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Integrating Augmented Reality and Geolocation for Outdoor Interactive Educational Experiences

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Abstract: This paper presents an augmented reality (AR) mobile application developed for Android devices, which brings five bust sculptures of historical personalities of the city of Komotini, Greece, to 'life' using the Unity engine. These busts narrate their achievements in two languages, Greek and English, to educate visitors on historical and cultural heritage and provide a comprehensive glimpse into the area's past using 3D models, textures, and animations tailored to the educational content. Based on the users' location, the application provides an interactive educational experience, allowing the users to explore the history and characteristics of the busts in an innovative way. The users may interact with the busts using markerless AR, discover information and historical facts about them, and stimulate their understanding of the busts' significance in the context of local history and culture. Interactive elements, such as videos and 3D animations, are incorporated to enrich the learning experience. A location-based knowledge quiz game was also developed for this purpose. The application was evaluated by statistical analysis to measure the effect of using the application on the involvement of users in the educational process and to study the users' satisfaction and experience. This approach revealed that the proposed AR app is effective in providing educational content, promotes active user participation, and provides a high level of user satisfaction.

Keywords: augmented reality; location-based AR; mobile application; educational AR; mobile learning; gamification

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1. Introduction

Augmented reality (AR) merges the real world with the digital world, adding information and interactive elements to the physical world through appropriate devices [1,2]. The most common access in AR content is through smartphones and tablets. These devices have cameras, GPS and other sensors, which are used to determine the user's position and location and add information about the objects or environments they may see. AR technology can be used in several fields, such as education, entertainment, e-commerce, human activity recognition, and industry, among others [3–7]. For example, AR can be used to create interactive educational experiences using 3D models and providing instructions for experiential activities [8]. In the field of entertainment, AR can be used to create games, applications, or virtual reality (VR) experiences [9].

Augmented reality may enhance employee productivity, efficiency, and safety by providing real-time instructions, identifying potential hazards, and enabling immersive virtual training environments [10]. Thus, AR may be used to change the way people interact with their surroundings. To this end, AR applications are expected to expand in the coming years, including more innovation steps and efficiency in the workplace [11]. Moreover, AR may also increase the levels of customer experience in e-commerce by providing detailed product information and offering personalized recommendations [12].

Also, in the field of cultural heritage, AR has been extensively studied over the past few years. This area explores how AR may be used to enhance the visitor experience at museums, historical sites, and cultural landmarks. By exploring the interactions between AR and historical museums, Tang and Zhou [13] considered factors such as the destination and context that influence the effectiveness of AR in cultural heritage. In recent years, research has focused on using AR to provide contextual information, visualizing historical reconstructions, and creating interactive storytelling experiences [14]. The main trends in the use of AR for cultural heritage may include 3D reconstruction and the representation of intangible cultural heritage, virtual museums, enhanced user experiences, and gamification. However, an active key point of research is to make cultural heritage accessible to a wider audience and to increase engagement with historical sites.

Furthermore, AR may be used as an educational tool for constant learning and knowledge acquisition. Several studies have examined how AR may be used to enhance student engagement, comprehension, and critical thinking skills [15,16]. Thus, it is important to incorporate AR technology in such a way as to positively impact learning outcomes. This way, we may boost student engagement, promote interactive experiences, and facilitate a better understanding of the subject matter.

The aim of this paper was to develop an AR educational application that focuses on the bust sculptures of the city of Komotini, Greece. This AR app improves the comprehension of historical content using interactive audiovisual cues. It effectively addresses the problem of distraction, ensuring focused learning. Also, it provides an interactive platform for users to better understand the history and define the traits of the busts in an enjoyable and engaging way. We aspire to tackle a primary challenge related to the passive nature of online searches and the subsequent potential distraction by providing an interactive experience, where the busts themselves narrate their history through the use of photogrammetry and 3D animation. Note that the lack of descriptive labels in traditional online resources is overcome by enabling real-time, contextualized learning using AR. Furthermore, the application enables users to interact with the busts, discover relevant historical information, and develop a stronger understanding of their role in the local history and culture.

In addition, challenges related to the development of AR educational applications include creating a user-friendly experience with accurate historical representations, as well as overcoming the issue of user distraction while learning. In this work, we addressed the challenges by utilizing AR technology to provide real-time, interactive engagement with the bust sculptures, allowing users to access detailed historical information directly from their interaction with the sculptures. The application incorporates an audiovisual context, such as 3D models, textures, 3D animations, and videos, to complement the educational content to attract the user's attention and facilitate active learning.

The intended audience for the proposed application includes students at secondary-level schools and undergraduate students, particularly those studying humanities, history, or cultural education and who may be interested in the local cultural heritage and history of the city of Komotini. More specifically, the application is designed to provide interactive features to the audience that want to explore historical figures and monuments through AR. Moreover, the application may be used by educators as a supplementary teaching tool to enhance classroom instruction. Although the AR app is also accessible to casual users and tourists, the structure and depth of the content are focused on users with basic-to-intermediate knowledge of historical information, which enables a targeted and effective educational experience.

The main contributions of this work can be summarized as follows:

- An interactive mobile and user-friendly AR educational application was developed with easy navigation and clear icons. This offers a novel approach for presenting historical content in an engaging and interactive way, contributing to the literature on 3D modeling and AR storytelling.
- The designed application effectively promotes learning, utilizing audiovisual educational content and quiz assessments that are accessible to users with different levels of skills and knowledge. To this end, this study contributes to the literature by exploring the use of AR technology to promote cognitive engagement of users and interactive learning.
- The limitations of traditional online resources, such as passive learning and lack of context-specific information, are addressed. Through using AR to provide contextualized learning, this study contributes to solving the challenge of user distraction in digital learning environments.
- A comprehensive assessment of the AR application's features, such as user experience, usability, satisfaction, and efficiency in delivering educational content, is deployed. This contributes to ongoing discussions in AR research on enhancing user experience and motivation in learning environments.

Moreover, this study contributes to the broader field of AR by providing useful information in developing applications using the Vuforia library [17]. It offers the technological implementation details of Vuforia's technical aspects, providing the developers with the necessary guidelines for constructing AR apps.

The remainder of this paper is organized as follows: In Section 2, a brief overview of the related work is presented. In Section 3, the designed AR educational application is described and the implementation details are given. The findings of our study regarding the evaluation of the AR app are presented and analyzed in Section 4. Finally, the paper conclusions are drawn in Section 5.

2. Related Work

Augmented reality has been proven to be a useful tool that augments real-world environments with interactive digital content that can be applied in several fields, such as education, healthcare, and entertainment. Especially for outdoor education purposes, AR has been employed to provide interactive and digital context-aware learning [18]. Extensive research in this field has demonstrated the effectiveness of AR to increase knowledge retention, while, at the same time, improving learning outcomes for a plethora of different subjects spanning cultural heritage education to history education and environmental awareness [19–21].

Recent studies have focused on integrating geolocation information with AR to further improve user involvement with real-time and location-based educational content. To this end, the work of Predescu and Mocanu [22] explored the combination of AR-based serious games' location data from the geographic information system (GIS) of users' devices to develop an immersive application for education, health, and urban planning. Their work also emphasized the ethical considerations of adopting these interactive technologies in education. Similarly, Lampropoulos et al. [23] examined the effectiveness of a combined AR app with gamification, object modeling, and discovery-based learning as a pedagogical tool in computer science education to increase imagination and creativity.

In recent years, advances in the use of AR technology in education have increased interactive learning by deploying 3D models and videos to traditional learning methods, such as textbooks and chalkboards [24]. The impact of AR on enhancing learning experiences using virtual content and 3D models to understand complex concepts was also studied by Tzima et al. [25]. The authors presented the problems, challenges, and opportunities in developing educational AR applications, and they also demonstrated the importance of AR visualization in increasing students' learning motivation. In the same spirit, Rodrigues and Pombo [26] analyzed the role of a mobile AR game for promoting education for sustainability among secondary students. The authors analyzed the effectiveness of this app in engaging students and enhancing learning experiences, particularly in terms of environmental awareness and sustainable practices.

AR, in particular, has the potential to create more engaging and effective learning experiences. To address challenges in AR interface development and improve the usability and impact of AR in education, special attention has been given to the role of user experience and interface design in AR educational applications [27]. This work explored the impact of AR on user experience to promote engagement, interactivity, and personalized learning, and it also investigated the best practices to propose effective and adaptable solutions for educational AR applications. The work of Lacoche [28] explored the validity of using VR simulations to evaluate AR applications in terms of usability and user experience. The results indicated minimal differences in user feedback and led to conclusions that VR simulations may be a viable alternative for assessing AR applications. Although VR simulations may streamline research time and reduce the waste of resources, further research needs to be done to confirm these results across different AR use cases. As revealed by Papakostas et al. [29], measuring the impact of AR applications based on factors such as learning engagement, user experience, usability, and interactivity may ensure better adaptability for learners.

Papaefthymiou et al. [30] proposed a novel methodology for creating life-sized AR digital characters and crowd simulations using mobile devices for efficient character transformations and realistic animations in cultural heritage environments. The proposed approach offered significant gains performance and interactivity. However, this approach may lead to a great reliance on specific software frameworks. Hendajani et al. [31] presented a 3D animation model and deployed AR techniques to improve the understanding of complex concepts of natural sciences education in elementary school students. Although their work showed that they increased student engagement with better visualization of scientific theories, the indoor classroom setting still posed great challenges in implementation. Finally, Afandi et al. [32] explored various AR models, such as 3D models, simulations, animations, video, and multimedia in learning complex content. However, the effectiveness of their approach may be limited by the detail of the visual quality of the graphics. An early example of incorporating historical heritage into education can be seen in the work of Quesada-Real et al. [33]. The authors explored using 3D-printed historical monuments to support learning in a Micro-Robotics course. While their approach focused on physical models and active learning strategies, our work builds upon this concept. It takes this idea further by visualizing culturally significant busts of classical figures using interactive, animated AR. Using interactive digital representations instead of tangible replicas allows for scalable, engaging, and contextually rich educational experiences.

Facing the challenges and opportunities of AR technology in education, Fu [34] proposed the use of 3D animation avatars of professional teachers to emphasize the potential of 5G-based AR in teaching when using immersive, intuitive, and interactive methods. However, the strong dependence on 5G network infrastructure may limit accessibility in areas with insufficient network coverage. Teplá et al. [35] studied the educational influence of AR using 3D models and animations on the intrinsic motivation and learning outcomes of students in natural sciences. Mobile AR applications have also been explored in neuroanatomy education by integrating interactive 3D models and addressing the challenges of learning complex concepts [36]. Although the findings demonstrated effective learning outcomes and high usability, the study sample size was limited.

A pilot study that implemented a mobile AR application to enhance structural analysis teaching by providing interactive 3D visualizations of structural members under different loading conditions showed that AR improved students' understanding of structural behavior, engagement, and retention [37]. The use of AR in mobile learning to present complex concepts in computer science showed that this technology may help students to visualize difficult concepts, leading to enhanced cognitive skills [38]. However, the effectiveness of these approaches in long-term knowledge retention and non-controlled environments remains unaddressed, especially in terms of cognitive load, cybersickness, equitable access, curriculum challenges, and instructional strategies.

Gamification in AR has been extensively studied, demonstrating its power to improve engagement, motivation, and learning outcomes using interactive 3D visualizations. In their work, Paliokas et al. [39] integrated AR and gamification techniques in museums to enhance visitor engagement, learning, and interaction by including interactive AR knowledge quiz games. Even though their method showed promising results for small-to-medium museums, improving navigation and content visualization with minimal distraction, heuristic violations affecting usability and challenges in maintaining the detection stability of AR markers was still not well covered. The role of user interface and user control in designing gamified AR experiences in chemistry education was studied by Lu et al. [40]. According to the work of Farooq et al. [41], AR gamification-based applications can be used to improve preschool children's learning engagement and performance. The findings of their research indicated that AR enhanced learning efficiency, effectiveness, and motivation, with positive feedback from both teachers and parents. However, challenges in usability and interface designing need yet to be addressed.

In light of these findings, AR technology in gamification and learning contexts enhances engagement, motivation, and social interaction while improving knowledge retention and user experience. However, concerns about privacy, accessibility, and long-term engagement must be addressed to optimize its effectiveness in educational and public settings. In their work, Noreikis et al. [42] developed a gamified AR experience and included an ARQuiz game to analyze user experience, engagement, and sociability based on survey and interview data. Their results reveal that AR gaming enhances visitor enjoyment, learning, and social interactions, though concerns about privacy and intrusiveness were noted. A flexible and remote learning AR app with parental control features and a game-based approach to improve students' performance in mathematics was also presented by Deng et al. [43]. By integrating multimedia elements, such as text, 3D graphics, and audiovisual information, the AR game enhanced learning and allowed students to practice math concepts in an entertaining and portable way. In recent years, AR applications in science and engineering education have also attracted researchers' interest [44,45]. For example, Hemme et al. [46] developed several virtual and augmented reality applications to teach biomedical science concepts using intuitive interfaces and 3D models to increase performance in learning without the need for wearing heavy headsets. The proposed apps have been positively received and integrated into curricula, with user feedback helping to improve the experience.

Memory retention refers to the ability of a person to recall previously acquired content and information. This process can be improved through AR-based learning because it offers an enhanced learning experience and visual representation of content [47,48]. Augmented reality exhibits a significant positive correlation between knowledge retention, engagement, and AR training modules by aligning with well-established cognitive science principles. It has been proven that it may emphasize the capability of immersive technologies to improve learning outcomes [49]. Geana et al. [50] showed that AR may efficiently provide a meaningful learning experience and promote information retention. The authors used different experiment setups, including eye tracking and video monitoring, and they demonstrated that AR was effective in increasing topic-related knowledge retention.

Also, virtual replicas of physical systems, which are commonly known as digital twins, are being used in virtual training environments, such as serious games, to create immersive, interactive simulations that enhance learning and skill development. In this context, the work of Luther et al. [51] presented a taxonomy of virtual museums in terms of the digital twins of physical museums, and it also provided valuable insights into how this technology may be used in the field of cultural heritage in a comprehensible manner. In [52], an interesting work was presented that explored the use of digital twins in the heritage construction sector. Technologies such as 3D scanning, virtual reality, heritage building information models, and the internet of things (IoT) were examined to highlight the opportunities and challenges in cross-cutting professions spanning energy, digital technology, and citizen engagement. Finally, Bevilacqua et al. [53] created immersive, interactive 3D environments to explore how the digital twins of virtual and augmented reality enhance the experience and understanding of cultural heritage in historical sites in Italy. The results demonstrate that digital twins may revive architectural heritage and support visitor engagement. The concept of digital twins provides a foundational reference for this work. By adopting this framework, the current application creates immersive digital replicas of the busts. To this end, we enable the users to interact with historically significant artifacts in an augmented environment. This approach aligns with the principles of digital twin technology and also justifies its application in enhancing cultural heritage in education using AR.

The contributions of this work lie in developing an interactive AR educational application focused on the bust sculptures of Komotini, Greece, which enhances learning through interactive 3D models, audiovisual content, and quiz assessments. To the best of our knowledge, this is the first time such an AR application has been developed to present the cultural heritage, specifically the bust sculptures, of the city of Komotini using dynamic, animated 3D models. Unlike traditional online resources in the literature [54–57], the proposed AR application addresses issues such as passive learning and distraction by providing real-time, contextualized, and engaging historical content. The proposed AR application also differs from the existing literature through using photogrammetry and 3D animation to enable real-time, interactive learning with historical context. In contrast to previous works, which integrate AR with geolocation or gamification for educational purposes, the proposed AR app emphasizes active learning through interaction with physical artifacts, thus bridging the gap between passive online resources and engaging, hands-on educational experiences.

It becomes apparent that although AR has been raised to be a transformative tool across multiple domains, the potential in using AR technology for improving engagement and knowledge retention is evident. Challenges such as accessibility issues, satisfaction, usability, educational usefulness, and maintaining long-term user engagement require further investigation.

3. Materials and Methods

This work aspires to present an approach that utilizes a range of AR technologies, geolocation, and photogrammetry to promote the history of statue busts of the city of Komotini, Greece, by bringing these busts to "life". The application works on Android devices and has an easy and understandable design to be utilized by users of various educational levels and skills. The user may also test their knowledge through a quiz game that is relevant to the corresponding busts. Finally, the user is given the opportunity to share, on social networks, the photos they have taken by clicking the option to take a photo through the application.

Note that the application was developed for Android because it allows for better performance, optimized use of device-specific features, and greater control over hardware resources. We chose to use such an approach to ensure a more responsive user experience, faster processing, and easier debugging as there is a wider range of native libraries and SDKs that are specifically designed for AR functionality. Additionally, Android is positioned as the leading mobile operating system worldwide, especially among our intended target users. This makes Android a practical choice for initial deployment. Nonetheless, we recognize the importance of platform independence and, in the future, we may explore several cross-platform frameworks to extend accessibility to iOS and/or web-based users.

This study consists of three main modules. The first module is to identify the historical statue busts that can be part of application scenarios. The second module corresponds to designing and developing the AR applications. This also includes techniques for developing high-fidelity 3D models of the busts by capturing images from multiple angles. Finally, the third module corresponds to testing and evaluating the proposed approach.

3.1. Selection of Historical Statue Busts

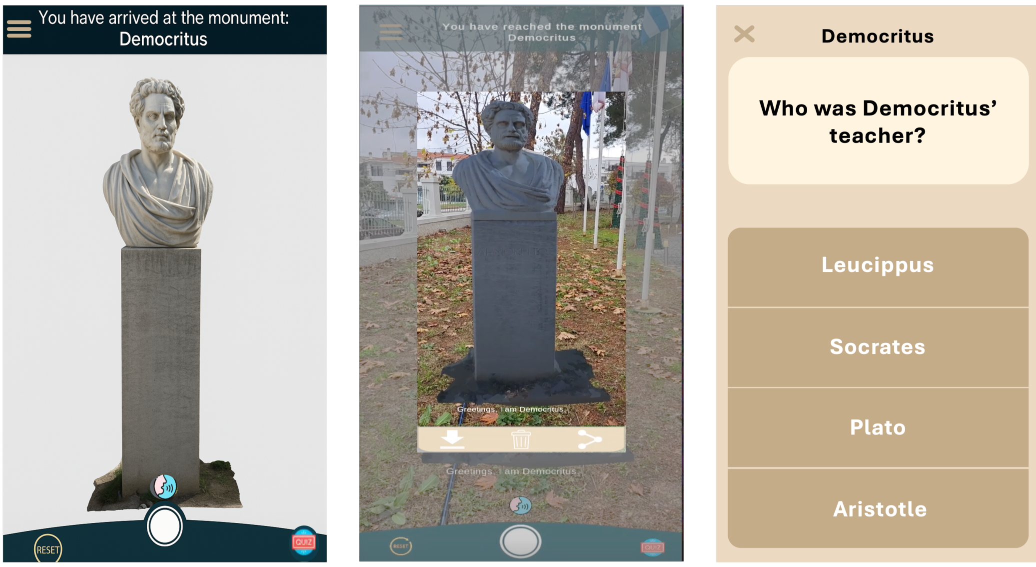
The proposed AR application includes the bust sculptures of Alexandros Symeonides, Georgios Vizyenos, Democritus, Konstantinos Kanaris, and Stilpon Kyriakides. We selected these historical busts because of their significant cultural, historical, and educational value, as well as due to their notable contributions in their respective fields. Each of these historical persons hold a prominent place in Greek history and culture. For example, Democritus is considered one of the key figures in philosophy, who is commonly known for his work on atomic theory. Georgios Vizyenos contributed significantly to the development of modern Greek literature. Alexandros Symeonides was a famous historian who played a vital role in contributing to the cultural legacy of Greece. Konstantinos Kanaris is considered to be a national hero as he was one of the key figures in the Greek War of Independence. Finally, Stilpon Kyriakides is known for his achievements in athletics, particularly for his triumph in the Boston Marathon.

By including these busts in the proposed AR app, we allow the users to explore the lives and legacies of these historical figures in an interactive way. Each bust represents important periods in Greek history in domains such as philosophy, literature, politics, and sports. Also, these historical figures are widely recognized, both locally and internationally, for their achievements to their respective fields. The selection of these busts was also influenced by the availability of adequate historical content and resources to develop accurate and informative 3D representations.

We aspire that, by including these busts, the proposed AR application may provide an immersive and educational content to promote Greek heritage. Their recognition and impact in Greek and international culture constitutes them as promising subjects for a wide range of users, spanning from students to history enthusiasts.

3.2. AR Application Design

When the application is launched, the camera of the mobile device begins searching for a nearby bust to locate. For user convenience, when the user approaches a bust, but it has not yet been detected by the camera, a message will appear on the screen stating, "You have arrived at the monument: [*Name of the Bust*]", based on the user's geographical position. Similarly, when the user moves away from the bust, a message will display "You have left the location of the bust: [*Name of the Bust*]". When the application successfully detects the bust through the mobile camera, a three-dimensional animation depicting a 3D reconstruction of the corresponding bust is triggered, which is superimposed on the bust, as illustrated in Figure 1a. Note that this animation provides motion and speech to the bust. Also, when the user activates the 3D augmentation feature, several options are presented, including the ability to start or stop the animation and speech. Additionally, there is a reset option that removes the current augmentation and causes the bust's 3D representation to reappear. The reset option is crucial in cases where the 3D augmentation does not align correctly or appears in the wrong location as the user cannot restore the 3D model manually. The aforementioned options are accessible only after the bust has been successfully detected by the mobile camera.



(**a**) (**b**) (**c**)

Figure 1. (**a**) Example of the bust 3D reconstruction, representing the bust sculpture of Democritus. (**b**) Example of the screen photo option. (**c**) An instance of the quiz game, as displayed to the user.

At the bottom of the screen, there are options to take a photo and access the quiz game, as illustrated in Figure 1a. The "Take Photo" option allows users to capture an image of the scene in front of them, including the 3D augmentation. After taking a photo, a new window pops up displaying the captured image. A mock-up figure is depicted in Figure 1b. At the bottom of this window, there are three more options: (i) "Download Photo", (ii) "Delete Photo", and (iii) "Share". The "Download Photo" option allows users to save the photo to their mobile gallery, and the "Delete Photo" option allows them to remove the photo. Finally, the "Share" option opens the device's notification interface, where the user may share the photo on different social media platforms. This includes options, such as posting to Facebook, sending via Messenger, Viber, WhatsApp, or emailing the photo.

In the "Quiz" option, questions related to all the busts supported by the application are presented to the user. Each question is accompanied by four possible answers, with one being correct, as illustrated in Figure 1c. If the user selects an incorrect answer, an error message is displayed and the user is not allowed to proceed to the next question. By selecting the correct answer, the application allows the user to proceed to the next question. Once the quiz is completed, a success message is displayed, providing options to either retake the quiz or return to the home screen. Note that the AR application shows only questions related to the recognized bust when the user is near to this specific bust sculpture. The quiz questions are retrieved from a server, allowing the administrator to modify or add new questions directly on the server. These updates can be made without requiring any user intervention, such as updating the application. A diagram of the application architecture is displayed in Figure 2.

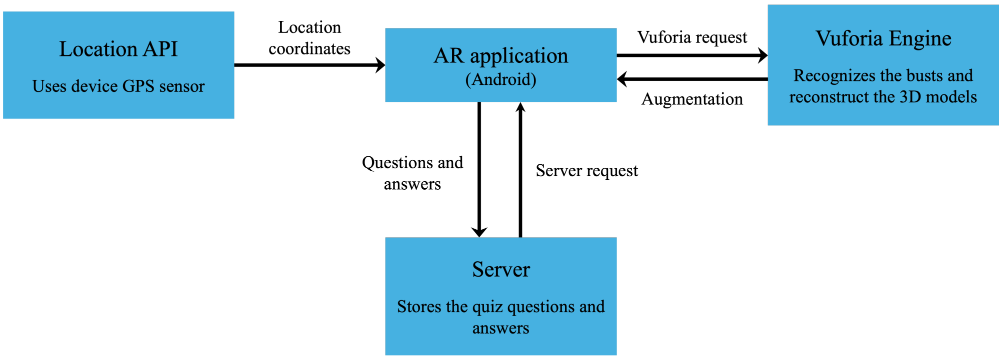


Figure 2. The proposed AR application architecture diagram. The diagram illustrates the flow of the AR application, showing how questions are selected based on the user's proximity to a bust. It also shows the process of retrieving quiz data from the server, enabling dynamic updates without requiring user intervention.

In the context of historical content presentation, the AR application can bring static busts to "life", that is, using 3D modeling, users may interact with and explore historical figures who narrate, through audio, their own life stories and make their historical life events more tangible and relatable to the public.

Also, the quiz game adapts according to the levels of knowledge or skills of the users. First, the total number of attempts by the user is calculated, including correct and incorrect answers. Then, the success rate is calculated based on the number of correct answers and the total number of attempts. The AR application displays the evaluation window and calculates the earned stars based on the success rate. The responsible script is called with the success rate and, depending on the range to which the rate belongs, it displays a text and the corresponding number of stars. In case the success rate does not belong to any of the defined ranges, the message "Good Try!" is displayed. According to the users' success rate in each quiz, a dynamic pool of questions is retrieved according to the answers and the success rate of the user. For instance, if a user has answered questions correctly and shown an understanding of earlier concepts, the next bust includes more advanced information or a more challenging quiz.

For a broad understanding of the proposed AR system, Figure 3 shows a high-level representation of each stage of the proposed approach in a form of a use-case diagram. The user can interact with the system in the following four options: (i) detect a preferable bust with the mobile phone camera, (ii) take a photo and save it to the system, (iii) take a quiz game, and (iv) use the SideMenu to interact with the application, where the user may change language to Greek and English or exit the application.

3.3. 3D Model Creation

For the creation of the 3D representation of each bust sculpture, we applied photogrammetry techniques, where multiple images with at least 40% overlap of the underlying bust were captured from different angles and processed into a 3D representation using the RealityScan application [58].

First, we need to describe how the 3D points in the real world are projected onto 2D image planes based on the assumption that the cameras can be approximated by the pinhole camera model. This transformation is described by the following equation:

$$s \cdot \mathbf{x}' = \mathbf{M} \cdot [\mathbf{R}|\mathbf{t}] \cdot \mathbf{X}\,, \quad (1)$$

where s is a scaling factor; $\mathbf{x}'$ represents a 2D image point; $\mathbf{M}$ is the intrinsic camera matrix; $[\mathbf{R}|\mathbf{t}]$ encodes the camera rigid transformation parameters, such as rotation $\mathbf{R}$ and translation $\mathbf{t}$, which define the relative motion between images; and, finally, $\mathbf{X}$ is the original 3D point.

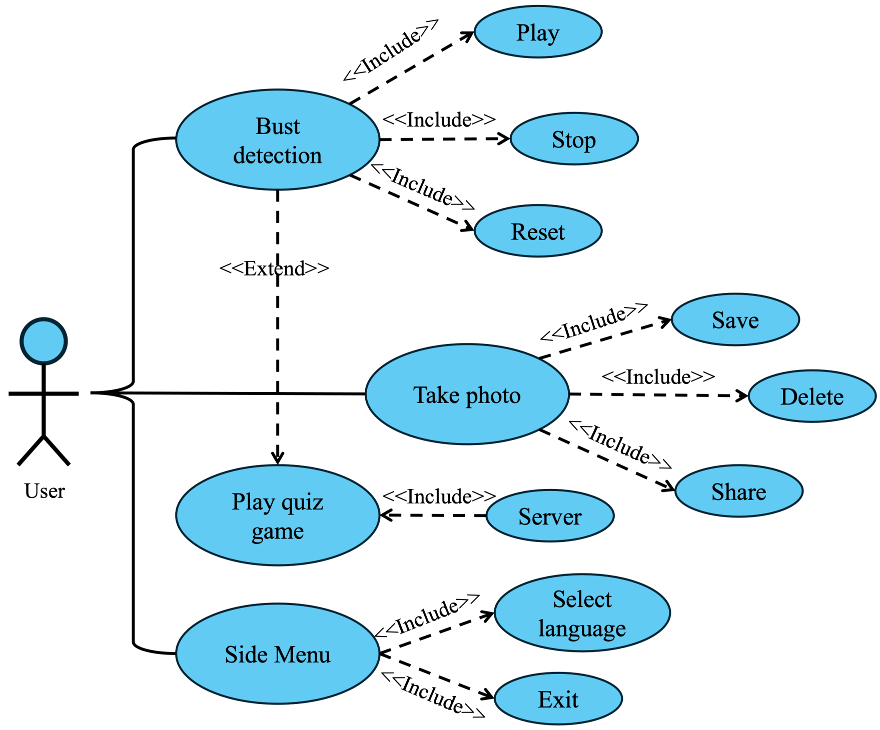


Figure 3. Use-case diagram of the AR application.

By capturing images from multiple angles with a respective overlap of at least 40%, we may reconstruct the spatial relationship between these points to ensure that the corresponding points in different images align along an epipolar line with the following equation:

$$\mathbf{x_2}^T \mathbf{F} \mathbf{x_1} = 0\,, \tag{2}$$

where $\mathbf{x_1}$ and $\mathbf{x_2}$ are the corresponding feature points in two different images, and $\mathbf{F}$ is the 3×3 fundamental matrix that relates the corresponding points in stereo images.

Thus, the relative motion between two images and the depth are estimated using the scale-invariant feature transform (SIFT) [59] algorithm to detect a set of key points in the images. SIFT generates a 128-dimensional descriptor through a four-stage process: (i) identifying scale-space extrema, (ii) precisely localizing keypoints; (iii) assigning an orientation to each keypoint; and (iv) generating the final descriptor. This process results in features that are significantly more robust than traditional key point features, allowing for reliable detection in low-resolution images even when subjected to rotation, scale changes, noise, varying illumination, and different viewpoints.

After having determined the camera motion, the 3D positions of the matched feature points are estimated by triangulating points from multiple images $\mathbf{x_1}$ and $\mathbf{x_2}$ and are then solved for depth values using the following projections:

$$\mathbf{X} = \lambda_1 \mathbf{P}_1^{-1} \mathbf{x_1} = \lambda_2 \mathbf{P}_2^{-1} \mathbf{x_2}\,, \tag{3}$$

where $\mathbf{P}_1$ and $\mathbf{P}_2$ are the projection matrices for two camera positions, and λ_1 and λ_2 are the depth parameters. The generated 3D point cloud is converted into a 3D mesh using the Delaunay triangulation algorithm [60]. Bundle adjustment is also employed to optimize the camera poses and the 3D point coordinates simultaneously and to minimize the reprojection error. Finally, texture mapping is applied using UV mapping to increase the visual realism of the model by projecting images onto the reconstructed surface.

For optimal results, the scanned bust should be placed in a well-lit environment. Note that, during image capturing, previously taken images are displayed on the screen to prevent redundant captures. If an image is not captured correctly, RealityScan identifies the erroneous image and indicates the precise location where it was taken, allowing the user to retake it. If the final model is satisfactory and requires no further modifications, such as the removal of extraneous elements (e.g., background trees or buildings), it can be refined accordingly. The final model is then exported to Sketchfab. Subsequently, the 3D model can be downloaded directly from the Sketchfab platform.

3.4. Aligning the 3D Models onto the Real World

Having created the 3D models, we may use the Vuforia Model Target Generator (MTG) to create model targets for the proposed AR application. The model target may be seen as an object-based AR feature, where the digital content is superimposed onto the reconstructed 3D model, and it is then tracked and recognized by the AR system. From the Model Up Vector tab, we confirm that the 3D orientation is correct with respect to the X, Y, and Z axes. In the case that something is not correct, a change is made from the right options, as shown in Figure 4.

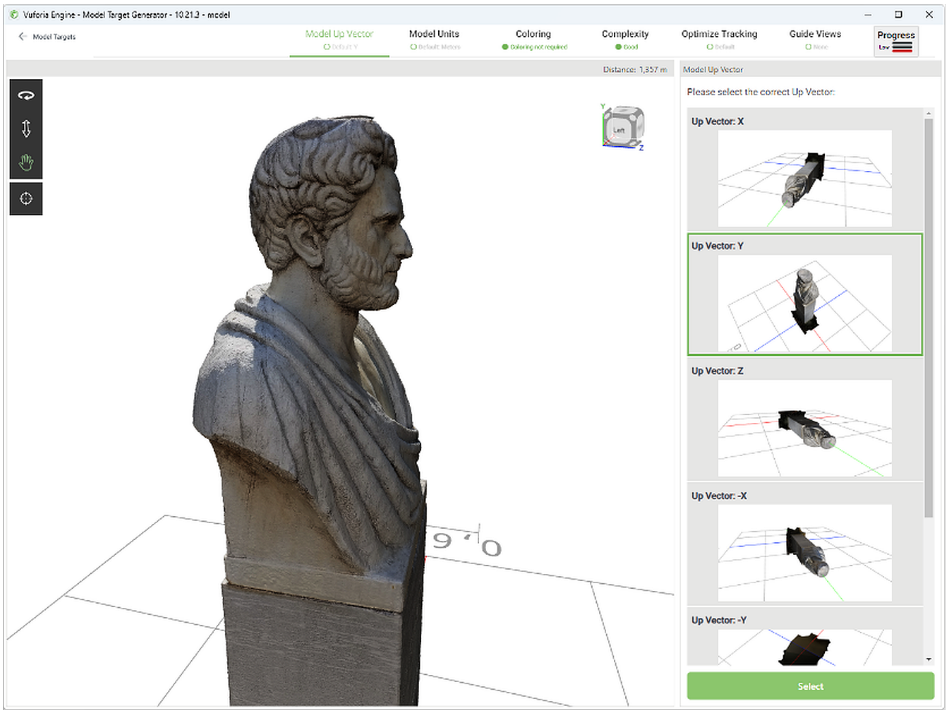


Figure 4. Example of the Vuforia model target generator model up vector.

Note that RealityScan employs photogrammetry to reconstruct a 3D mesh from a series of multi-view images of the physical bust. To ensure optimal alignment, the bust was photographed on a sunny day to maximize the clarity and consistency of image captures. Also, RealityScan provides real-time feedback by displaying previously captured viewpoints. This allows us to retain the surface coverage and avoid redundant or low-quality inputs. Finally, after reconstruction, the 3D model was visually inspected to verify geometric coherence. For the alignment process, the reconstructed models were uploaded to Sketchfab and subsequently used in the MTG. This allows us to perform a precise positioning of the 3D model onto a real-world reference by overlaying the virtual mesh onto the physical bust using predefined guide views. During testing, the model alignment with the physical object was monitored visually, and misalignments were adjusted by refining the Model Target's bounding box and field of view settings.

To mitigate AR visualization rendering errors, the following features were enabled in MTG: "Extended Tracking" and "Consider Target as Visible If Status". These options were used to maintain the model's stability in cases where the target may temporarily exit the camera's field of view and thus ensure that the overlay remains in place once realignment occurs.

Using the Coloring tab, it is recommended that the imported 3D models that consist of many parts and do not include a texture or multiple colors can be automatically colored by the MTG. Note that coloring the different parts of a model can help improve tracking performance. Models that consist of a single mesh receive only one color and, therefore, tracking cannot properly improved. Models with textures do not need coloring; meanwhile, assuming that the texture represents the physical object, we select the setting 'Realistic appearance' before proceeding to the next step.

The Complexity tab calculates the complexity of the 3D model, which should be below a certain number of vertices. Specifically, it should be a maximum of 400,000 triangles, as any number above this limit may affect smooth operation and efficient processing. Also, the maximum number of 3D segments recommended is 20. Using more segments may result in poor processing performance and make tracking more difficult. The recommended number of textures is 5. Using many textures may affect performance and processing time. However, in the case that the 3D model exceeds these numbers, MTG provides the option to simplify the model. In the case that we do not wish to perform any related simplification of the 3D model, we are given the option continue without simplification.

The Optimize Tracking tab allows us to select an optimization function for tracking the 3D model. The selection of the appropriate function depends on the physical object and its use. The default option works well for most 3D models. Finally, in the Guide View tab, tracking of the 3D model can be initiated. Here, a guide view is created and displays a transparent outline of the 3D model, where users must align with the physical object in the real world to activate the AR experience. Furthermore, when creating the guide view, the field of view must be defined based on how users are expected to hold the device. The available configurations include (i) digital wearable glasses, (ii) horizontal view, or (iii) vertical view. This setting can also be selected through the three icons located in the upper right corner of the 3D viewer window. Depending on the selection, the dotted line within the 3D viewer window adjusts the application's display area on the screen.

3.5. Scene Representation

The application consists of a scene where the quiz is located, and all of the actions are performed from this scene. The layout of the screen, as it appears in Unity, is shown in Figure 5. To create the application, we had to make sure that the Vuforia extension was installed in Unity and that we had already created the 3D material so that the application could recognize it and display the AR content on them.

The device screen only shows the objects that appear inside the white frame. The following settings are set in the canvas scaler menu to ensure the best resolution for the application:

- UI scale mode: Scale with the screen size to work with most device screens.
- Reference resolution: 1080 × 1920.

- Screen match mode: Match width or height depending on the screen to adjust the height and width of each object in the scene.

Figure 5. Creating the initial scene in Unity.

To insert a 3D model in the scene, we created a new model target object from the Vuforia library. The model target object is accompanied by two scripts that allows us to display the 3D model. The first script is the model target behavior, where, with the database option, we select the database that contains our 3D model. This action assumes that we have imported, into our project, the files created by the previous Vuforia MTG application. Next, we selected the desired 3D model and set the size of the corresponding object in the physical world. The default observer event handler script is responsible for providing feedback when a 3D model has been detected or when the device camera or GPS sensor cannot detect the underlying bust. This is useful so we can project the 3D animation onto the real-world bust sculpture. Furthermore, the 'Consider target as visible if it has status' option enables the system to retain the coordinates where the initial bust detection occurred, even after the target is temporarily lost. This functionality facilitates a quick re-detection of the 3D model, ensuring that the model will remain in the scene even when it is not directly visible in the camera's field of view. Figure 6 depicts the location of the model target object in the scene when it is aligned with the original 3D model.

The AR application relies on the device's GPS sensors to track the user's location and detect nearby bust sculptures. However, this feature may pose a predominant dependence on an internet connection and external positioning data for accurate functionality. Thus, the application may face challenges when operating offline as real-time location tracking would be limited without internet access. To cope with this challenge, we allow the core AR features, i.e., displaying 3D models and the interactive quizzes, to work offline by preloading all the necessary data onto the device. Note that the scope of the AR application is specifically designed for outdoor environments, where the busts are usually located, and the GPS signals are typically strong and reliable for location tracking. However, the app is not optimized for indoor environments, where GPS signals may be weak or distorted. In such cases, alternative positioning technologies, such as Bluetooth low-energy beacons or Wi-Fi-based positioning, should be considered to provide accurate location tracking in indoor environments.

To provide a clearer visual representation of the user experience and interaction with the AR application, the flowchart of the proposed AR app was illustrated, as shown in Figure 7.

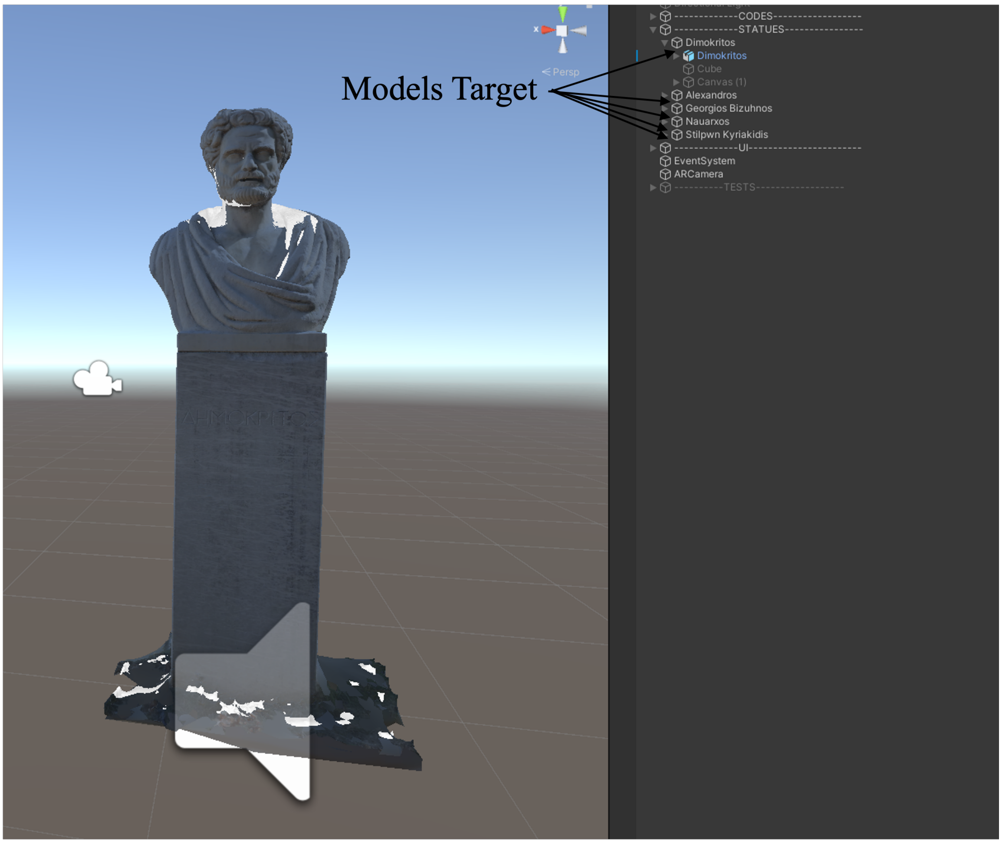


Figure 6. Example of a model target object aligned with the 3D model.

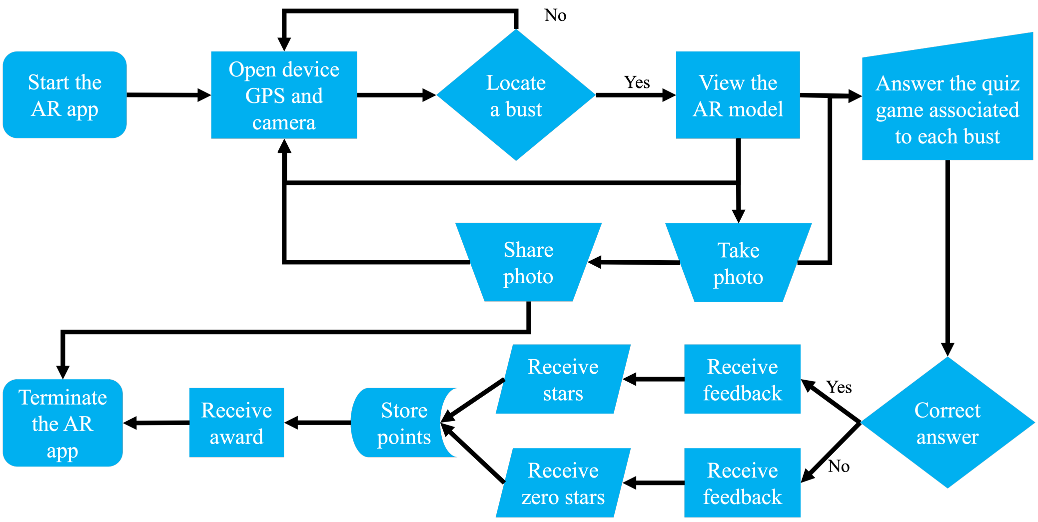


Figure 7. Flow chart diagram of the AR application.

4. Evaluation and Discussion

To evaluate the alignment of the reconstructed 3D model onto the real 2D image that corresponds to the bust sculpture, we computed the mean reprojection error (MRE). This compares the projected points of size N of the 3D model onto the image plane with the corresponding original feature points detected in the input images, and it is computed as follows:

$$MRE = \frac{1}{N} \sum_{i=1}^{N} \| p_i - \mathbf{M}[R|t] P_i \| \,, \tag{4}$$

where p_i is the observed 2D feature points, P_i is the corresponding 3D points, $\mathbf{M}$ corresponds to the intrinsic camera matrix, and $[R|t]$ is the estimated extrinsic (i.e., rotation and translation) parameters. The corresponding MRE is shown in Table 1. Lower MRE values indicate better alignment. The results indicate that the achieved alignment between the reconstructed 3D points and their corresponding 2D projections is of good fidelity. However, slight misalignments may be visible in high-detail models, mainly because of mismatches in the SIFT key points and inconsistent lighting in outdoor environments.

Table 1. A mean reprojection error in pixels for a pairwise relationship estimation between the 3D points of each bust aligns with their corresponding 2D projections in the input images. The downwards arrow denotes the smaller MRE value the better.

3D Model	MRE (Pixels) ↓
Alexandros Symeonides	0.44323
Georgios Vizyenos	0.46245
Democritus	0.48631
Konstantinos Kanaris	0.45881
Stilpon Kyriakides	0.49152

To evaluate the AR application and analyze the objectives of this study, a self-administered questionnaire that consists of 16 seven-point Likert scale items was developed, ranging from one (corresponding to strongly disagree) to seven (corresponding to strongly agree). The questionnaire is presented in Appendix A. The questionnaire was delivered to 40 adult subjects of different age groups, from whom 29 were male and 11 were female, as shown in Figure 8. The AR application was presented, and participants had the opportunity to interact with it. Afterward, the participants were asked to complete an anonymous questionnaire, and each question was rated on a range of one to seven, with one corresponding to strongly disagree and seven standing for strongly agree. Participants provided their feedback about the AR experience, the usability, their satisfaction, the visual quality of the application, and the educational usefulness they achieved. To protect the personal data of the participants, all of the collected data were fully anonymized by removing any personally identifiable information prior to analysis. We ensured the anonymity and confidentiality of the data as the management of personal matters was performed with absolute discretion, ensuring that the information remained confidential. The data were stored securely on a password-protected server accessible only to authorized members of the research team. In addition, participants were informed, both verbally and in writing, that any anonymous data collected for the purposes of this study would be accessible exclusively to the researchers involved, with external access being strictly restricted and prohibited.

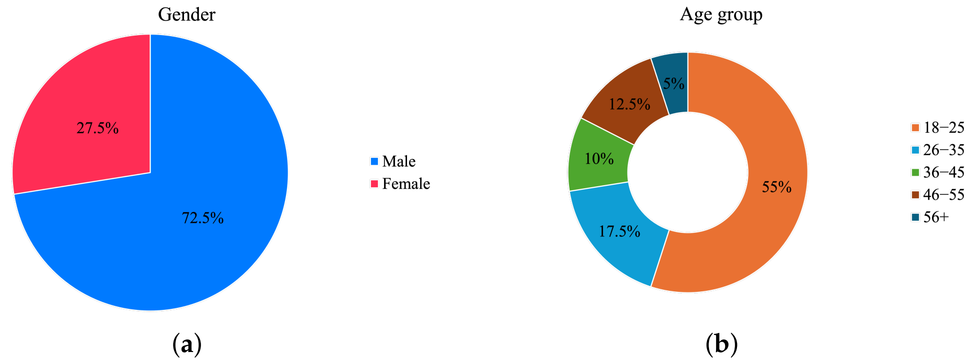


Figure 8. The (**a**) gender and (**b**) age-group distribution of the participants.

The level of education of the participants is depicted in Figure 9a. The vast majority of the participants, 87.5%, had a higher level of education i.e., possessed undergraduate, Master's, or PhD degrees. Only 12.5% had a Lyceum degree, which stands for the last three grades of secondary education. We may highlight that the majority of participants had a high level of education, with 60% holding an undergraduate degree and 25% holding a master's degree. This might indicate a potential bias toward participants who are more familiar with academic content, which might influence their interaction with the app and their learning outcomes as higher education levels are related to stronger problem-solving abilities or a better ability to understand complex content. Thus, the participants with an undergraduate degree or higher may have interacted more actively with the AR application and had a better performance in the displayed quizzes. The age range of these participants was above 50 years old. Also, Figure 9b illustrates the levels of the familiarity of the participants with relevant AR applications prior to using the proposed AR app. The majority of participants, 92.5%, had seen or used augmented reality applications, suggesting that AR is becoming increasingly popular and accessible to the general public. A significant portion (i.e., 57.5%) reported being "very familiar" or "expert" with AR, which may have improved their interaction with the AR app. Prior experience with AR may have also helped some of the users explore advanced features and increase their overall interaction time and satisfaction with the AR app compared to participants who were less familiar with AR. On the other hand, the small group of participants who were unfamiliar with AR may have faced difficulties in navigating the interface, which may have led to a steeper learning curve.

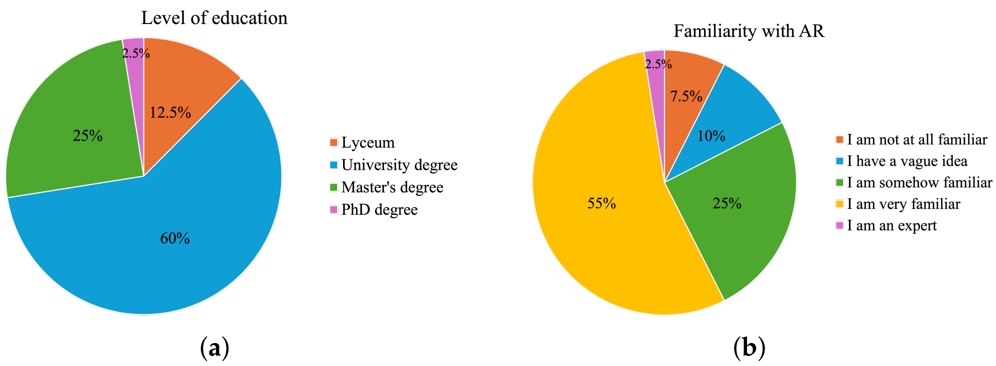


Figure 9. (**a**) Level of education and (**b**) familiarity with AR technologies.

As shown in Table 2 the mean values, standard deviation, 95% confidence intervals, and the standardized coefficients of the questionnaire items are presented. Based on the results, the users left with a high feeling of AR experience (M = 6.03, std = 0.82) and satisfaction (M = 6.19, std = 0.92). Although the immersion feeling were moderate (M = 5.48, std = 0.75), the overall AR experience was positively rated, with users appreciating its pleasant usability and the realistic quality of the graphics. It is important to note that the users would highly recommend the AR application to others as the underlying question had a mean score of 6.85 and a standard deviation of 0.36. This indicates intense feelings of acceptance and satisfaction from the users. Also, moderate-to-high levels of usability were achieved by the users' preferences (M = 5.97, std = 1.32). The visual quality of the graphics and the 3D models also achieved high scores and contributed to an engaging user experience (M = 6.46, std = 0.88). Finally, the educational usefulness of the AR application also achieved high scores (M = 6.03, std = 1.04), indicating a high impact on learning engagement and knowledge acquisition of the history that the bust sculptures represented. However, Q14 received moderate ratings from the participants (M = 5.45, std = 1.13), which demonstrates that, although the quiz might be seen as an effective tool for understanding the content, there may be space for improvement in terms of challenge level or engagement to increase user satisfaction.

Table 2. Evaluation of the questionnaire measuring the AR experience, usability, user satisfaction, visual quality, and educational usefulness.

	Mean Scores	Standard Deviation	CI (95%)	Standardized Coefficients
AR experience				
Q1. I had a pleasant experience with the AR app.	6.15	0.89	5.87–6.43	0.95
Q2. I felt immersed while using the AR application.	5.48	0.75	5.24–5.71	2.03
Q3. The AR elements feel realistic and well integrated into the real world.	6.48	0.82	6.22–6.73	0.64
Usability				
Q4. I found the AR app useful.	5.90	1.28	5.50–6.30	0.86
Q5. I found the AR interface easy to navigate.	5.88	1.57	5.39–6.36	0.72
Q6. I easily found the information I needed.	6.13	1.11	5.78–6.47	0.79
Satisfaction				
Q7. I am satisfied with the overall AR experience.	5.80	1.18	5.43–6.17	1.02
Q8. I would recommend using this AR experience to others.	6.85	0.36	6.74–6.96	0.41
Q9. I would use this AR application again.	5.93	1.21	5.55–6.30	0.89
Visual quality				
Q10. The AR objects were clearly visible and of high quality.	6.70	0.61	6.51–6.89	0.49
Q11. The visual alignment between the virtual 3D object and real-world objects was accurate.	6.23	1.14	5.87–6.58	0.68
Educational usefulness				
Q12. I learned about the history of the Komotini busts from the app better compared to traditional learning methods.	5.98	1.17	5.61–6.34	0.88
Q13. The information presented in the AR application was clear and easy to understand.	5.78	1.21	5.40–6.15	1.01
Q14. The AR app was helpful in understanding the information it provided me.	6.30	1.02	5.98–6.62	0.69
Q15. The quiz was useful in assessing my knowledge of the subject.	5.45	1.13	5.10–5.80	1.37
Q16. The quiz questions align with the educational content provided in the AR application.	6.63	0.67	6.42–6.83	0.56

To measure the relationships between the different factors, such as experience, usability, levels of satisfaction, visual quality of the 3D graphics, and educational usefulness, we computed Pearson's r correlation coefficient. The results are shown in Table 3. As may be observed, there was a moderate-to-high correlation between the user AR experience and factors such as usability, satisfaction, and educational usefulness. Users were more likely to perceive a better AR experience because they could navigate and interact with the app easily, and their satisfaction was also high, indicating that they tended to rate the AR app positively. Nevertheless, small and moderate correlations occurred between the visual quality of the 3D graphics with the rest of the factors, indicating that the visual quality of the 3D graphics has a moderate influence on these factors and is influenced by additional elements beyond just graphical fidelity. However, other factors, such as usability, experience, and educational usefulness, may also play significant roles in explaining the overall perception. Analyzing the usability across distinct user segments, such as digital natives versus older adults, would provide valuable insights into interaction patterns and accessibility. However, this level of segmentation and comparative analysis falls outside the scope of the current study, which was primarily aimed at evaluating the overall usability within a general user population. It is important to note that, for all relationships, the p-value was < 0.001, indicating that the observed correlations were statistically significant. This means there is a low probability that the relationships between the different factors may have occurred by chance, also supporting the argument that these factors play a meaningful role in enhancing the user experience and satisfaction.

Table 3. Pearson's r correlation analysis, showing the strength, direction, and statistical significance of the relationship between the different factors.

		AR Experience	**Usability**	**Satisfaction**	**Visual Quality**	**Educational Usefulness**
AR Experience	Cor. Coe.	1.000	0.719	0.777	0.345	0.891
	p-value	-	<0.001 **	<0.001 **	<0.001 **	<0.001 **
	N	40	40	40	40	40
Usability	Cor. Coe.	0.719	1.000	0.770	0.606	0.774
	p-value	<0.001 **	-	<0.001 **	<0.001 **	<0.001 **
	N	40	40	40	40	40
Satisfaction	Cor. Coe.	0.777	0.770	1.000	0.435	0.798
	p-value	<0.001 **	<0.001 **	-	<0.001 **	<0.001 **
	N	40	40	40	40	40
Visual quality	Cor. Coe.	0.345	0.606	0.435	1.000	0.553
	p-value	<0.001 **	<0.001 **	<0.001 **	-	<0.001 **
	N	40	40	40	40	40
Educational usefulness	Cor. Coe.	0.891	0.774	0.798	0.553	1.000
	p-value	<0.001 **	<0.001 **	<0.001 **	<0.001 **	-
	N	40	40	40	40	40

** Correlation is significant at the $p < 0.05$ level (two-tailed).

All subjects indicated that they acquired new knowledge about the Komotini busts using the proposed AR application. This finding highlights the educational value of AR and demonstrates its effectiveness in providing useful information. Furthermore, these findings confirm that the proposed AR application allows for easy integration of historical knowledge related to the underlying busts.

Also, the users reported that their interaction with the proposed AR application enhanced their interest in the history of the busts and motivated them to search for additional information. This suggests that the AR app may positively influence user engagement in education.

Finally, as may be observed, the user satisfaction was high, with the majority of the participants reporting that they would recommend this app to others. The proposed AR application attracted the interest of uses of various age groups, sex, and education levels, and it effectively met their expectations. Overall, the questionnaire responses suggest that the proposed AR app is effective in delivering educational content, achieving a high level of user satisfaction.

5. Conclusions

In this study, we developed an educational AR application based on the user's location to increase users' engagement and understanding of the history of the bust sculptures of the city of Komotini in Greece. The AR application is easy to install and has a user-friendly interface, which makes it an accessible educational tool. Also, the proposed AR application demonstrated its effectiveness in enhancing user experience, learning, and knowledge retention through interactive 3D visualizations and educational quizzes. The moderate-to-high scores for educational value, graphical realism, and usability demonstrate its potential as a valuable learning tool. The application also achieved moderate-to-high scores regarding its educational usefulness, and it shows that it may be used to reinforce users' understanding about local history and culture. Overall, the proposed application integrated AR technology to provide a satisfying and educational experience and enhanced user interaction.

The results provide quantitative support of the effectiveness and educational value of the developed AR application. The Pearson's r correlation analysis revealed statistically significant relationships ($p < 0.00001$) between the AR experience and factors such as usability ($r = 0.719$), user satisfaction ($r = 0.777$), and educational usefulness ($r = 0.891$), indicating that users who perceived a more positive experience using the AR app also rated the app as easy to use and navigate, satisfying, and educationally valuable. The usability, satisfaction, and educational usefulness evaluation items revealed moderate-to-high positive correlations with the user AR experience. These findings reinforce the claim that users found the AR application accessible and enjoyable to use. However, visual quality revealed only small-to-moderate correlations with other factors (ranging from 0.345 to 0.553). This may suggest that, while visual fidelity contributes to immersion, it is not the primary factor of perceived educational effectiveness, satisfaction, experience, or usability. In addition, 27.5% of participants were from the 36–56+ age group, indicating a diverse sample and showing that the proposed AR app was easy to use across different age ranges.

This work serves as a foundation for further research and innovation. By leveraging the insights and methodologies presented in this work, researchers may refine their expertise, test their skills, and design cutting-edge applications tailored to different fields for exhaustive future research.

In the future, the AR application could integrate AI-driven features to allow real-time, dynamic conversations with the busts to enhance the immersive AR experience. This AI capability would enable users to engage in interactive dialogues in order to gain personalized and context-aware historical insights. Finally, future work may incorporate more immersive AR features and integrate artificial intelligence (AI) models, such as natural language processing (NLP), speech-to-text or text-to-speech, and AI sentiment analysis, to enable real-time conversations with the busts. However, NLP usage outdoors may be challenging due to noise and microphone quality. To address the potential limitations of integrating NLP in an outdoor environment, the AR app could incorporate noise-canceling algorithms, such as convolutional neural networks (CNNs) for noise suppression and adaptive Kalman filters to filter out background sounds. Also, adaptive speech recognition models could be deployed to cope with varying audio quality and outdoor environmental factors, improving the accuracy of real-time interactions. Lastly, we will explore targeted usability assessments and tailored design adaptations for diverse age groups and digital literacy levels in future work.

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Institutional Review Board Statement: Ethical review and approval were waived anyway for this study because participants had already signed the informed consent protocol, either electronically or in writing. Moreover, the rules and procedures suggested in the reference handbook of the "Research Ethics Committee" of the UoWM, the guidelines of the Helsinki ethics protocol, and the relevant European provisions regarding the GDPR had been fully complied with.

Informed Consent Statement: Informed consent was obtained from all the subjects involved in this study.

Data Availability Statement: Data available on request due to privacy restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Items Included in the Likert Scale Questionnaire

AR experience

Q1. I had a pleasant experience with the AR app.

Q2. I felt immersed while using the AR application.

Q3. The AR elements feel realistic and well integrated into the real world.

Usability

Q4. I found the AR app useful.

Q5. I found the AR interface easy to navigate.

Q6. I easily found the information I needed.

Satisfaction

Q7. I am satisfied with the overall AR experience.

Q8. I would recommend using this AR experience to others.

Q9. I would use this AR application again. **Visual quality**

Q10. The AR objects were clearly visible and of high quality.

Q11. The visual alignment between the virtual 3D object and real-world objects was accurate.

Educational usefulness

Q12. I learned about the history of the Komotini busts from the app better compared to traditional learning methods.

Q13. The information presented in the AR application was clear and easy to understand.

Q14. The AR app was helpful in understanding the information it provided me.

Q15. The quiz was useful in assessing my knowledge of the subject.

Q16. The quiz questions align with the educational content provided in the AR application.

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