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Underwater virtual exploration of the ancient port of Amathus

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ABSTRACT

Underwater cultural heritage sites, spanning from submerged settlements to ancient ports and shipwrecks, captivate researchers and the public, providing insight into civilizations along coastlines and riverbanks. However, their accessibility and exploration are hindered by the sea's physical barrier. Virtual Reality (VR) offers a transformative solution by providing digital accessibility to these underwater artifacts, enabling immersive exploration without physical limitations. VR enables people to embark on virtual tours of these sites, fostering a deeper appreciation of maritime archaeology and cultural heritage. Yet, fully realizing VR's potential in underwater environments poses challenges, such as realistic virtual reconstruction and accurate simulation of marine life and coral reefs. Photogrammetry emerges as an effective technique for creating detailed 3D models, although underwater conditions often hinder quality outcomes. To address these challenges, our work focuses on digital underwater cultural heritage, presenting a gamified VR exploration of the ancient harbor of Amathus in Cyprus. Through photogrammetry, our VR environment enables users to explore and interact with the historic site seamlessly. Integrated guided tours, procedural generation, and machine learning algorithms enhance realism and user engagement. Evaluation through user studies demonstrates high-quality VR experiences with minimal discomfort, highlighting the efficacy and potential impact of our approach in enhancing underwater exploration and conservation efforts.

1. Introduction and research aim

The Mediterranean is home to a plethora of underwater archaeological sites, ranging from submerged settlements to ancient ports and shipwrecks, which, unlike their terrestrial counterparts, remain largely inaccessible due to environmental constraints e.g., depth. While maritime museums offer partial exhibitions of these sites through photos and surfaced artifacts, the full extent of their historical significance lies in their interpretation and contextualization. In other words, the sites themselves largely remain concealed from public view. Thus, exploring the underwater world is not only captivating but also essential for preserving our cultural heritage. Delving into underwater cultural heritage unveils the rich history of civilizations that thrived along coastlines and riverbanks (see the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage [1]). However, accessibility to underwater exploration faces significant challenges. Activities like scuba diving demand considerable resources, equipment, and expertise, making them inaccessible to many people. Moreover, the vastness of the sea poses navigation challenges for divers and increases the risk of disorientation. Additionally, scuba divers pose environmental threats like coral reef destruction and the depletion of fish populations, which further hinder natural underwater navigation.

In response to these challenges, immersive virtual reality (VR) technologies emerge as a transformative solution. Immersive VR offers a unique opportunity for digital accessibility to these submerged artifacts, enabling immersive exploration without physical constraints. Through VR, individuals can embark on virtual tours of underwater sites, gaining unprecedented insights into maritime archaeology and fostering a deeper appreciation of our cultural heritage. This innovation not only facilitates enhanced research, education, and entertainment but also extends its benefits to fields such as marine biology, oceanography, and archaeology. By leveraging the power of VR, we can transcend barriers and engage broader audiences in the wonders of underwater exploration and conservation [2], ensuring that these invaluable cultural and historical sites are not only preserved but also celebrated for generations to come.

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The potential of underwater immersive VR for ocean literacy and marine environmental education was experimentally investigated in a swimming pool environment [3]. Experimental results showed technological and psychological potentials, including: high levels of presence, infrequency of motion sickness, and powerful emotions and affective states. However, fully exploring immersive VR's potential in underwater environments faces several difficulties, primarily due to the challenge of crafting realistic and intricate virtual settings that mirror the sea's complexity. Accurately simulating specific sea areas proves difficult, hampered by the gathering of precise data and replicating real-life environments.

Moreover, traditional modeling techniques struggle to capture the nuances of underwater realms, such as marine life and coral reefs. The difficulties become more apparent when crafting underwater cultural heritage sites that involve representing submerged monuments like shipwrecks, sunken cities, or ancient harbors. Extracting these monuments in detail poses a challenge, with photogrammetry [4,5] emerging as one of the most effective yet demanding techniques for creating the desired 3D model. Underwater conditions, such as water turbidity and light diffusion, often hinder achieving high-quality results. Additionally, the harbor's shallow waters present further obstacles to obtaining precise photogrammetry outcomes due to constant water movement and waves. Indeed, the lack of exploration in this realm presents obstacles to crafting lifelike and interactive virtual environments that authentically convey the sea's rich cultural legacy. A seamless VR navigation and exploration experience demands careful attention to user experience, ensuring that the users can safely and comfortably explore the virtual environment without encountering any issues.

Previous works in exploring underwater cultural heritage have included 3D reconstruction and navigation in virtual reality (VR), as demonstrated by works such as [6–10]. Nevertheless, these applications lack physical interaction with points of interest, unlike gamified VR learning experiences found in serious games. As a result, they miss the immersive sensation of diving into the site and observing monuments firsthand. They also do not facilitate direct exploration through swimming in water or observing marine life. Consequently, some users perceive these applications as having limited engagement and interactivity, particularly those seeking a more immersive experience.

In this paper, we present our work on digital underwater cultural heritage, including 3D documentation, reconstruction and gamified virtual exploration, providing users with a fully immersive experience. Focusing on the ancient harbor of Amathus situated in Limassol, Cyprus, dating back to the Hellenistic period, our work enables the exploration and interaction with this historic site. By leveraging immersive VR technology and procedural techniques commonly used in serious games, our project transcends the limitations of traditional literature, offering individuals a unique opportunity to engage with underwater cultural heritage while blending education and entertainment. With potential applications in tourism, education, and marine conservation, our project pioneers a new level of engagement with underwater environments.

Our method entails utilizing photogrammetry to digitize the underwater harbor of Amathus. Originally, the ancient harbor remains were digitized as part of the ANDIKAT project [11], which aimed to enhance public engagement and raise awareness for the protection of cultural and natural heritage. In our present work, we have utilized the repurposed and expanded 3D model to create a comprehensive representation. This model forms the basis of our immersive VR environment, which can be accessed without requiring extra equipment or expenses. Furthermore, we have integrated a guided tour feature designed to navigate users through key points of interest, aligning with the objectives outlined in the ANDIKAT project, coupled with authentic features of underwater environments to enhance the overall realism of the experience. This is complemented by procedural generation to enrich content diversity, such as the underwater flora, and machine learning algorithms for lifelike fauna movements, including fish and turtles; these techniques also offer great benefits for project scaling and future-proofing the application. Users have the option to wander freely in the site or follow specific route and learn about the history as well as about the fauna of the area. This work represents an innovative response to the challenges of underwater exploration, setting a new standard for immersive VR experiences. Our VR application underwent evaluation through a user study with 30 participants, yielding compelling results that underscore the efficacy and impact of our approach. The study involved interactions with the VR environment and post-experience assessments to evaluate knowledge acquisition and VR-related discomfort. The results revealed a notable learning rate, aligned with high-quality VR experience metrics, and minimal cybersickness issues. Additionally, an additional expert evaluation study provided valuable insights into the application's strengths and areas for improvement, highlighting positive user interactions and immersion, along with suggestions for enhancing content completeness and navigation methods.

2. Related work

In this section, our literature review focuses on several key aspects: underwater diving and navigation in VR, underwater archaeology with an emphasis on reconstructing cultural heritage sites, the concept of virtual underwater museums, and the exploration of underwater environments through virtual means.

2.1. Diving in underwater navigation in virtual reality

Various approaches have been explored to simulate diving and swimming experiences in VR. Early efforts, such as those by Fels et al. [12], aimed to simulate swimming mid-air using harnesses and weights but lacked the ability for users to dive. One of the cheapest and easiest solution is to use 360° videos in XR environments. An interesting approach was introduced by Thompson et al. [13] that illuminates and blends virtual objects into underwater 360° videos in real-time performance, based on automatic ambient and high frequency underwater lighting. VR experiences can be blended with 360° storytelling and a recent study in underwater cultural heritage found that this combination can offer high levels of presence, immersion, and general engagement [14]. In more recent efforts, SCUBA VR by Hatsushika et al. [15], submerged users in swimming pools with waterproof VR headsets, allowing realistic underwater exploration. Jain et al. [16] introduced the Amphibian prototype, an immersive VR SCUBA diving simulator emphasizing hand movement tracking, that is based on a terrestrial simulator that simulated buoyancy, drag, and temperature changes through various sensors. Similarly, DIVR [17] offers VR snorkeling experiences in real water, providing sensations of weightlessness. While DIVR's primary focus is entertainment and it cannot be classified as a serious game, its potential for entertainment, education, and training is noteworthy. Despite limitations such as visual fidelity and interaction constraints, DIVR demonstrates promise due to its innovative integration of physical and virtual environments and its potential to reduce motion sickness. However, its reliance on mobile hardware limits computational power and interactive capabilities.

2.2. Underwater archaeology in extended reality

Digital underwater archaeology has historically received limited attention, primarily due to challenges associated with reconstructing and recreating virtual representations of underwater sites. However, in recent years, several projects have emerged aimed at accurately creating 3D models of underwater cultural heritage sites and improving diving and navigation tools. Among these initiatives are the iMareCulture [18], VISAS [19], and VENUS [20], and VIRTUALDiver [21] projects.

The VENUS project developed VR/AR tools for archaeologists and the general public for exploring deep underwater archaeological sites out of reach of divers. Withing this project, Chapman et al. [22] focus on developing scientific methodologies and technological tools for virtual exploration of deep underwater archaeology sites. Leveraging the capabilities of VR and AR, the project aimed to create immersive and interactive digital models of these sites by merging optic and acoustic sensor data [23]. Additionally, an archaeological database engine was proposed to automate data input and generate Mixed Reality experiences. Similarly, Haydar et al. [2] emphasized 3D visualization and interaction modalities in VR/AR for studying and preserving cultural heritage. They employ Cultural Computing techniques for creative cultural translation. By utilizing VR's immersive capabilities and multimodal interactions, including audio, video, and haptics, they targeted to achieve presence. Their project employed scientific methodologies and technological tools such as photogrammetric tools to reconstruct artifact shapes from multiple angles. The resulting virtual environment offered configurable levels of immersion and interaction, facilitating the study of underwater wrecks by archaeologists.

Within the VISAS project, the process of recreating diving and underwater cultural heritage sites as accurate 3D models involves a comprehensive series of steps, as outlined by Bruno et al. [24]. An inspection of the potential diving site was conducted to identify points of interest, while the entire area was scanned using Multibeam echosounders to generate bathymetric maps, providing a low-resolution representation of the seabed. Then, an optical survey was conducted at selected points by divers equipped with underwater cameras, capturing numerous overlapping photographs. These images were enhanced to increase their chromatic quality and were then used to create 3D models via photogrammetry technology. The optical and acoustic models were merged to form a complete 3D reconstruction of the diving site, with techniques such as geolocation systems and direct measurements ensuring accuracy. Textures were applied to the mesh, resulting in highly accurate and realistic models. The collected data and reconstructed models are stored in a database and made accessible through a web service software [19,24]. In addition, a VR system named “Virtual Dive Experience” was designed and developed to provide instructions and information to users in a playful manner [25]. This system simulates dives in a couple of regions in South Italy, enabling non-divers to explore underwater archaeological findings safely and realistically.

Within the content of iMareCulture project, a VR CAVE application for the 4th-century BC Mazotos shipwreck site in Cyprus was developed with the focus of educating researchers about it [26]. Later, Liarokapis et al. [6] developed an immersive VR experience, using head-mounted displays (HMDs), of the same shipwreck that is now combined with realistic models and mapping techniques to teach visitors archaeological knowledge and strengthen cultural awareness. Efforts are made to create a realistic environment, with features such as simulated light rays passing through water, simulated plant life, and groups of fish. Additionally, interactions are simplified to allow users to interact with objects such as wood and rocks to learn more about artifacts. In a later work, Liarokapis et al. [27] focuses on search techniques to discover artifacts in a playful environment through educational games. The Serious Game developed allows players to experience maritime archaeological searches, emphasizing techniques such as circular and compass search. Players can interact with objects and learn more details about their archaeological significance while engaging in game features such as scoring points.

The VIRTUALDiver project [9] provided an immersive underwater VR experience of three-dimensional models of Santorini's sea floor with the aim of providing information about the flora and fauna of the seabed, shipwrecks, as well as geological phenomena. In respect to AR, the iMareCulture project designed, implemented and evaluated two hybrid archaeological guides for underwater cultural heritage in the open sea [8]. The first one used acoustic visual-inertial tracking allowing for larger area of operation, while the second one on was based on marker-based visual-inertial tracking offering high precision but in much shorter range [28]. Before the iMareCulture project, underwater AR systems were proposed only for swimming pools and they were not focused on cultural heritage [29–31].

Recently, some efforts have been initiated to introduce the concept of virtual underwater museums, offering an opportunity to delve into these historic time capsules. Notably, the Malta Virtual Underwater Museum [32] utilizes 3D, virtual reality, and other media to bring underwater cultural heritage to the surface, enabling access to and sharing of Malta's unique underwater cultural legacy. Other initiatives, such as the project “Exploring theBlu” at the Natural History Museum in Los Angeles [33], simulate underwater adventures and interactions with sea creatures, while the Virtual Museum of Wrecks [34] showcases various wrecks in the Gulf of Gdańsk. The Bermuda 100 challenge [35] also presents several wrecks, facilitating the study and conservation of Bermuda's underwater ecosystems, among other similar endeavors.

While previous research has explored 3D reconstruction and navigation in immersive VR underwater archaeological sites, our primary contribution stands out as it offers an interactive, gamified VR learning experience focused on the accurate reconstruction of an ancient port. Our VR implementation presents users with a distinct opportunity to engage with underwater cultural heritage. This project seamlessly blends education and entertainment, with potential applications in tourism, education, and marine conservation.

2.3. Amathus port: documentation and reconstruction

The ANDIKAT project [11], a collaborative initiative supported by the European Union along with national funding from Greece and Cyprus via the Interreg Program, was dedicated to safeguard the marine ecosystem of Amathus, along other coastal regions of Greece and Cyprus, to enhance public consciousness concerning the conservation of both natural and cultural heritage sites. As part of this initiative, various methodologies have been employed, with a particular emphasis on utilizing aerial and underwater photogrammetric techniques for documenting the ancient harbor structures of Amathus. Additionally, a user-friendly mobile application named “Amathus Harbour” [11] has been developed to provide visitors with personalized information about the area, available in both Greek and English languages. This digital tool enriches visitor experiences by providing information and audio-visual content for remote exploration of the underwater site, complete with interactive maps. Users can navigate points of interest at their leisure, gaining insights into the site's history and environment. However, these applications lack the physical interaction with points of interest found in virtual reality games, thereby missing the immersive experience of diving into the site and observing monuments firsthand.

3. Materials and methods

3.1. The ancient city of Amathus

Amathus was an ancient city located on the southern coast of Cyprus, about 10 km east of Limassol. It flourished during the Ar-

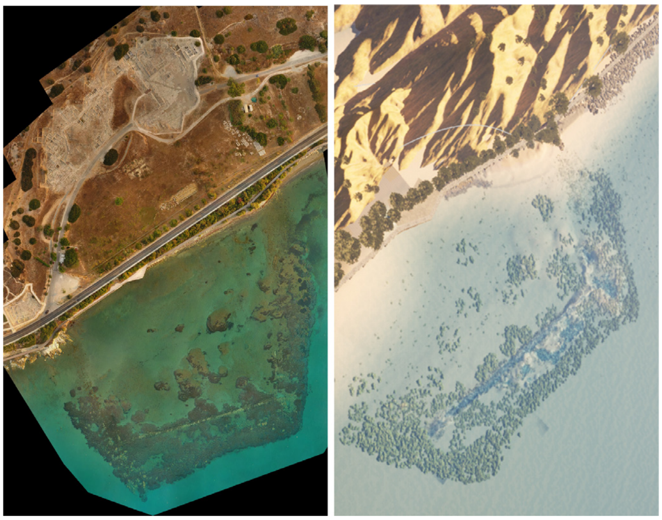

Fig. 1. Orthophoto of the area surveyed by drone, with two-media photogrammetry (left), alongside our 3D reconstructed model (right).

chaic and Classical periods as a significant city-state in Cyprus. Amathus was also an important commercial hub, benefiting from its strategic coastal location [36,37]. The site is under excavation since 1975 by the French School at Athens and is among the main archaeological sites on the island that are open to visitors [38]. Its well-preserved external harbor was partly excavated, between 1984 and 1986 [39] (see Fig. 1 for an orthophoto of the area). In 2022, Amathus ancient port became Cyprus' first underwater archaeological park.

In a more detailed topographical analysis of the area, it is revealed that the submerged structures of the port lie at shallow depths, ranging between 1–6 m [40]. The accuracy of bathymetric maps surrounding the ancient port of Amathus was evaluated by comparing depth values with data obtained from traditional multispectral sensors and validated through in-situ LiDAR measurements [41]. Despite the lack of significant land movements affecting the immediate vicinity, the site has been impacted by coastal changes such as erosion and fluctuations in sea levels. Additionally, the presence of nearby urban and industrial areas contributes significantly to these influences.

Previous efforts to digitize the ancient harbor of Amathus for preservation and online access have resulted in the creation of the "Amathus Harbour" application. This tool aims to enrich visitor experiences by offering information and audio-visual materials for remote navigation. Users can explore the ancient harbor of Amathus at their own pace, learning about its history and environment through an interactive map and audio touring function. However, the application has limitations; it lacks physical interaction with points of interest and may not provide the immersive experience some users desire, compared to a virtual reality game.

3.2. 3D Reconstruction

Two distinct methods were employed for the 3D reconstruction of the ancient harbor. As part of the ANDIKAT project [11], the submerged harbor itself was reconstructed using the Structure From Motion (SfM) and Multi View Stereo (MVS) method [4,42]. This widely-used digitization process involves acquiring 3D data of physical objects and structures, commonly applied in cultural heritage projects, and includes texture information. MVS computes a dense point cloud on an object's digital surface based on overlapping images along with camera position and orientation information, known as exterior orientation [43,44]. Conversely, the surrounding area of the ancient port, comprising the modern wooden boardwalk, lighting fixtures, and local flora, was modeled to replicate their real-world counterparts.

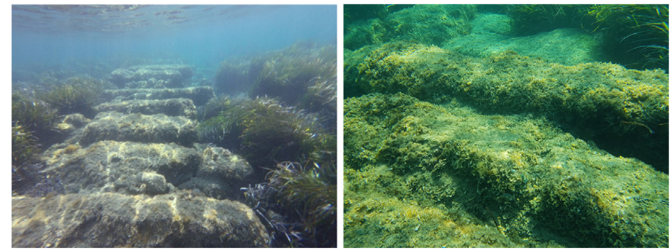

Fig. 2. Condition of the south jetty, before cleaning, with Posidonia on both sides (left) and flora on the stones (right).

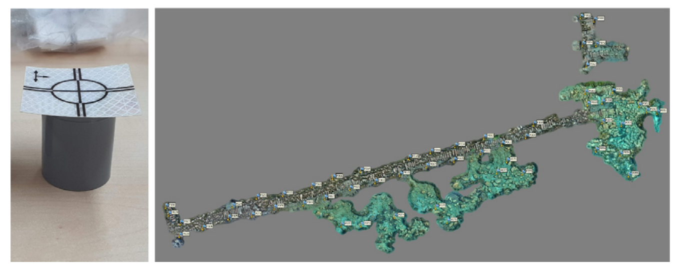

Fig. 3. The PVC cup for 1-inch pipe, with and without the retroreflective target (left). The area surveyed underwater with control points overlayed, with one-media photogrammetry (right).

3.2.1. Structure-from-motion

Surveying underwater 3D reconstructions in a harbor setting using SfM techniques encounters several challenges. These include the dynamic presence of underwater flora (such as the vast Posidonia Oceanica meadow surrounding the Amathus harbor structure), the need for a corridor survey approach due to the structure's length and shape (spanning 174 m of the south jetty, alongside smaller jetties and adjacent areas), the necessity for accurate control points, the requirement for capturing numerous photos to ensure complete coverage (due to the small distance between objects and the camera, especially on top of the jetty where depths range from 0.7 to 1 m, resulting in small frame footprints), and the challenge posed by strong surface currents hindering survey lines. This section discusses the steps and strategies taken to address these challenges.

Posidonia. In order to enable photogrammetric 3D documentation of the underwater site, a decision was made to clear Posidonia from a one-meter buffer zone around the jetty walls (see Fig. 2). Stones were also cleaned of flora to the extent possible. This decision aimed to strike a balance between effort, minimal intervention, and ensuring adequate space for capturing oblique photos of the walls' sides. The removal process, undertaken by a team of underwater biologists with permits from relevant authorities, lasted six weeks. Posidonia was trimmed rather than fully removed to allow regrowth, with care taken to ensure that the remaining vegetation would not interfere significantly with the subsequent SfM-multi-view stereo (MVS) processing.

Control point network. Establishing stable control points for such extended underwater area posed considerable challenges, particularly in ensuring non-invasive placement while facilitating their usability for both close-range underwater surveys and aerial drone flights. This necessitated a novel approach, resulting in the adoption of retroreflective targets measuring 4×4 cm, securely affixed atop PVC cups mounted on steel rods (see Fig. 3).

Throughout the project, markers were strategically placed in pairs along both sides of the jetty, with an average spacing of

10 m. However, this distance was subject to variation, primarily influenced by the penetration of the steel rods into the seabed, necessitating adjustments in marker positioning. In total, 79 markers were strategically positioned and measured (as depicted in Fig. 3), ensuring comprehensive coverage of the underwater area.

Measurement of control points was conducted utilizing a total station from the coastline. For markers at depths up to 1.8 m, measurements were relatively straightforward, employing standard aluminum rods attached to the reflectors. However, markers deeper than 1.8 m presented greater challenges, requiring diver-assisted measurements, with one diver positioning the reflector over the marker while another one on surface was observing a bubble level to ensure vertical reference.

Despite inherent challenges, the accuracy of these control points, ranging from 20 to 40 cm horizontally and approximately 10 cm in depth, remained critical for georeferencing purposes. This was especially pertinent given the limitations of the drone's Global Navigation Satellite System (GNSS) capabilities and the potential for photogrammetric block deformations exacerbated by water refraction.

While acknowledging the limitations of control point accuracy, the project underscored their indispensable role in achieving precise georeferencing, essential for subsequent data analysis and model generation. Notably, even though there are strong control point inaccuracies, the robustness of the photogrammetric block, coupled with appropriate weighting methodologies, facilitated valid scale determination and accurate positioning within a 3D geodetic reference system, ensuring the project's overall success.

Data acquisition strategies. The selection of the best approach is complex and varies depending on the object's environment, equipment availability, and personnel resources. There is no one-size-fits-all solution.

For this project, two pairs of action cameras were chosen: two Garmin VIRB XE'[45] and two GoPro 3 Hero Black'[46]. Despite their lower resolution, the small object-to-camera distance compensated for details and precision, while good light conditions negated the need for larger sensors or better optics to handle low-light situations. Mounting two cameras on a pole created a rigid rig, ensuring side overlap and reducing the number of diver passes required.

Two rigs were constructed: one with a 0.5 m camera base for the Garmin VIRB XE cameras and another with a 1.75 m base for the GoPro 3 Hero cameras. These rigs were tailored for different object-to-camera distances, with the smaller rig suitable for the jetty and the larger one for deeper areas outside the jetty. An Insta360 One 1-inch action camera [47] was used for supplementary video coverage, leveraging its larger sensor and better optics. Additionally, a Sony SLT-A65 [48] with a 16 mm lens was utilized to capture detailed images of specific areas within the harbor for archaeological documentation and research purposes.

Processing. The harbor and its surrounding areas were reconstructed into a comprehensive model using frames extracted from action camera videos. Approximately one frame was extracted every 8 frames ($\approx$ 3 frames per second), totaling 53,727 frames for 3D reconstruction, with 48,985 properly aligned in Agisoft's Metashape v.1.7.4 [49]. Due to the volume of photos, processing occurred in 13 separate blocks, each georeferenced using control point markers. Block sizes ranged from 977 to 7841 images, and underwent thorough processing up to detailed 3D textured models.

As a final step all blockes were unified in a single block with an average ground pixel size of 1.07 mm and a final reprojection error of 1.51 pixels. The root-mean-square error on the control points was 0.12 m, 0.14 m, and 0.14 m in X, Y, and Z directions respectively. The final model from the MVS reconstruction was limited to 10M faces to optimize for a VR application's performance.

In conclusion, while video frames are generally considered as a suboptimal solution for photogrammetric processing, they were utilized for data acquisition in this project, to overcome other limitations. The challenges encountered during alignment can be attributed to residual Posidonia presence in some frames despite efforts to remove it, particularly at the peripheries where most markers were situated. Additionally, the repetitive pattern of trimmed Posidonia in frames led to mismatches that internal filters could not fully address. Furthermore, inadequate ground control point coordinates increased the connectivity issues among the separate blocks, contributing to poor self-calibration and bad alignment.

3.2.2. 3D Modeling

Landscape. In this work, we aimed to create a lifelike and immersive environment using Unreal Engine 5's landscape mode [50]. This feature allowed us to craft expansive and detailed outdoor settings tailored for gaming experiences. We carefully sculpted the landscape of Amathus, referencing satellite maps and images from Google Earth to mirror the real-world location. This process involved shaping the coastline, defining the overall map dimensions, simulating underwater features, and adjusting lighting angles to mimic the area's natural conditions. Mountains were carefully chosen and positioned to match the region's topography, with procedural generation techniques used to populate them with trees, plants, and rocks, resulting in a diverse and intricate environment (see Section 3.2.3 for more details).

Moving forward, we replicated the beach of Amathus, the starting point of our virtual reality game. By incorporating real-world measurements and high-quality textures, we recreated the beach's appearance with accuracy. Rocks were strategically placed, and procedural generation was employed to scatter additional natural elements along the coastline, contributing to the visual richness and immersion. The map size was expanded to around 300 square meters to provide users with ample space for exploration.

Furthermore, we modeled the wooden bridge and boardwalk along Limassol's coastline, utilizing SketchFab assets [51] to achieve as close as possible to the environment authenticity. Reference images guided the bridge's design, and attention was paid to texturing and detailing for realism. To add further depth to the landscape, we included details like electric poles, wires, and streetlamps sourced from Sketchfab [52], thoroughly selected to blend seamlessly with our environment. Fig. 4 depicts Amathus beach as it exists in the real world (top) alongside our 3D reconstructed model (bottom).

Ocean and Underwater Environment. Our work heavily relies on water and the underwater environment, which are central to our application's essence. Utilizing Unreal Engine's Water System plugin [53], that facilitates the generation of rivers, lakes, and oceans through a spline-based workflow, we have achieved to seamlessly integrate the sea with our landscape terrain. The Water System consolidates the shading and mesh rendering pipeline, empowering us to construct surfaces capable of supporting physics interactions and fluid simulations. We positioned the water within our landscape, adjusting spline lines along the coast for accuracy. Using customized wave settings, we achieved a calm sea appearance. By modifying water materials, including absorption and scattering, we replicated the sea's appearance at Amathus Beach. Post-processing effects further enhanced realism, adapting fog and depth dynamically.

Integrating *caustics* (see Unreal Engine's Water System plugin [53]) enhances realism in the underwater world (see Fig. 5). Using decal actors, we applied caustic materials atop water areas, creating dynamic effects with scrolling textures. Detailing included

Fig. 4. Amathus Beach in the real world, as depicted in Google Maps (top), and our 3D reconstructed site (bottom).

tremors for added realism. This approach offered flexibility in adjusting intensity, contributing to a visually stunning underwater experience.

Finally, to truly immerse the player in the underwater world of our environment, attention to detail was paramount to immerse players in the authentic underwater world of Amathus Beach. Procedural placement of rocks with green mold and seaweed from Quixel Bridge added realism [54]. Posidonia and coral elements were randomly placed on the ocean floor, mimicking the ecosystem (see Fig. 5). Importing the 3D model of Amathus harbor completed the underwater environment, ensuring fidelity to the real location.

3.2.3. Procedural modeling

Procedural modeling played a crucial role in the development of our project, enabling the creation of an expansive and intricate environment while effectively managing our workload. It granted us the flexibility to thoroughly place foliage, rocks, and plants, empowering us to swiftly and easily tweak their arrangements. Furthermore, procedural modeling proved instrumental in infusing our oceanic realm with life, as it facilitated the dynamic placement of fish, thereby fostering a captivating underwater experience. Although simpler methods might be suitable and effective for certain aspects of the project, we selected machine learning and procedural generation to leverage their benefits for scalability and future-proofing the application.

Utilizing the boid algorithm [55], originally designed for flocking behavior simulation, we govern the movement and interactions of each boid in our virtual environment. This algorithm encompasses basic rules such as separation, alignment, and cohesion, which dictate how each boid avoids crowding or collisions, maintains group direction, and stays close to others, respectively. Additionally, fish in our simulation react to the player as a threat within a designated area, enhancing the overall realism.

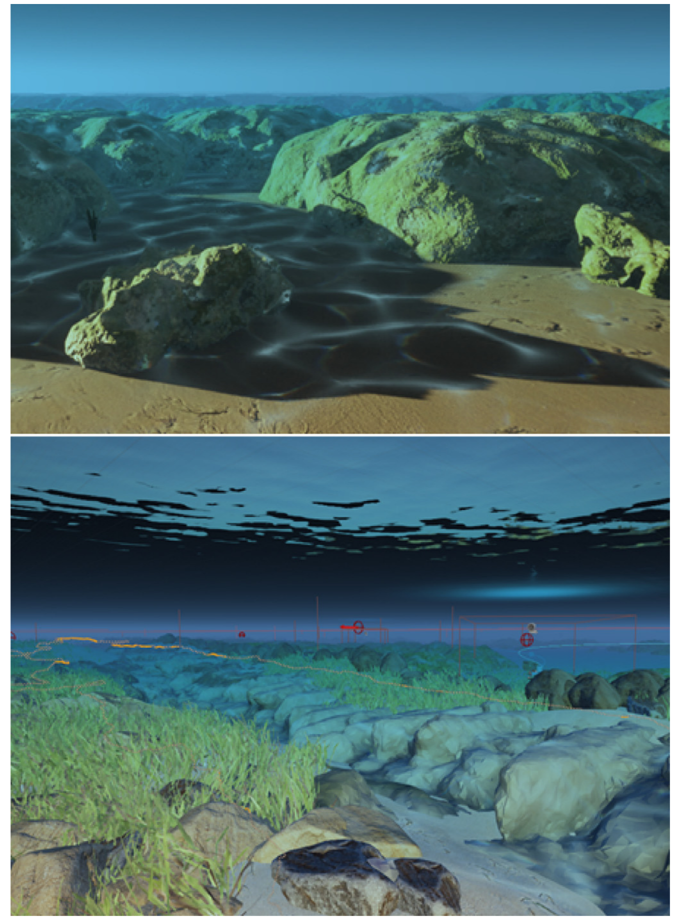

Fig. 5. The underwater environment effect following the application of caustics (top), and the 3D model depicting procedural placement of rocks adorned with green mold, seaweed, sand and foliage (bottom). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Implementation of the boid algorithm in our project is facilitated by Ghislain Girardot’s adaptation for creating boids using the Niagara effect [56], a robust visual effects system in Unreal Engine known for its efficient particle simulation and advanced rendering capabilities. In our virtual underwater environment, a diverse array of marine life, including five fish species and a green sea turtle, provides players with an immersive experience (see Fig. 6); the 3D models of the fishes and the turtle were sourced from Sketchfab, and were modeled using photogrammetry [57,58]. Fish spawn dynamically in groups of 4–10 instances at random locations throughout the map, ensuring a dynamic and lifelike gaming experience [59]. Employing a procedural approach, fish spawning locations are randomized each play-through, adding unpredictability and realism to the gaming experience. The movement of the green turtle, adapted from the AI algorithm of the ABK free birds project, enables seamless navigation in all directions and rotation upon encountering obstacles or reaching boundaries. Through integration with the Niagara effect, we translate the algorithm’s principles into fluid swimming motion, enhancing user immersion (see Fig. 6).

Each fish species, carefully sourced and faithfully recreated, contributes to the ecosystem’s richness, dynamically spawning to enhance unpredictability and engagement. This dynamic spawning process, supported by procedural algorithms, ensures that each gameplay session offers a fresh and unpredictable encounter, heightening the sense of exploration.

Fig. 6. At the top, we showcase the five local fish species utilized in our project, presented in order of appearance: Goatfish, Grouper, Seabass, Smaris, and Seabream, alongside the Green Turtle. At the bottom, we demonstrate the implementation of boids [59] using the Unreal Engine 5 Niagara system [56], enhancing ecosystem richness by dynamically spawning to increase unpredictability and engagement.

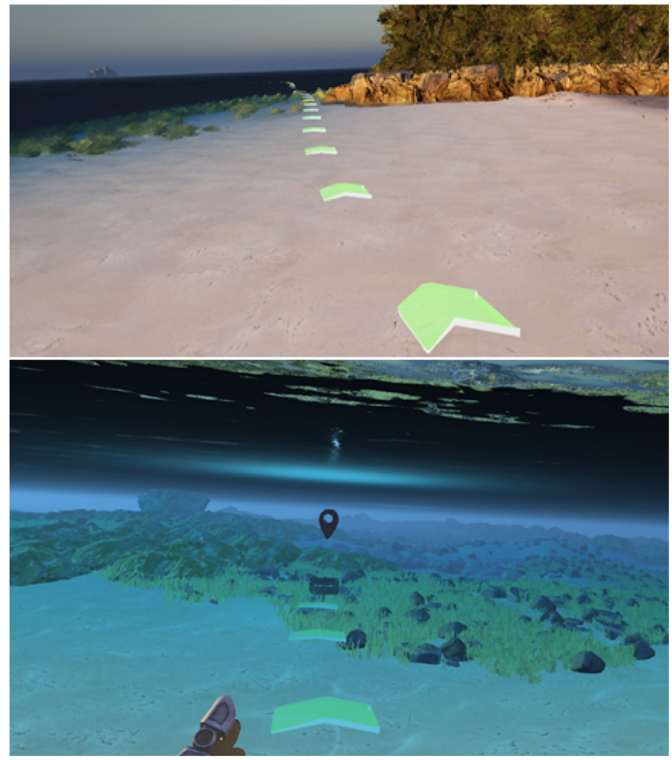

Fig. 7. Player navigation to the first point of interest (top), and navigation arrows aiding user guidance through the game environment (bottom).

Attention to detail extends to flora, with foliage placed and manipulated to evoke the natural beauty of the seabed. The integration of Unreal Engine's Procedural Foliage Spawner [60,61] empowered us to populate our underwater world with an assortment of flora, each contributing to the immersive experience. This allowed automatic and semi-manual placement of rocks, plants, and seaweed while controlling their distribution. Through its collision, clustering, and growth functionalities, we managed the distribution and growth of foliage realistically, in a manner mirroring natural ecosystems. In our map's foliage creation, we utilized assets such as the black alder tree from the Unreal Engine marketplace [62], lemon grass, grass clumps, and Posidonia from Quixel Bridge [54]. We modified the wind effect on Posidonia to mimic underwater movement, enhancing realism. This attention to detail, coupled with manual intervention via Unreal Engine's Foliage mode, ensured that no nuance of the underwater environment was overlooked, yieldeding an immersive and lifelike representation of the ancient Amathus harbor and its surrounding seas.

3.3. Virtual exploration and user interface

In this section, we delve into the character design and navigation features of our project, tailored to enhance user interaction and exploration within the virtual environment. Through a customized character pawn, users gain improved control and flexibility, enabling seamless movement, swimming, and teleportation. Additionally, two navigation modes cater to varying player preferences, offering intuitive interaction and enhancing immersion.

3.3.1. Character and navigation

The character was tailored to facilitate user interaction and navigation within the virtual environment. Replacing the default VR pawn with a Character pawn provided enhanced control and flexibility, enabling users to move, swim, and teleport throughout the environment seamlessly. A collision capsule was integrated into the character to prevent collisions with objects, while visible hands allowed users to interact with various elements.

Two navigation options are offered to cater with player preferences: guided tour and free exploration. In the guided mode, transparent arrows direct players to nine points of interest, aiding safe and efficient navigation, and to avoid disorientation. At each location, players can hear audio descriptions generated by LOVO AI [63], enhancing immersion. In addition to audio, users can watch videos providing information about the points of interest, e.g., the history and architecture of the port, its flora and fauna. Free exploration, on the other hand, allows players to explore the underwater world at their own pace, with objectives visible from a distance. Wooden signs provide information at points of interest in both modes. Both options are user-friendly, employing common VR navigation techniques for intuitive interaction, while enhancing immersion with sound effects and clear waypoints. The guided tour can be completed in 5–10 min, offering players flexibility and replayability in their exploration of the environment. In Fig. 7, examples of navigation trails are highlighted using arrows to aid the user in navigating through the environment, along with points of interest.

3.3.2. Menu and controller input

The menu system comprised options for controls, restart or quit the application, ensuring ease of use. Implementation involved attaching the menu widget to follow the player's movements seamlessly. A laser system enabled intuitive interaction with menu options in 3D space, enhancing user experience.

Real hands replaced default virtual hands, offering responsive animations to user interactions for added realism; these real hands respond to user actions, allowing gestures like pointing, grabbing objects, and giving thumbs-up gestures (see SteamVR [64] for more details). Key bindings for motion controllers facilitated interaction, with the right controller primarily used for teleportation, triggering, and interaction, while the left controller controlled locomotion and menu access.

3.3.3. Transportation

Two teleportation systems were implemented for navigation: (i) Motion Controller Teleportation, and (ii) Thumb Stick Locomotion. Motion Controller Teleportation utilized static meshes to trace a path, providing ground-based teleportation to prevent motion sickness. Thumb Stick Locomotion allowed for smooth, intuitive movement in all directions, enhancing exploration and interaction in the underwater environment. Speed adjustments and realistic swimming physics ensured an enjoyable user experience during transportation.

4. Results and data analysis

The Amathus's harbor virtual exploration application aims to engage visitors through a gamified experience, immersing them in a digitally recreated underwater cultural heritage site. The design emphasizes user autonomy and navigation, while ensuring accessibility and interactivity. For a more comprehensive understanding of our implementation visualization, please refer to the animated video available in our supplementary materials.

To evaluate the effectiveness of our immersive virtual underwater environment, we conducted a comprehensive user evaluation to (a) assess the level of immersion and presence experienced by users, (b) gather subjective feedback and evaluations, and (c) identify any negative consequences such as cybersickness resulting from the immersive VR application. The primary goal of this evaluation is to yield valuable insights into the user experience, pinpointing areas for potential refinement to enhance overall satisfaction and engagement.

4.1. Implementation

This project primarily utilizes Unreal Engine 5; its standout features include advanced graphics capabilities, like Nanite technology, enabling detailed underwater environments. Additionally, its procedural generation tools streamline environment creation, while built-in VR support simplifies integration of VR elements. For both user navigation and evaluation, we employed the Meta Quest 2 head-mounted display (HMD). It features a resolution of 1832×1920 per eye, a refresh rate of 90Hz, a horizontal field of view of 104°, and a vertical field of view of 98°. The HMD weighs 503g and offers an adjustable interpupillary distance, with settings available for 58 mm, 63 mm, and 68 mm. The Meta Quest 2 specifications offer high visual clarity and a wide field of view, enhancing immersion and realism in underwater scenes. Its high refresh rate ensures a smooth visual experience, reducing motion blur and discomfort. These features are crucial for understanding user perspectives and evaluating participant experiences, as the headset is the primary tool for interacting with our VR underwater environment.

Smooth operation is crucial for an immersive VR experience. Ideally, a VR application should maintain a frame rate consistent with the headset's refresh rate, such as the 90 Hz of the Meta Quest 2. However, the large size of the 3D reconstructed model, such as in our case, may impact the performance of the VR application, resulting in motion tracking delays and dropped frames that detract from the experience. While upgrading to a better GPU or reducing graphics quality may improve gameplay smoothness during stationary moments, it may not fully resolve the issue. To address this, we implemented two commonly used techniques: *distance culling*, which automatically disables rendering of objects beyond a certain distance from the camera, and *level of detail*, a method to switch between different versions of the same object based on its distance from the camera. These techniques optimized performance by preventing the engine from wasting resources on assets that the player cannot see and by reducing the number of polygons that need to be rendered for distant objects. As a result, we achieved a consistent 90 fps without encountering issues such as lagging, ensuring a seamless gaming experience.

4.2. Aims and procedure

The evaluation aimed to gather insights (perceptions and opinions) into the user experience of the VR application, including immersion, presence, flow, and cybersickness. An evaluation of the knowledge retention about the objectives of the VR experience was conducted by a multiple-choice test.

Immersion and presence are commonly used terms referring to the quality of the VR experience. *Immersion* in immersive VR resembles diving into a new world; the goal of immersion is to create an environment captivating enough to disconnect users from reality and fully engage them in the virtual world. It represents the objective degree of sensory engagement, closely tied to the concept of flow [65]. The state of flow is a mental state characterized by focused involvement, a sense of control, and enhanced performance [66].

Presence, on the other hand, refers to the subjective sensation of being physically present in a virtual environment, despite awareness of the virtual nature of the experience [67]. Unlike immersion, presence is a perceptual illusion, wherein users respond to virtual stimuli as they would in the real world [68]. This sensation can be so compelling that users may instinctively react to virtual events, such as dodging virtual objects or experiencing fear in response to virtual stimuli [69].

In the evaluation, we aimed to test the following hypotheses:

H1 Majority of participants will rate the quality of the VR experience positively (i.e., in the upper half of the scale).
H2 Majority of participants will score at least 50% in the test evaluation.
H3 Majority of participants will report low cybersickness (i.e., in the lower half of the scale).

The evaluation process began with an introduction to the project for participants. The participants were then given the opportunity to explore the VR dive navigation application organically, without prior knowledge of controls or specific tasks. This approach aimed to encourage natural interaction and gather initial impressions. Participants remained seated throughout the VR experience, starting with a guided tour before being encouraged to freely navigate and explore the virtual environment. On average, participants spent 9 min and 44 s (SD = 66.3 s) in the VR environment. Following the VR session, participants completed questionnaires and a multiple-choice test assessing their knowledge acquisition.

4.3. Participants demographics

Our VR underwater application was evaluated with a sample size of 30 participants, comprising 19 males, 10 females, and one non-binary individual. The median age of the participants was 23.5 years (SD = 4.1). Participants reported a median rating of 5 for their time spent working with computers on a scale of 1 to 7, with SD = 1.1. Additionally, the median reported level of experience with VR was 2, with SD = 1.3. In this project, we targeted a diverse user profile to ensure a thorough evaluation of the application's usability and appeal. We selected younger participants, who are more likely to adopt and be attracted to such applications. This group included individuals with varying levels of computer experience and familiarity with virtual reality, allowing us to assess their confidence and willingness to engage with this new technology. By capturing a range of perspectives, we aimed to refine the application to better meet the needs and expectations of a broad audience.

4.4. Data collection

We employed several questionnaires to gather data about our application. Firstly, we utilized a subset of the Virtual Reality User Experience (VR UX) questionnaire [70], which investigated immersion, presence, subjective experience judgment, emotional attitude, flow state, and negative consequences of the VR application. Additionally, we employed the CyberSickness in Virtual Reality Questionnaire (CSQ-VR) [71,72] to collect data on nausea, oculomotor symptoms (issues affecting the eyes and vision), and visuo-vestibular disorientation.

Furthermore, we conducted a multiple-choice test evaluation to assess participant learning post-VR exploration, focusing on knowledge acquisition in archaeology, history, and marine biology. Pre-experiment questionnaires were administered to assess participants' existing experience with immersive VR and their time spent working with computers, aiming to discern any influence on learning rates or subjective application ratings.

4.5. Data analysis

We analyzed the per-category data from the VR UX questionnaire and CSQ-VR questionnaire, as well as the accuracy rate from the test evaluation. The accuracy rate was computed using the following formula:

$$\text{Accuracy Rate} = \left(\frac{\text{Number of Correct Answers}}{\text{Total Number of Questions}}\right) \times 100\%$$

Descriptive statistics were calculated for each category of the VR UX questionnaire, yielding scores for subjective judgment of the immersive VR experience (judgment), immersion, presence, state of flow, emotional attitude towards the experience (emotion), and negative consequences of immersive VR exposure, primarily simulator sickness (exp. consequences). Additional insight into negative consequences was gained through the CSQ-VR questionnaire, focusing on experiential consequences such as nausea, oculomotor symptoms, and visuo-vestibular conflicts.

Responses were recorded on a 7-point Likert scale (where 1 represents the lowest rating and 7 represents the highest), and medians along with standard deviations (SD) per category were calculated. Hypotheses were tested using a binomial test, categorizing responses as falling above or below the 50% criterion. Moreover, correlations (Spearman correlation) between demographic and questionnaire data were explored. All statistical analyses were conducted using R [73].

4.6. Results

In this section, we present an analysis of the user rating of the immersive VR experience, evaluation accuracy rate, correlations between different variables, and the incidence of cybersickness.

4.6.1. Rating of the VR experience

Users provided highly positive ratings for the VR environment, with a median judgment of 6.1 (SD = 0.7). Participants reported being in a state of flow (median 6, SD = 1.0) and expressed enjoyment during the experience (median 7 on the emotion scale, SD = 0.9).

Regarding the quality of the immersive VR experience, immersion (the degree of absorption and engagement in the virtual environment) received a median rating of 4.75 (SD = 1.1). Although in the upper part of the scale, immersion was partly limited in some users probably due to cybersickness issues (users experiencing discomfort; see below). Nevertheless, ratings for presence (the subjective sensation of being physically present in the VR world) were notably higher, with a median of 5.7 (SD = 0.8).

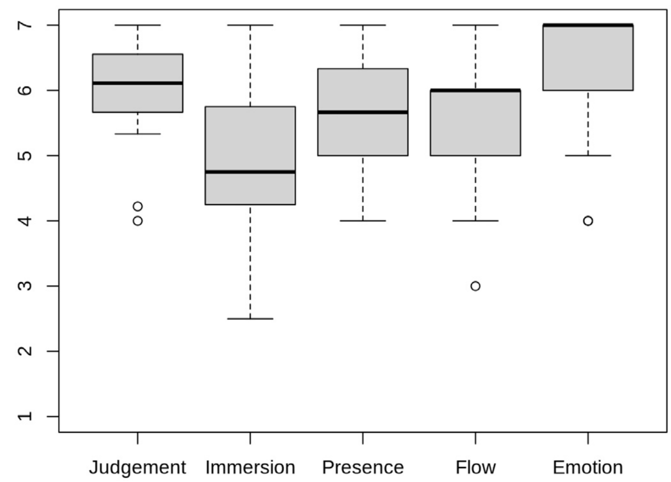

Fig. 8. Boxplots for questionnaire results (rating and quality of the VR experience). The whiskers extend to cover the range up to 1.5 times the interquartile range (IQR) from the first (Q1) and third quartiles (Q3), and circles represent outliers from that range.

The results of the binomial test supported hypothesis *H1*, indicating that the average user rating significantly surpassed the neutral point ($p < 0.01$) for immersion, presence, flow, emotion, and judgment. For visual representations of the questionnaire evaluation, please refer to the boxplots presented in Fig. 8.

4.6.2. Evaluation accuracy rate

The median test accuracy rate was 70% with an SD = 17.4%, indicating a decent level of knowledge acquisition (see Section 5). Statistical analysis revealed support for the proposed hypothesis *H2*, with a significant majority of participants (26 out of 30) achieving 50% or more in the evaluation ($p < 0.01$). The achieved test accuracy rate had no relationship to the questionnaire rating of the application, presence, immersion, state of flow, or metrics of cybersickness.

4.6.3. Correlations

No correlations have been found between time spent using computers or pre-experimental immersive VR experience and the questionnaire metrics. We, however, found a positive correlation between age and the accuracy rate (Spearman $\rho = 0.5$, $p < 0.01$); age and the VR experience (Spearman $\rho = 0.5$, $p < 0.01$); and the VR experience and the accuracy rate (Spearman $\rho = 0.5$, $p = 0.01$). Age was not correlated to any of the questionnaire metrics.

4.6.4. Cybersickness

The average experiential consequences were low (median 1.75, SD = 1.0). However, two users reported significant issues from the VR exposure (see Fig. 9). Medians for all three categories of the CSQ-VR (nausea, disorientation, oculomotor conflicts) were 1.5, whereas nausea had the largest standard deviation (SD = 1.1), followed by oculomotor conflict (1), and vestibular disorientation (0.9). These results indicate that the immersive VR application induced very little nausea and cybersickness for the majority of the users, but some sensitive individuals may feel uneasiness from interacting with the virtual environment.

A p-value of less than 0.01 strongly supports the hypothesis *H3* in all scales of experiment consequences, nausea, disorientation, and oculomotor symptoms.

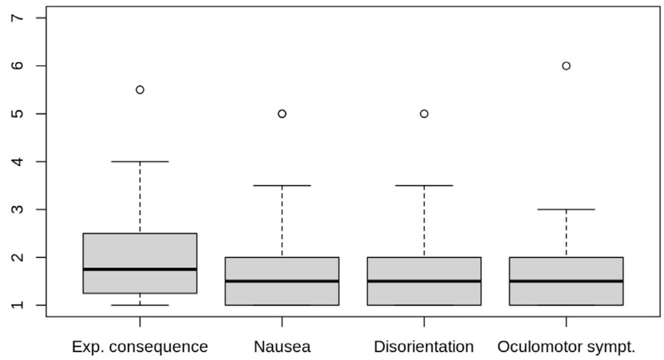

Fig. 9. Boxplots for experiential consequences (cybersickness). The whiskers extend to cover the range up to 1.5 times the IQR from Q1 and Q3, and circles represent outliers from that range.

4.6.5. Expert evaluation

We also conducted an expert evaluation involving individuals with extensive expertise in VR and graphics technologies. The panel comprised four members from various age groups and professional backgrounds, selected for their substantial involvement in VR-related projects at CYENS - Centre of Excellence, which is located in Nicosia, Cyprus. Leveraging their expertise in graphics and psychology, we anticipated insights into both technical and psychological aspects of the VR experience. Despite their limited diving experience, their feedback provided valuable perspectives on accessibility and clarity within the application.

The evaluation process began with an overview of the project's objectives, followed by an opportunity for experts to explore the immersive VR dive navigation application without prior knowledge of controls or tasks, aiming to elicit natural interaction and initial impressions. Following a guided tour, experts freely navigated the virtual environment, followed by structured conversations to gather deeper insights into their experiences and opinions. Additionally, participants were provided with a questionnaire covering key aspects of the VR dive navigation experience, including usability, immersion, graphics quality, educational value, and overall user experience. The questionnaire utilized rating scales, multiple-choice questions, and open-ended responses to collect both quantitative and qualitative feedback.

In particular, the questionnaire was divided into two sections. The first section assessed user interactions, movement, and immersion within the environment. Feedback was generally positive, with users finding interactions intuitive and movement natural. Visual clarity and predictability of actions were highlighted as strengths, contributing to an engaging experience. In the second section, educational aspects were evaluated, revealing users' understanding of the project topic and learning effectiveness. While users acquired knowledge about the Amathus harbor, some expressed a sense of incompleteness in the provided information, indicating potential areas for further expansion. Experts also recognized VR's potential in promoting cultural heritage and enhancing learning experiences compared to traditional methods. Finally, the feedback on navigation methods and transportation options was positive, with suggestions for improvements such as clearer visual cues and alternative locomotion methods.

5. Discussion

This section discusses the findings of our user evaluation study, focusing on the effectiveness and user experience of an immersive VR application. The user evaluation study was carefully planned and conducted with appropriately selected and balanced groups of participants. Throughout the evaluation, participants interacted with the VR environment and underwent post-experience assessments to evaluate knowledge acquisition and VR-related discomfort. The results provided insights into the effectiveness of the VR application in promoting learning and the prevalence of cybersickness among users.

Results from the post-VR multiple-choice test showed a learning rate of 70%. This number indicates a decent level of knowledge acquisition, comparable to results in other studies exploiting VR for teaching and training in various fields (e.g., a test score of 56.5% in plant cell biology [74], 50.5% in motorcycle parts labeling task [75], or 59.6% of new words learned in a VR teaching tool [76]). These results align with the questionnaire results confirming the high quality of the VR experience in terms of immersion, presence, and other investigated metrics. All these results are based on statistical testing with a-priori-stated hypotheses. While we did not find correlations between learning rate and presence or immersion, previous research suggests that both immersion [77] and presence [78] serve as learning facilitators in virtual environments.

The metrics of cybersickness indicated minimal issues resulting from the VR experience. With the exception of a few participants, users in the study did not report experiencing nausea, disorientation, or oculomotor symptoms leading to discomfort. However, there is room for improvement; increasing the frame rate of the visual content in the HMD could mitigate cybersickness issues for affected participants. Additionally, refining the locomotion system to better synchronize with the user's movements could reduce the disparity between perceived motion in VR and the user's physical movement.

We observed a statistically significant correlation between age, immersive VR experience, and the learning rate. This indicates that either previous VR experience, age, or both factors had a substantial impact on knowledge acquisition from VR exposure. While this finding does not fully disentangle the relationship, it is evident that participants in our sample, with a median age of 23.5 and a standard deviation of 4.1 years, had more VR experience with older ages (with some of them being VR professionals). There are two plausible conclusions regarding the accuracy rate: older participants may have been better able to concentrate on the content, resulting in higher knowledge retention compared to younger participants. Alternatively, the level of preexisting VR experience may have influenced this effect. Particularly the latter is an interesting hypothesis, suggesting that the novelty of the VR experience and the associated "wow" effect may hinder learning. Indeed, participants encountering VR for the first time may have been overwhelmed by the immersive nature of the experience, potentially having a harder time focusing on the learning objectives (the VR content).

Finally, the expert evaluation provided valuable insights into the strengths and areas for improvement of the immersive VR dive navigation experience. Their feedback highlighted positive aspects of user interactions, movement, and immersion within the environment, with users finding interactions intuitive and movement natural. The visual clarity and predictability of actions were also noted as strengths, contributing to an engaging experience. However, users expressed a sense of incompleteness in the provided information about the Amathus harbor, suggesting opportunities for further expansion. Moreover, experts recognized VR's potential in promoting cultural heritage and enhancing learning experiences compared to traditional methods. Positive feedback on navigation methods and transportation options was received, with suggestions for improvements. Overall, the expert evaluation provided valuable insights into the strengths and areas for improvement of the immersive VR dive navigation application, informing future development and refinement efforts.

6. Conclusions

Underwater cultural heritage sites hold immense fascination for researchers and the general public, yet their accessibility is hindered by the physical barrier of the sea. Currently, only divers or people in submarines can explore these sites. Thus, our project marks a significant advancement in the domain of digital underwater cultural heritage exploration. By focusing on the ancient harbor of Amathus in Limassol, Cyprus, and employing cutting-edge immersive VR technology alongside procedural techniques commonly utilized in Serious Games, we have created an immersive and realistic experience. Our work allows users to delve into the depths of history, offering opportunities for education, tourism, and marine conservation.

The digitization process, utilizing photogrammetry and modeling, has enabled the creation of a detailed 3D model of the underwater harbor, forming the cornerstone of our immersive VR environment. This environment is easily accessible without additional equipment or expenses, ensuring widespread availability. Moreover, our incorporation of guided tours, procedural generation for content enrichment, and machine learning algorithms for lifelike fauna movements further enhance the user experience, fostering a sense of realism and engagement. Throughout the development process, we have prioritized immersion and realism, integrating techniques such as underwater environment effects, caustics, and crowd simulation. Additionally, attention has been paid to user interface and navigation, ensuring intuitive interaction within the virtual environment.

The outcomes of our user evaluation confirm the effectiveness and impact of our approach. We observed significant learning outcomes, which were supported by excellent immersive VR experience indicators and only minor discomfort issues. Additionally, an expert review provided valuable insights, highlighting positive user engagement and immersion, while also suggesting enhancements in content depth and navigation. Nonetheless, our work underscores the transformative capacity of VR technology in underwater exploration, setting a new benchmark for immersive experiences and paving the way for further innovation in the field.

Limitations. In contrast to the underwater ancient harbor scanning, the surrounding area has been modeled instead of being scanned. This decision resulted in a reduced level of realism, particularly evident in the portrayal of trees, sand, and other detailed elements. However, employing photogrammetry for 3D reconstruction demands significant resources to capture and integrate such details, especially those involving animated fauna affected by wind, thus requiring extensive post-processing. Overall, challenges associated with creating a 3D model of the underwater archaeological site have partially impacted realism and quality, highlighting areas for improvement.

Finally, rendering trees in our immersive VR environments posed another challenge, with flickering leaves negatively impacting the experience. We attempted to mitigate this by experimenting with different anti-aliasing methods, although at the cost of slightly blurred visuals. Additionally, while most users found the transportation system intuitive, some suggested alternative methods that are now under investigation. Motion sickness, particularly during underwater travel, also emerged as a concern, detracting from the overall experience.

Future Work. Based on the insights gained from this work and the remarks of the participants in the user evaluation, several observations and recommendations for future improvements have been identified. One notable suggestion involves augmenting the environment by introducing a wider variety of marine species and emphasizing notable landmarks to enrich the user experience. Efforts to incorporate mixed reality content are also underway to further enhance and enrich the experience. Additionally, initiatives to optimize performance, streamline user guidance, and broaden the educational content with more historical details are under development, aiming to enhance overall usability and educational value. Enhancing clarity on game controls and menu options aims to improve user-friendliness, ensuring a more enjoyable and engaging experience overall. In another significant future implementation, we plan to integrate procedural modeling and machine learning into a gamified experience, such as using procedural strategies for defining large-scale universes. Additionally, in future work, we intend to expand our participant pool for user evaluations to include a broader demographic, enhancing representativeness.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.culher.2024.09.006

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