting in a specific way means that a user engages with a sculpture through pre-defined actions or gestures set in the rules of the system, for example, a combination of touch, rotation, or zoom actions indicating that a user intends to take a closer or different angle look at a sculpture. This rule was aimed at raising the user's awareness of interactivity in the virtual environment and at optimizing his experience for the exploration of that space. In fact, as we noted in our analysis, this feature contributed significantly to the achievement of smooth navigation and manipulation of the sculptures. As they interacted with the sculptures, in touch, rotation, or zoom functions, users welcomed the interactive real-time guidance. It is intuitive with the guidance provided in this respect: how to travel, zoom in on minute details, or rotate the sculpture to view it from another angle. For users with basic computer/VR skills, the assistive messaging triggered by interactions with sculptures focuses on providing simple, step-by-step guidance, such as "tap here to rotate" or "use this gesture to zoom". The goal is to build their confidence in navigating the virtual environment by giving them clear and understandable tips. On the other hand, when the system identifies a user with advanced computer/VR skills, the guidance provided is more concise and sophisticated, offering advanced tips or shortcuts that enable them to explore the sculptures more efficiently, such as suggesting specific angles for viewing.

# Rule 4: if user_expresses_confusion or user_asks_question:
offer_explanations()

This is a rule for explanation generation when the user becomes confused or has questions regarding a sculpture. That is, it was going to give them all the clarity and information the user would look for, hence enhancing understanding and appreciation of the artworks. For users with basic computer/VR skills, the explanations provided are typically simplified and direct, focusing on clarifying the core concepts or addressing specific points of confusion. In contrast, for advanced users, the explanations provided are more comprehensive and in-depth, corresponding to their higher level of expertise and curiosity.

# Rule 5: if user_spends_significant_time_exploring_sculpture:
recommend_similar_sculptures()

Rule 5 recommends similar sculptures in case a user spent a considerable amount of time looking at a certain type of artwork. The main purpose of this rule was to satisfy users, based on their interests and preferences, by providing a selected list of sculptures that best matched their demonstrated interest. For users with basic computer/VR skills, the recommendations are presented in a straightforward and easy to explore format, with brief descriptions highlighting the key features that make them comparable, guiding user to smoothly transition between artworks. For advanced users, the system suggests other artworks with detailed justifications, as well as more complex or rare pieces.

# Rule 6: if user_completes_interactions_with_multiple_sculptures:
offer_summary_or_quiz()

The above rule provides the user with a summary after he has completed a set of interactions involving multiple sculptures. The main objective of this rule was to strengthen learning and provide engagement through the use of interaction and education. For users with basic computer/VR skills, after completing interactions with multiple sculptures, the system presents a summary in a clear and concise format, summarizing the key points related to the sculptures they interacted with. By limiting the amount of information displayed and keeping the focus on essential facts, the system ensures that basic users do not feel disoriented within the virtual environment. In contrast, advanced users are presented with a more interactive and dynamic environment. Instead of just a summary, the system offers an interactive quiz after the user has explored multiple sculptures. Since these users have a higher level of familiarity within VR environments, they are better equipped to handle a more engaging and complex interaction, such as navigating between questions or interacting with the sculptures directly as part of the quiz.

# Rule 7: if user_demonstrates_advanced_knowledge_or_interest:
suggest_educational_resources()

Rule 7 recommends related educational resources when the user's interest in the artwork is advanced. The rationale behind this rule was to provide knowledgeable users with enough information and to give them more valuable additional information so that their understanding of art and sculpture can be enhanced. If users have low technical skills, the system tends to avoid overwhelming them with a large volume of additional educational material, focusing on easily accessible content that can gradually deepen their knowledge without disrupting their navigation through the VR environment. For advanced users, the system may even suggest interactive virtual tours of museums, online lectures, or discussion forums where they can engage further with experts and peers.

# Rule 8: if user_is_inactive_for_period:
provide_gentle_reminder_or_suggestion()

This rule triggers a gentle reminder when a user remains inactive for a certain period. Its primary objective was to re-engage users who may have become momentarily disengaged or lost focus during their virtual exploration. For users with basic technical skills, the system's reminders are kept simple and supportive, acknowledging that they might need extra time to adjust to the VR environment or process the information presented to them, such as "Would you like to rotate the sculpture for a different view?" or "Tap here to learn more about the artwork". For advanced users, the system recognizes that their inactivity may be due to deeper contemplation or a need for more meaningful content. In these cases, the reminder includes a more engaging suggestion, such as offering additional information or inviting them to explore a different feature of the VR environment. In the context of SculptMate, an "inactive period" refers to a predefined duration during which the user does not engage with the application or interact with the VR environment. SculptMate identifies a duration of 35 seconds of inactivity. When a user goes inactive in that time, it becomes one kind of signal for the system to understand that a user may need to be addressed again or given further hints. The decision to set the idle period to specific seconds was informed by expert input and considerations of user behavior and patterns of interaction. This duration strikes a good balance between respecting the pace at which the user chooses to explore and stepping in to offer assistance when necessary.

# Rule 9: if user_explores_sculptures_from_specific_artist:
offer_information_about_artist()

This rule can be read that if a user views several sculptures of one artist, provide more information about this artist. The goal of this rule was to deepen the information given to the user on an artist's body of work and thus make a closer relationship with their style and contributions possible. For users with basic computer/VR skills, the system displays a pop-up or sidebar with brief artist details, such as a short biography, a couple of key facts, or an introductory overview of the artist's style, with large, clear buttons for further actions, such as viewing more sculptures or learning basic additional facts. On the other hand, advanced users receive a dynamic panel or interactive timeline that shows detailed information about the artist's life, works, and artistic evolution.

Rule 10: if user_interacts_with_sculptures_from_specific_art_movement:

explain_characteristics_of_art_movement()

If the user looks at multiple sculptures from an art movement, it explains the nature of the movement. The main purpose of the rule was to give users general knowledge regarding typical features of the art movement and its historical context. For users with basic skills in computer and VR technologies, the system provides simplified and easy-to-navigate explanations, such as a short summary with minimal text and a few images to illustrate the movement's features, offering a "Learn More" button for further information. While, for expert users, the system provides a more interactive and in-depth experience, such as detailed article explaining the movement in greater depth, including links to related movements, comparisons with other styles, interactive timelines, and other multimedia elements.

Rule 11: if user_expresses_admiration_for_specific_sculpture:

provide_background_stories_or_anecdotes()

Rule 11 provides background stories or anecdotes related to a certain sculpture if the user has expressed admiration for it. This rule, primarily aimed at increasing this emotional bonding of the user with the art piece by telling additional stories that complement his admiration. For basic users, the system presents these background stories in a simple and engaging format, including minimal text and visuals or audio clips to make the story more engaging without requiring too much interaction. For advanced users, the system offers richer, more detailed stories or anecdotes, including multiple layers of content and interactive elements, such as clickable sections.

Rule 12: if user_shows_interest_in_sculpture_symbolism:

explain_sculpture_symbolic_meaning()

This rule explains the intention of the sculpture if the user asks about the meaning of the sculpture. The primary motivation for including this rule was to provide users with a greater level of understanding about the artistic intent and meaning associated with the symbolism in the work. For basic users, the system presents a short, easily understandable explanation, including visual aids and/or highlight of specific features of the sculpture that represent symbolic meaning, making the content more accessible and visually engaging for users who are still building their understanding of the art and the virtual environment. For advanced users, the system provides a more in-depth and detailed explanation of the sculpture's symbolic meaning, allowing for interactive exploration, where users can click on different parts of the sculpture to learn about the specific symbolism associated with each element. This provides a more immersive and intellectual experience to users who are comfortable navigating and interacting with detailed content within the virtual environment.

Rule 13: if user_asks_for_recommendations_based_on_preferences:

suggest_sculptures_from_relevant_genres()

Rule 13 suggests sculptures of similar genres or styles as requested by the user in relation to taste in art. This is achieved through a user interface that allows users to request recommendations based on their tastes. In particular, a question mark icon is overlaid within the user's view in the virtual environment. A user can trigger this icon by looking directly at it. The main purpose of this rule was to provide personalized recommendations, and thus tailored, to the user according to his taste and art preferences. When a user with basic computer/VR skills activates the question mark icon, the system presents a list of recommended sculptures in an easy-to-read format, with large buttons and arrows that allow users to scroll through the recommended sculptures without feeling overwhelmed. When an expert user triggers the question mark icon, the system provides detailed recommendations, being presented in a more immersive layout, allowing advanced users to interact with multiple sculptures directly within the virtual space, viewing them from various angles or zooming in for detailed inspection, as well as offering filters options.

Rule 14: if user_expresses_desire_to_learn_sculpting_techniques:

provide_learning_resources_for_sculpting()

This rule makes provisions for learning techniques in sculpture if the user expresses an interest to that effect. The overall objective of this rule was to satisfy the aspirations of users for artistic growth and development of related skills, thus engaging and improving their experience. When a basic user expresses a desire to learn sculpting techniques, the system displays introductory materials, such as simple tutorials, step-by-step guides, or short videos, with clear navigation options, ensuring that the user can easily follow along without getting lost in the virtual environment. For advanced users, the system provides more comprehensive and advanced learning resources, including interactive elements.

Rule 15: if user_interacts_with_sculptures_depicting_historical_event:

provide_contextual_historical_information()

This rule gives contextual historical information whenever a user interacts with sculptures showing some historical events. The rule was mainly put in place to make the user understand more about the artwork by providing relevant historical information that will enhance their understanding of the importance of the sculptures. For users with basic technical skills, the system offers automated prompts that guide the user through the content, include tutorial-style hints on how to interact with the historical information. As such, instead of offering too many choices, the system follows a linear path for presenting information, guiding the user step by step. On the other hand, for advanced users, the system provides an immersive storytelling experience, where advanced users are invited to explore the historical context through a combination of videos, interactive timelines, and audio-visual content.

Rule 16: if user_indicates_interest_in_specific_sculpture_materials:

offer_information_about_sculpture_materials()

The user's gesture to indicate interest in the materials used for particular sculptures. The system recognizes these gestures to present information on the materials. Rule 16 informs a user about the material used in certain sculptures when such a user indicates interest in artworks made from those very materials. The primary intention of this rule was to enlighten the users about the artistic process and meaning associated with the chosen materials. For basic users, the information is presented in a static format, without needed to navigate through multiple menus or sub-options. In contrast, for expert users, the system offers layered content where the information is accessed through clickable sections or expandable menus.

Rule 17: if user_shows_curiosity_about_sculptor_creative_process:

explain_artist_approach_and_techniques()

Rule 17 illustrates the process of a sculptor's work when interest and curiosity are demonstrated by the user. The rule, in essence, gave insight into the approach and techniques which the artist takes up to the user for betterment in appreciating the crafts and creativity of the sculptures. For basic users, the system presents the artist's creative process in the form of a step-by-step story, giving users a simple overview of how the sculpture was made, or audio guides without requiring them to read or navigate complex menus, or infographics, without needing to explain in great detail. For advanced users, the system presents the sculptor's creative process in a dynamic way, allowing users to navigate through content in a non-linear way, and offers the opportunity to participate in a virtual sculpting simulation, where they can practice the techniques they have learned about.

Rule 18: if user_provides_ratings_for_sculpture:

express_gratitude_and_offer_related_suggestions()

This Rule 18 is intended for a virtual environment of interaction with the sculptures. This rule would thank a rating by the user and provide complementary content. The rule would target all ways of user engagement and feedback, guiding users into the use of other sculptures or features of their interest. When a basic user rates a sculpture, the system displays a simple pop-up thanking them for their feedback, suggesting a small selection of related sculptures in a simple grid layout. Moreover, the system offers gentle, non-intrusive prompts encouraging the basic user to continue exploring features like "Add to Favorites" or "Leave a Review". After an advanced user rates a sculpture, the system provides more detailed suggestions with filters options, appearing in a carousel format.

Rule 19: if user_demonstrates_interest_in_sculpture_restoration:

provide_information_on_conservation_techniques()

The final rule informs about conservation techniques if a user shows interest in sculptural restoration/preservation. This rule was included primarily to arm the user with useful information relating to the important question of preservation and handing artistic treasures down to posterity. Users who were interested in sculptural restoration or preservation valued additional information, as it gave them further insight into the efforts taken to preserve an artwork's longevity and historical significance. For basic users, the system focuses on delivering clear and simple explanations about the conservation process, with minimal interactive elements like "Learn More About Cleaning" or "What Tools Are Used". For advanced users, the system offers a deeper and more technical exploration of the conservation techniques, allowing them to engage with detailed information and explore the topic in greater depth.

4.1. Example of operation

The skills level of a user is represented by the quintet (F, B, I, A, E), which allows for full or partial assignments to different fuzzy sets. For instance, a user with quintet (0, 1, 0, 0, 0) is classified as 100% "Basic", while another user with quintet (0, 0, 0, 0.30, 0.70) is classified as 30% "Advanced" and 70% "Expert". Regardless of the quintet values, based on Equation (1), i.e., $\mu_F(x) + \mu_B(x) + \mu_I(x) + \mu_A(x) + \mu_E(x) = 1$, the sum of the fuzzy weights holds true, ensuring that the user's skills level is fully accounted for across all fuzzy sets. This approach allows for a more flexible and nuanced representation of a user's skills and expertise, accommodating varying degrees of proficiency in different areas.

The rest of the subsection serves as an example that illustrates how the rule-based system provides different content to the above students based on their classification. In the virtual environment of SculptMate, these two users approach a sculpture for the first time. The first one (user A), classified as basic user (0, 1, 0, 0, 0), is relatively new to the world of virtual art exploration, while the other one (user B), classified as mainly expert (0, 0, 0, 0.30, 0.70), has extensive knowledge in art and sculptures. The system tailors its messaging to each user:

For user A: When the basic user approaches the same sculpture, the system recognizes that the user has less experience and knowledge about computer and VR technologies. The rule-based system fires a different message, tailored for basic users: "Step forward to watch closer. Learn about the story of the artwork and its place in history. Be prepared to be engaged!". That is what the system provides for the user, in a user-friendly message that guides through the initial interaction with the sculpture. This message invites the user for a closer view, to learn about the story of the artwork, and sets the scene for an immersive experience. This message is meant to be provocative of curiosity and interest from the user, but at the same time provides some basic background information that could enrich his understanding.

For user B: While the expert user approaches a sculpture for the very first time, the system recognizes that he has a high level of expertise in computer and VR technologies. The rule-based system triggers a message, in particular, for experts: "Welcome, Art Connoisseur! Delve into the masterpiece. Feel free to explore the intricacies, learn about its history, and appreciate the fine artistic nuances". A clearly highly developed knowledge base is recognized by the system, which then invites the user to engage with the sculpture at depth. Advanced insights, historical context, and scholarly information are part of this message, catering to her already existing expertise. It is as if the user is invited to view the sculpture from an expert's perspective, enabling one to fully acknowledge the intricacies of the artwork.

It provides relevant support to users of different levels of skills of computers apart from those whose proficiency rates fall either below or above the defined ranges. In particular, the package provides introductory tutorial guidance to less computer-savvy individuals, together with intuitive navigation controls and voice commands that would best help them move around the VR environment and inspect cultural heritage-related artifacts. At the other end, very advanced users are provided with advanced features and interactions, ranging from settings of customizable interface layouts down to in-depth historical analyses of artifacts.

The summary of the key takeaways is (a) personalization – personalized messages by the system based on the skills level of the users; (b) advanced and basic users are distinguished in the following way: the former receives advanced insights, while the latter receives introductory guidance; (c) enhancement of engagement, these are messages aimed at engaging users to motivate them to respond to the sculpture from their own related perspective, either advanced or basic; (d) increase in understanding: the tailored content empowers both expert and basic users to augment their understanding and appreciation of artworks in cultural heritage to create a more user-friendly and informative virtual environment. The example delineated how the rule-based system forms the messaging that suits the particular demands and levels of technical skills of different users at large, thereby enhancing their overall experience in the VR cultural heritage environment.

Figure 3 depicts a screenshot of SculptMate, showing a renowned artwork by Giannoulis Chalepas (1851–1938), a Greek sculptor celebrated as one of the prominent modern artists of the nineteenth century in Greece. Chalepas is recognized for producing deeply emotional and expressive pieces, influenced by his personal struggles with mental health. The image showcases his most widely recognized creation, the "Sleeping Female Figure".

This sculpture, crafted in marble, was specifically designed for the memorial of Sofia Afentaki, an 18-year-old, in Athens' First Cemetery. Chalepas conceived the sculpture in 1877, and subsequently, a replica of the artwork was fashioned in 1980 within the studios of the National Archaeological Museum.

Figure 4 presents the corresponding 3D model of the aforementioned sculpture, exactly as it was generated and imported into SculptMate. The digital modeling depicted in Figure 4 faithfully captures the intricate details and emotive essence of the sculpture, allowing viewers to engage with its beauty and symbolism in a virtual environment. Through meticulous attention to detail, the digital rendition preserves the legacy of Chalepas' artistic vision, offering viewers a captivating and immersive experience that honors the enduring significance of this iconic artwork in cultural heritage.

Figure 3. The sleeping female figure in Athens' First Cemetery.

5. Evaluation

This section provides an evaluation of the performance and effectiveness of the system. In doing so, the application was evaluated in detail for its potential and effectiveness with different kinds of participants. Some of the most important ethical considerations that were followed up during the study include informed consent, confidentiality, and voluntary participation. Participants were fully informed on the nature of the study, its purpose, and possible discomfort or inconvenience resulting from participation. They were clearly told of their right to volunteer in the study and be free to withdraw from the study at any point of choice without penalty. Consent forms were distributed to each of the subjects before their interaction with the SculptMate application and collected thereafter. Second, some measures were taken to help maintain the anonymity and confidentiality of information from the respondents. Extracted personal information, such as age and gender, was recorded only for demographic analysis purposes and kept confidential. Each participant in this study was given a pseudonym so their responses could be anonymized and kept private. Also, in each case, it was made sure that the well-being and comfort of participants were the first priority during the study. The flexible interaction duration meant each participant could work with the app at their own pace, ensuring that all participants, despite different preferences, got good user experience without pressure or hurry. The maximum test duration did not exceed 20 minutes on average in this study, reducing

Figure 4. A provided three-dimensional model from the era of modern sculpture.

the likelihood of potential discomfort caused by a longer interaction.

The SculptMate application was made to interact with the users through a mobile platform. It provided multiple advanced features of personalization for increasing users' appreciation and comprehension of sculptures in the cultural heritage setting by incorporating fuzzy weights. This group consisted of 64 undergraduate students from various academic disciplines within the university. Crucially, the age and gender of the subjects, as encountered in the random sample selected, was computed to rule out the effects of these extraneous variables on the findings of the study. The demographic analysis (Table 4) provides a view into the attributes of the appraisal participants.

Although the researchers did not impose a strict minimum, the interaction duration spanned several minutes for each user. The testing period did not exceed a maximum of 20 minutes. This flexibility in interaction duration thus enabled participants to work with the application at their own pace and depending on their preference or level of interest. This approach ensured that participants were able to freely explore the VR experience without feeling hurried or constrained by the pressure of a fixed time limit.

The participants orally expressed their keen interest in cultural heritage at the beginning of the evaluation session. This initial expression of interest served as a qualitative indication of participants' motivation and enthusiasm for the subject matter. While this qualitative assessment was not quantified, it helped the authors ensure that participants engaged willingly and earnestly with the VR experience.

To evaluate the personalization of the system, we considered the following four questions:

- *Question 1 (Q1)*: How well did the system cater to your individual preferences during the cultural heritage experience?

This question aims to assess the system's ability to adapt and cater to each user's unique preferences. It seeks feedback on how well the system personalized the experience based on individual user characteristics and preferences, as well as how effectively it presented relevant content to enhance their overall interaction.

Through the evaluation process, we can identify strengths and weaknesses in the system's personalization capabilities.

Table 4. Sample population.

Measure	Item	Frequency	Percentage (%)
Sample size		64	100.0
Gender	Male	37	57.8
	Female	27	42.2
Age	18–19	24	37.5
	20–21	21	32.8
	Over 22	19	29.7
Level of virtual environment (VE) knowledge	Novice	13	20.3
	Intermediate	30	46.9
	Advanced	21	32.8
Motivation	Every student displayed a keen interest in cultural heritage and its history		

This feedback enables iterative improvements and empowers the development team to enhance the virtual environment, ensuring it consistently meets the unique needs and expectations of each user. Additionally, positive user experiences driven by personalization are more likely to encourage repeat usage and positive word-of-mouth recommendations, which are essential for the long-term success and adoption of the virtual environment.

- *Question 2 (Q2)*: Did you feel engaged in the virtual environment?

This question focuses on user engagement within the virtual environment. It explores whether the contextual assistive messaging contributed to a heightened sense of presence, making users feel more connected and involved with the cultural heritage experience.

It centers around the concept of user engagement, which refers to the level of involvement, interest, and emotional connection that users feel while interacting with the virtual environment.

- *Question 3 (Q3)*: How much were you satisfied with the system's adaptability to different styles of interaction?

The question, therefore, assesses the adaptability of the system concerning catering to different user interaction styles. This item seeks to determine whether a system can support both novices and experienced users by modifying the difficulty level of the interaction and, as a result, impact user satisfaction.

This adaptability is important to ensure an inclusive and user-friendly VR cultural heritage experience. In this way, by recognizing and accounting for individual differences, the system will work out how to provide engagement and learning opportunities, making them maximal for all categories of users, independent of their previous knowledge or experience with VR.

- *Question 4 (Q4)*: How does the contribution of knowledge modeling to the system make for a more intuitive experience?

The question deals with the effectiveness of fuzzy-based knowledge modeling in delivering information and content concerning the cultural heritage experience. More specifically, it investigates whether the approach chosen by the system with fuzzy weights helped to present information in a more understandable and intuitive way, therefore, enhancing the understanding of the cultural heritage content.

In the article, a modified version of the Lynch–Ghergulescu framework (Lynch & Ghergulescu, 2016) was used to structure the questionnaire. The choice to modify an existing framework was based on the fact that the context of our study was unique, relating as it did to cultural heritage and VR interaction.

Cronbach's alpha coefficient for the questionnaire is high, coming out to be 0.95, with high internal consistency. This might mean that items measure a coherent construct from different perspectives, reflecting the comprehensiveness of the questionnaire. Traditional binary logic may fail to fully capture subtleties and uncertainties of real-world computer knowledge involved in cultural heritage information. Fuzzy weights introduce more flexible and subtle representations, thus providing a better understanding of complex computer-related content. Fuzzy-based knowledge modeling proposes a solution for one of the most important issues concerning VR cultural heritage environments, that is connected with the representation and delivery of information. Computer knowledge-based content is often multi-dimensional and open to multiple conceptions, while traditional binary logic has limited possibilities of capturing the richness of such contexts. Fuzzy weights, as tools for working out problems with uncertainty and imprecision, are one of the most promising approaches that can improve the representation of computer knowledge related to cultural heritage.

5.1. Descriptive analysis

The feedback from the students offered valuable perspectives on their human–computer interaction. This input can assist in identifying areas that require enhancement and customizing future VR environments to better suit their requirements.

The authors performed a descriptive analysis of the questionnaire responses by summarizing the data using frequency calculations for each question (Figure 5).

According to the responses to the first question, it seems like a significant percentage of participants were satisfied with how well the virtual environment catered to their individual preferences and interests during the cultural heritage experience. The majority of respondents, or almost 63% of the total respondents, gave the combined responses of “strongly agree” and “agree” (40). This shows that a sizeable percentage of the participants believed the virtual environment successfully catered the experience to match their unique preferences and interests.

Nevertheless, it should be noted that very few respondents checked “neutral” (13) or “disagree” (7) when they selected the response to this question. Such participants possibly experienced a more negative or ambivalent view of how well the virtual environment catered to unique tastes and interests.

In addition, a small fraction of the respondents strongly disagreed with the statement (4), showing that some kind of user felt that the virtual environment was much less interested in considering personal preferences and interests in the course of navigating the cultural heritage.

While most agreed that the customization possibilities of the virtual environment were positive overall, there is room for further improvement to ensure that all users consistently enjoy a personalized experience. Analyzing the factors of this customization toward which people felt positive and addressing the concerns of those who disagreed or were neutral will help inform future refinements for the personalization and improvement of the cultural heritage virtual environment and user satisfaction.

The majority of study participants acknowledged satisfaction with their involvement and immersion in the virtual environment as well as the effect of the system’s contextual supportive messaging on their sense of presence, according to the data collected for the study’s second question. About 58% of participants gave the combined “strongly agree” and “agree” response, which shows that a sizable proportion of users felt involved and engaged in the virtual environment. Additionally, contextual assistive messaging seemed to positively influence their sense of presence, enhancing their feeling of being present within the virtual cultural heritage experience.

However, there were some respondents who selected “neutral” (15) and a smaller number who chose “disagree” (6) or “strongly disagree” (6). These participants might have experienced mixed or less favorable feelings about their engagement and immersion in the virtual environment or perceived limitations in the effectiveness of the contextual assistive messaging.

The findings suggest that while the majority of participants had a positive experience in terms of engagement and immersion, there is room for improvement to further enhance the sense of presence through contextual assistive

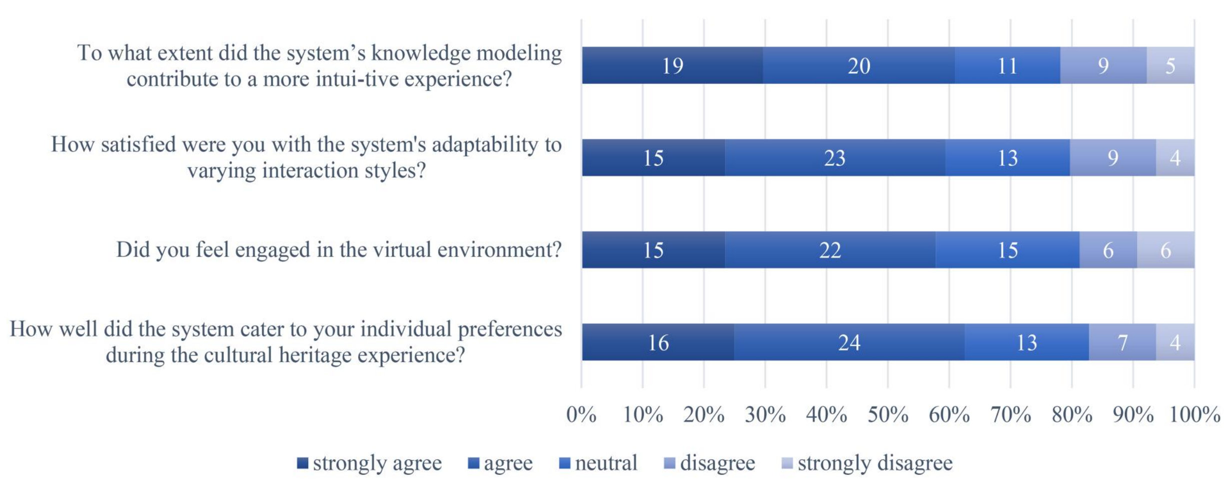

Figure 5. Frequency of the answers in stacked-bar mode.

messaging. Addressing the concerns of those who felt less engaged and immersed can lead to valuable improvements and contribute to a more captivating and fulfilling virtual cultural heritage experience.

The distribution regarding participants' satisfaction with the system's ability to adapt to different interaction styles and user proficiency levels was relatively positive. The combined responses of "very satisfied" and "satisfied" with 38, account for approximately 59% of the total participants; hence, a majority of the users were content with the adaptability of the system. This infers that the level of flexibility displayed by the virtual environment in accommodating different interaction preferences and expertise of the users was reasonable.

Nevertheless, a fair number of them opted for "neutral" with a response of 13, which may suggest that they were still not convinced, or at least unsure, about the flexibility of the system. Thirteen were recorded who had opted for "dissatisfied" and "very dissatisfied"; hence some participants were not very satisfied.

This implies that although a good number of the participants realized the adaptability of the system, it still has development potential. In addition, the concerns of unsatisfied users and an understanding of the reasons for neutral responses can add valuable insight into ways of fine-tuning the system's adaptability to accommodate a greater diversity of user needs and preferences. That way, developers could use such feedback to further refine the adaptability of the virtual environment, hence providing a more user-sensitive experience that helps to ensure a higher satisfaction level for all participants in future cycles.

Finally, to the 4th question, their responses to the fuzzy-based knowledge modeling generally contributed positive experiences to their virtual cultural heritage. The total combined "extremely" and "very much" amounts to 39 responses, approximately accounting for 61% of the total number of participants, indicating that most of them felt the fuzzy weights approach significantly contributed to its being more intuitive and informative. That is, with fuzzy weights and a mechanism based on rules, users can really understand and participate in cultural heritage contents.

However, some of the participants responded with "moderately" 11 and "slightly" 9, indicating that they perceived a somewhat good improvement in their understanding and experience from the application of fuzzy-based knowledge modeling. Nevertheless, very few returned the survey form with "not at all" 5, showing they did not find the fuzzy approach to impact or enhance substantially.

The user experience, effectiveness of interaction, and perceived usefulness of our system were also assessed by interviews with participants. Besides, from interviews with students, they reported to be satisfied with individualized guidance that, according to them, the system provided people with little experience in art exploration pointed out how well the guidance worked out, and expert users responded to its engaging features. Examples of the relevant answers to system personalization are: "I really enjoyed how the system personalizes its messages based on the user's expertise. Since I was totally new to the sphere of art exploration, such help was very useful to get me started – all the guidance" and "The personalized messages gave me a feeling that the system understands my interests and needs. For an art expert like me, they were very engaging and stimulating".

Finally, because of the system's messaging, cultural heritage students reported that they felt more engaged and immersed into the VR cultural heritage environment. They explain how messages helped them further engage with the sculptures, provoking curiosity and exploration that enriches the experience as a whole. Examples of the answers of engagement and immersion are: "The messages encouraged me to interact more deeply with the sculptures", "I felt more engaged and motivated to explore the artwork details and history", and "The system's messages make me feel I was part of a journey through history and art, which made the VR environment truly attractive".

The students reported that the messages were clear and easy to comprehend. They further acknowledged the fact that there was not much information in the message, hence as a group, they could focus on exploring the art with freedom to develop interpretations at their own pace. Examples of answers regarding the clarity and ease of use: "The messages were clear and understandable", "They put the amount just right to increase my understanding but not over-whelm me", and "I liked how the messages came to the point. It guided me, but it wasn't too intrusive. I could focus on exploring the artwork in my own pace". In general, satisfaction of all was rather high, yet students provided constructive feedback for further improvement.

They wanted more variety in the system's content and more interactivity that would allow them to provide their input or feedback: "While the system did a great job of providing me with tailored messages, I think there could be more variety in the content provided", "It would have been good to get alternative insights into the artwork, different readings", and "I found the messages useful but sometimes I wanted to ask questions and get the system's feedback on my responses". Finally, students were very positive in their overall satisfaction with using the system.

They described it as a pleasant experience, allowing them a better understanding of the cultural heritage artwork. They also praised the system for the possibility of tailoring interests and levels of expertise. Examples of their responses are: "The system not only made me understand better the cultural heritage artworks but also made the VR environment more welcoming and inclusive", "I enjoyed my time interacting with the system", and "It's obvious how much work was put into it". Overall, the findings demonstrate general acceptance of the implementation of fuzzy-based knowledge modeling and rule-based assistive messaging in the virtual environment for cultural heritage experience.

The majority of the participants felt that it made the experience more intuitive and informative, enhancing their understanding of the cultural heritage content. Such feedback from users who did not feel any considerable impact definitely warrants further investigation that may include useful insights into refining the fuzzy weights implementation or other potential enhancements to make the virtual cultural heritage experience even more immersing and informative.

5.2. Statistical analysis

A *t*-test was used in this study to determine the statistical significance of the results and respond to the research questions. The participants who took part in this phase of the experiment are divided into two groups: group A, the experimental group, comprising all participants who utilized the proposed system (as depicted in Table 3), and group B, the control group, which includes individuals with similar characteristics to those in group A, but who used a conventional version of the system, which actually was the same application as the experimental group, but without the fuzzy logic and rule-based mechanisms for personalized assistance. In the control version, the messages displayed were standard, generic messages designed for users with average experience levels. The conventional version of the system features an identical user interface and exhibits the same cultural heritage artifacts as the proposed system. However, it lacks the integration of fuzzy logic and rule-based mechanisms. This conventional version served as a baseline for comparison, enabling assessment of the impact of the integrated mechanisms on user experiences and outcomes. The *t*-test was used to compare the performance of the two groups in order to see if there was a significant difference or if any detected differences could be attributable to random fluctuations.

It is expected that the difference in effect on the experience of virtual cultural heritage by participants will be assessed using a *t*-test between a personalized approach based on fuzzy weights, together with a rule-based module. This offered a comparison between the experimental and control groups for further investigation on the effectiveness of fuzzy-based knowledge modeling and rule-based assistive messaging in enhancing user engagement, immersion, personalization, and understanding of the cultural heritage content.

Both groups received a questionnaire following the VR experience. They were asked to answer the questions using a Likert scale with a maximum score of 10. Participants were asked to use this scale to indicate how much they agreed or disagreed with each statement. The questionnaire aimed to gather feedback and perceptions from the students regarding their experiences throughout the VR experience.

The null hypothesis of the study stated that the means of the two groups (condition 0) were equal, while the alternative hypothesis suggested that they were different (condition 1). To assess the statistical significance of the results, a *t*-test was conducted, and a significance level of alpha $=$ 0.05 was chosen.

The results of the *t*-test, presented in Tables 5–8, provide insights into the level of statistical significance, allowing researchers to draw conclusions about the effectiveness of the personalized approach. A significant difference between the groups would suggest that the use of fuzzy weights in conjunction with the rule-based assistive messaging for the system's personalization had a meaningful impact on the participants' experience and understanding. On the other hand, a lack of significant difference would indicate that any observed variations were likely to be due to chance and not attributed to the presented personalized approach.

The findings revealed that the 32 participants who utilized the fuzzy-based algorithm (*mean* $\approx$ 8.07, *variance* $\approx$ 4.16) exhibited significantly better peak flow scores in the first question compared to the 32 participants in the control group (*mean* $\approx$ 6.85, *variance* $\approx$ 3.13), with $p < 0.05$ (Table 4).

Similarly, in the second question, the 32 participants in the experimental group (*mean* $=$ 7.84, *variance* $\approx$ 4.92) demonstrated notably higher peak flow scores than the participants in group B (*mean* $\approx$ 6.40, *variance* $\approx$ 6.14), with $p < 0.05$ (Table 5).

Moving to the third question, the participants of group A (*mean* $\approx$ 8.09, *variance* $\approx$ 3.73) showed considerably higher peak flow scores compared to the participants of group B (*mean* $\approx$ 6.31, *variance* $\approx$ 3.02), with $p < 0.05$ (Table 6).

Finally, the fourth question revealed that the participants of the experimental group (*mean* $\approx$ 8.04, *variance* $\approx$ 4.29) also demonstrated significantly better peak flow scores than the participants of the control group (*mean* $\approx$ 6.51, *variance* $\approx$ 3.80), with $p < 0.05$ (Table 7).

Overall, the results of the *t*-test provided strong evidence to reject the null hypothesis, indicating that there were significant differences in peak flow scores between the two groups. The use of the fuzzy weights in conjunction with rule-based mechanism in the experimental group led to noticeably better outcomes compared to the control group in all four questions assessed.

This difference in the mean effectiveness ratings is statistically significant, suggesting that the personalized approach,

Table 5. *t*-Test results of Q1: how well did the system cater to your individual preferences during the cultural heritage experience?

	Group A	Group B
Mean	8.078125	6.859375
Variance	4.168403	3.138641
Observations	32	32
Hypothesized mean difference	3.653522	
df	0	
t Stat	126	
P ($T \leq t$) one-tail	3.606897	
t Critical one-tail	0.000223	
P ($T \leq t$) two-tail	1.657037	
t Critical two-tail	0.000445	

Table 6. *t*-Test results of Q2: did you feel engaged in the virtual environment?

	Group A	Group B
Mean	7.84375	6.40625
Variance	4.927579	6.149802
Observations	32	32
Hypothesized mean difference	5.53869	
Df	0	
t Stat	126	
P ($T \leq t$) one-tail	3.455249	
t Critical one-tail	0.000375	
P ($T \leq t$) two-tail	1.657037	
t Critical two-tail	0.00075	

Table 7. *t*-Test results of Q3: how satisfied were you with the system's adaptability to varying interaction styles?

	Group A	Group B
Mean	8.09375	6.3125
Variance	3.737103	6.027778
Observations	32	32
Hypothesized mean difference	4.88244	
Df	0	
t Stat	126	
P ($T \leq t$) one-tail	4.560174	
t Critical one-tail	5.97E − 06	
P ($T \leq t$) two-tail	1.657037	
t Critical two-tail	1.19E − 05	

Table 8. *t*-Test results of Q4: to what extent did the system's knowledge modeling contribute to a more intuitive experience?

	Group A	Group B
Mean	8.046875	6.515625
Variance	4.299355	3.809276
Observations	32	32
Hypothesized mean difference	4.054315	
df	0	
t Stat	126	
P ($T \leq t$) one-tail	4.30192	
t Critical one-tail	1.68E − 05	
P ($T \leq t$) two-tail	1.657037	
t Critical two-tail	3.36E − 05	

based on fuzzy-based knowledge modeling and rule-based assistive messaging, made the experimental group participants feel that the experience with the investigated cultural heritage content was more intuitive and informative compared to the control group.

In summary, the *t*-test and further evaluation have brought out very valuable evidence in regard to establishing the efficiency of the proposed approach for personalizing the experience of virtual cultural heritage according to the preference of users and their interests. The findings further enhance the understanding of how such personalized approaches, including fuzzy-based and rule-based systems, can have positive effects on user engagement and comprehension within VR settings for cultural heritage.

The personalization technique is very important in VR environments, more specifically if referred to the case of cultural heritage experiences. Since people have different interests and learning preferences, the one-size-fits-all approach could lead a person either to be bored or frustrated. Adopting personalization based on fuzzy-based knowledge modeling and using a rule-based mechanism for contextual assistive messaging, the system can increase user engagement and boost knowledge retention, fostering a more immersive and meaningful experience, novel compared to existing literature.

Considering the results obtained by the experiments presented in the present article and its previous version (Strousopoulos et al., 2023), though incomparable, since fuzzy logic was applied and the sample used is different, it allows realizing that fuzzy logic is a very strong tool for personalization in VR experiences within cultural heritage environments. It is important to note that the current research truly bridges the research gap, identified in Section 1 of multiple research articles, therefore offering great novelty in the relevant literature. Given that the challenge of choice in this article is the increase of personalization for more viewers in VR cultural heritage applications, the application of fuzzy logic for modeling users' knowledge level in computers presented here is more effective for providing a more personalized and accessible experience for all users, independent of the users' knowledge of computers.

5.3. Behavioral analysis of user interaction

Besides subjective feedback obtained through questionnaires, data were recorded regarding objective behavior, including interaction time and frequency of triggering assistive messages (Table 9). These metrics represent a glance quantitatively at how the system addressed users at different levels of expertise. In fact, the level of dependence on assistive messages turned out to be higher for users in the "Fundamental" and "Basic" categories. In these groups, users triggered an average of nine assistive messages per session – mostly when first exploring the sculptures. The most common assistive messages were simple navigational hints, such as "Tap here to zoom" and "Swipe to rotate". Lower-expertise users interacted with assistive messages 65–70% more than intermediate and expert users, showing how well the system was guiding them through the VR environment. This reliance on guidance highlights how the system cradled the users who had limited experience in VR to make sure frustration and confusion did not arise while trying to navigate virtual space.

Fewer assistive messages were triggered by expert users. Expert users, on average, only triggered assistive messages three times per session. That usually happens when they explore new or unfamiliar sculptures. As a matter of fact, these subjects spent 35% more time independently surveying individual sculptures, having required less guidance because they relied on their prior knowledge of VR systems. The system thus responded to the behavior of such users by reducing the number of basic instructions and adding more complex or in-depth information, such as detailed background information about the sculpture's historical significance or artistic techniques. The expert users spent an average of 16–18 minutes exploring the VR environment, with less than 20% of that time being spent interacting with system-generated prompts.

These behavioral data underline the capability of the system for personalizing the experience of its users: while users of lower expertise levels received enough guidance, more experienced users could freely explore the VR environment with only minor interference. The variance in message frequency and interaction time between novice and experienced users reveals the flexibility in the system, catering to the needs of given users with a view to increasing engagement and learning outcomes among users with diverse natures.

In fact, low-expertise users, such as those in the Fundamental and Basic categories, relied on more frequent help – as evidenced by higher assistive message triggers they received. Their equivalent counterparts, expert users, would have thus explained their better familiarity and comfort with VR systems by having triggered fewer assistive messages.

Table 9. Summary of user interaction and assistive message frequency by expertise level.

User expertise level	Average assistive message triggers	Average total interaction time (min)	Average time spent on sculptures (min)	Percentage of time using assistance (%)
Fundamental	10	12	7	65
Basic	9	13	8	60
Intermediate	6	15	11	40
Advanced	4	16	13	25
Expert	3	18	15	20

The overall time spent by the expert users in virtual space was also much longer, averaging at 18 minutes per session compared to 12-minute averages for the Fundamental category. The time spent when expert users were focusing on sculptures individually was also considerably longer – averaging 15 minutes – whereas lower-expertise users spent about 7–8 minutes on the same task. The users with lower expertise also relied more on the system's assistance, hence spending a larger percentage of time interacting with the assistive messages, while the expert users spent most of their time exploring independently, with very little reliance on system prompts.

The above results are in good agreement with the findings of previous works but also allow us to point out some unique contributions of the current work in the field of VR and cultural heritage. Especially, large improvements in user engagement and satisfaction, as revealed by this study, are in good agreement with previous works that explored advantages created by integration of smart systems into VR environments.

For example, the higher level of engagement for the experimental group, identified through the *t*-test analysis, is indicative of similar findings in the study by Bachiller et al. (2023) on how augmented and VR improve experience outcomes for visitors to technological heritage museums. Indeed, their use of intelligent feedback systems led to a greater depth in users' engagement, while our approach yields an increase in user engagement via the personalized nature of the assistive messages used in our experiment. This significant difference in user satisfaction of the system with Q1 (individual preferences) and Q3 (adaptability to interaction styles) is further supported by findings from Rambaree et al. (2023), who showed that context-sensitive VR environments improve intercultural empathy and interaction.

Further, the article extends findings from the work of Marougkas et al. (2023) by identifying a lack of personalized experiences in existing VR applications for cultural heritage. This study bridges the identified gap by Marougkas et al. (2023) through the proposal of a fuzzy-based system that might be able to adapt to user expertise, thus opening possibilities for more personalization and better engagement if combined with fuzzy logic and rule-based systems.

User feedback regarding Q4, on the system's capability of enhancing their knowledge with respect to cultural artifacts thanks to adequate assistive messages, also falls in line with research by Doz et al. (2022) and Chandrashekara et al. (2018), which underlined how fuzzy logic may be used to enhance knowledge delivery in education and culture alike. These studies showed that user-specific adjustments due to fuzzy logic not only improved interaction quality but also supported users' learning processes, in line with the increased comprehension reported in our study.

The improvements in user satisfaction in respect of the experience of the VR environment in this study are also in concord with Leon-Garza et al. (2020), who similarly assessed the use of fuzzy logic to enhance user interaction in augmented reality environments. Their results, similar to ours, showed that personalized guidance positively influenced user engagement and immersion.

Beyond the previous works, this research supports the usefulness of personalization in VR systems and can be regarded as a novelty for implementing fuzzy-based knowledge modeling and rule-based assistive messaging into the cultural heritage context, hence filling an important gap in the literature.

6. Conclusions

This article presents an intelligent approach using fuzzy weights in modeling knowledge and rule-based contextual assistive messaging for better user experiences and interactions within VR cultural heritage environments. Thanks to the application of fuzzy weights, the system is capable of making pertinent evaluations regarding users' levels of computer skills and VR familiarity, therefore offering users appropriate, tailored, and personalized conditions. These technically correct and relevant assistant messages are then presented by the rule-based system.

The fuzzy logic approach in SculptMate ensures that this tailored assistance will remain effective across a wide range of scenarios involving users who have various technical and artistic expertise. One of the most important challenges in this context is having a balance among the different aspects of user experience, technical proficiency, and artistic appreciation. Those who have very rich experience regarding computers but have not been widely exposed to VR may need different kinds of guidance from those who have a lot of experience with VR but with fewer computer systems. The fuzzy weights contribute to the dynamic adjustment of the system's responses, thus ensuring that the most relevant information is revealed to the user. The rule-based system adds another layer of personalization according to the user's interests and experience in the artistic domain. Having this two-layer approach ensures that the system is oriented not only toward technical competence but also toward enhancing user engagement with the artistic content presented within the VR environment. For example, the system will describe more precisely the cultural and historical value of the artifacts, with basic technical support, to an art lover who does not have much technical competence. On the other hand, a user with high technical competence but a low level of interest in art will receive messages focused on the technical details of moving around the VR space but with less overall artistic detail.

Results in this research show the effectiveness of the proposed approach for improving user engagement and personalization within VR cultural heritage environments. SculptMate acts as an agent for enlightenment on cultural heritage, as it immerses users into an experience where they can discover and appreciate historical artifacts in a virtual environment. This platform serves not only to preserve cultural heritage but also to facilitate access to it by a wider audience, overcoming geographical and other logistical barriers. By offering a virtual platform to engage with celebrated works of art, users are able to understand more about the legacy of an artist and the historic importance of the work.

It uses fuzzy weights and rule-based messaging to make sure that all these dimensions are appropriately dealt with to provide coherent and enriching user experience. Such a multi-dimensional approach ensures enhanced user engagement and that the assistance provided shall be both technically sound and contextually relevant.

There are some prospects of possible future improvement and development. First, related to fuzzy weights, it might not catch all the subtlety regarding users' computer and VR skills. Last but not least, even though the rule-based system will allow for user-tailored assistive messages, it might become very tough in case unexpected user behaviors or preferences happen, hence setting a boundary to the personalization and adaptation possibilities of the experience.

Future work includes how to integrate machine learning algorithms into SculptMate, so that it lets the system dynamically evolve from the users' interactions. It would further enhance the system in rendering the system with personalized assistive messages and improving the overall user experience. Additionally, we plan to extend the evaluation process by incorporating a broader set of questions, allowing for a more comprehensive analysis of user engagement and system effectiveness.

We also intend to augment audio components with ambient sounds, background music, and narration, making it more engaging for the user by eliciting a multi-sensory experience. Optimizing VR experience is also very important to ensure smooth performance on a wide variety of platforms and devices, like frame rate, rendering optimization, and file size, all toward trying to make things smooth for users with different hardware configurations.

Finally, a number of features, such as text size adjustment, audio description, and possibilities of different styles for interaction, are envisaged in order to make the VR experience of cultural heritage available for as wide a spectrum of users as possible. Very strong attention paid to inclusivity and accessibility will ensure that SculptMate can be used by people with different abilities and preferences. What is more, we will work out a reasoned scene design framework for 3D apps in order to make the process of scene development in an application more rational and hence of higher quality and more efficient. All of these new features will enrich the user experience even more and fit into the long-term development of SculptMate as a versatile and immersive platform for the exploration of VR cultural heritage.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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