DM

Extended Reality Interfaces for Enhancing User Engagement and Learning in Onshore Whale-Watching

MASTER DISSERTATION

Telmo Gonçalves Silva

MASTER OF INTERACTIVE MEDIA DESIGN

UNIVERSIDADE da MADEIRA

A Nossa Universidade

www.uma.pt

May | 2025

Extended Reality Interfaces for Enhancing User Engagement and Learning in Onshore Whale-Watching

MASTER DISSERTATION

Telmo Gonçalves Silva
MASTER OF INTERACTIVE MEDIA DESIGN

SUPERVISOR
Marko Radeta

CO-SUPERVISOR
Filipe Marco Andrade Alves

Extended Reality Interfaces for Enhancing User Engagement and Learning in Onshore Whale-Watching

Telmo Gonçalves Silva

Master of Interactive Media Design
Universidade da Madeira, Funchal, Portugal
`2031615@student.uma.pt`
Supervised by Prof. Dr. Marko Radeta and Co-Supervised by Prof. Dr. Filipe Alves

Abstract

Nowadays, the image of great whales has been dramatically shifted from being viewed as a dangerous species and a source of resources to a species that has been protected and turned into a symbol for marine life sustainability, being whale-watching an important touristic and economic activity. Whale-watching is a globally significant activity that provides public engagement with marine life; however, traditional methods often fall short due to ecological disturbances, limited accessibility, and a lack of deep educational and emotional connections. This thesis explores the potential of Extended Reality (XR) technologies—specifically Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR)—to address these challenges in coastal whale-watching experiences. The research aims to evaluate the effectiveness of AR, VR, and MR in enhancing user engagement, educational outcomes, and conservation awareness. Through simulated whale-watching experiences in coastal settings, the study collected participant feedback, pre- and post-experience questionnaires, and observational data to assess the usability, educational impact, and emotional connection facilitated by each technology. Key findings reveal that AR is particularly effective in promoting user engagement and educational impact, while MR excels in fostering a strong emotional connection to marine life. Despite these benefits, each technology faces distinct challenges related to ease of use and environmental constraints, highlighting areas for further optimization. This research contributes to the growing field of XR in marine tourism by providing valuable insights into how these technologies can be optimized to create more engaging, educational, and sustainable whale-watching experiences. The findings offer a foundation for future research and development in the application of XR technologies within marine environments.

Keywords

Mixed Reality, Educational engagement, Marine Conservation, Augmented Reality, Virtual Reality, Whale-watching.

Resumo

Atualmente, a imagem das grandes baleias mudou drasticamente, passando de uma visão de espécies perigosas e fonte de recursos para uma espécie protegida e transformada em símbolo da sustentabilidade da vida marinha, com a observação comercial de baleias sendo uma importante atividade turística e económica.

A observação comercial de baleias é uma atividade globalmente significativa que promove o envolvimento do público com a vida marinha; no entanto, os métodos tradicionais frequentemente falham devido a distúrbios ecológicos, acessibilidade limitada e falta de conexões educacionais e emocionais profundas. Esta tese explora o potencial das tecnologias de Realidade Estendida (XR)—especificamente Realidade Aumentada (AR), Realidade Virtual (VR) e Realidade Mista (MR)—para enfrentar esses desafios em experiências de observação comercial de baleias em ambientes costeiros.

O objetivo da pesquisa é avaliar a eficácia da AR, VR e MR em melhorar o envolvimento dos utilizadores, os resultados educacionais e a conscientização sobre a conservação. Através de experiências simuladas de observação comercial de baleias em cenários costeiros, o estudo recolheu feedback dos participantes, questionários antes e depois das experiências, e dados observacionais para avaliar a usabilidade, o impacto educativo e a conexão emocional promovida por cada tecnologia.

Os principais resultados revelam que a AR é particularmente eficaz na promoção do envolvimento dos utilizadores e no impacto educativo, enquanto a MR se destaca em fomentar uma forte conexão emocional com a vida marinha. Apesar destes benefícios, cada tecnologia enfrenta desafios distintos relacionados com a facilidade de uso e as restrições ambientais, destacando áreas para otimização futura.

Esta pesquisa contribui para o crescente campo da XR no turismo marinho, fornecendo informações valiosas sobre como estas tecnologias podem ser otimizadas para criar experiências de observação comercial de baleias mais envolventes, educativas e sustentáveis. Os resultados oferecem uma base para futuras pesquisas e desenvolvimentos na aplicação de tecnologias XR em ambientes marinhos.

Palavras-Chave

Palavras-chave: Realidade Mista, Envolvimento Educacional, Conservação Marinha, Realidade Aumentada, Realidade Virtual, observação comercial de baleias.

Acknowledgements

This thesis would not have been possible without the support and encouragement of several individuals and organizations, to whom I owe my deepest gratitude.

First and foremost, I want to extend my heartfelt thanks to my fiancé, Margarida Giestas, a fellow University of Madeira alumnus, who has been an unwavering source of emotional support. Her understanding and patience, especially during the long hours spent on this thesis, often at the expense of our time together, have been invaluable. Her belief in me kept me motivated throughout this journey.

I am profoundly grateful to my thesis advisor, Prof. Dr. Marko Radeta, for his guidance and encouragement throughout this challenging project. His patience, willingness to provide support regardless of the time passed, and his insightful feedback have been instrumental in shaping this work and my development as a researcher.

I would like to express my sincere appreciation to Prof. Dr. Filipe Alves, whose connections and support made the testing phases of this study possible. His advice and assistance were crucial in navigating the logistical challenges of this research, and I am deeply thankful for his involvement.

My colleagues at MARE, Jocelyn Pestana and Francisco Silva, deserve special thanks for their collaboration and technical expertise in developing the MRDome app, which was critical to the success of this study. Their dedication and teamwork have been integral to this project.

I am also deeply thankful to VMT Madeira marine tourism company for their generosity in allowing me to use their facilities and clients for the study. Their cooperation and the credibility they lent to my research were vital in ensuring the quality and success of the fieldwork.

Finally, I want to thank my friends and family, whose encouragement and occasional pressure to "just finish it already" provided the necessary motivation to complete this project. Their understanding and support, whether through patience during my absence or by pushing me to keep going, have been essential to my success.

To all of you, I offer my deepest gratitude.

This dissertation is part of the following projects: **INTERWHALE** - Advancing Interactive Technology for Responsible Whale-Watching, with grant no. PTDC/CCI-COM/0450/2020 by FCT; **LARGESCALE** - Location-based Augmented Reality Gadgets and Environment-friendly Sightseeing of Cultural Attractions for Locals and Excursionists, with grant no. PTDC/CCI-CIF/32474/2017 by FCT and Portuguese National Funds (PIDDAC); **INTERTAGUA** - Interfaces Aquáticas Interativas para Deteção e Visualização da Megafauna Marinha Atlântica e Embarcacoes na Macaronésia usando Marcadores Rádio-transmissores, with grant no. MAC2/1.1.a /385 by Programa de Cooperación INTERREG V-A España-Portugal MAC (Madeira-Azores-Canarias) 2014-2020; This study had the support of FCT through the strategic project UIDB/04292/2020 awarded to MARE and through project LA/P/0069/2020 granted to the Associate Laboratory ARNET. Project has been conducted with the support of the Wave Labs[1] - interactive technologies for depicting the anthropogenic impact on the marine biosphere.

Telmo Gonçalves Silva

---

[1] `https://wave-labs.org`

Table of Contents

List of Figures

1 Introduction

Whale-watching has become a prominent form of nature-based tourism, often promoted for its potential to raise public awareness of marine life and conservation. In Portugal, tours are typically priced at around thirty euros, lasting three hours, with approximately fifteen minutes of cetacean observation, where whale sightings are less frequent than those of dolphins [55]. The typical visitor tends to be relatively well-educated, of higher income, and motivated by an interest in nature and conservation. Despite its popularity, whale-watching depends on unpredictable whale presence, and participation is restricted to those with the financial means and geographical access to coastal areas. An alternative for bringing humans closer to such remote species lies in Extended Reality (XR) technologies — including Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) — which may enable visitors to explore whales virtually from shore, thereby reaching broader audiences. These technologies may also be further used to fulfill the expectations of tourists on sea-vessels, particularly when encounters with large whales are brief or absent. This dissertation work intends to use XR technologies to set in motion the initial steps to new innovative and resourceful ways of broadening whale-watching, while also supporting conservation awareness. In doing so, it may contribute to the gradual expansion of whale-watching and highlight Madeira Island as a relevant destination for sustainable marine tourism.

1.1 Paradigm Change

Marine conservation has gained unprecedented importance in recent years, as the health of our oceans and the species that inhabit them are increasingly under threat from human activities. Whales, as apex predators and vital contributors to the ocean's carbon cycle, play a crucial role in maintaining marine ecosystem balance. Despite global conservation efforts, whales continue to face significant challenges, including direct collisions with ships, noise pollution, and the lingering effects of historical whaling.

The practice of whale-watching has emerged as a popular activity worldwide, offering a unique opportunity for the public to engage with these majestic creatures in their natural habitats. However, traditional educational whale-watching methods present several challenges. These methods often involve close proximity to whales, which can lead to ecological disturbances. Furthermore, the accessibility of whale-watching experiences is limited by geographical and economic barriers, restricting participation to those who can afford the cost and live near coastal areas. Given these limitations, there is a growing interest in exploring how technology can be leveraged to enhance whale-watching experiences while minimizing their negative impacts. XR technologies present a promising solution. These technologies offer the potential to create immersive, educational, and less intrusive whale-watching experiences, making them more accessible to a broader audience. Traditional whale-watching practices, while popular, often fail to provide the deep educational and emotional connections necessary for sustained conservation efforts. The ecological impact of these activities, combined with their limited accessibility, highlights the need for alternative approaches that can engage and educate the public in a more responsible and impactful manner.

In response to these challenges, this dissertation explores the potential of XR technologies to revolutionize onshore whale-watching experiences. By creating virtual encounters with whales, XR can offer immersive and educational experiences that are accessible to a wider audience, reducing the ecological footprint of whale-watching while enhancing public awareness and engagement with marine conservation.

1.2 Problem Statement

Whale-watching has become an increasingly important and growing activity worldwide, offering people the opportunity to observe these magnificent creatures in their natural habitats. However, traditional whale-watching methods often fall short in providing a fully engaging and responsible experience, particularly in coastal settings where whales may be distant or difficult to observe. The passive nature of these experiences can leave participants feeling disconnected from the marine environment and the broader conservation efforts. While XR technologies, have shown promise in enhancing various sectors, their application in marine settings, particularly for whale-watching, remains underexplored. The potential of XR to revolutionize coastal whale-watching experiences by providing immersive and educational interactions with virtual marine environments is significant.

1.2.1 Limitations of Traditional Educational Whale-watching Methods and Opportunities for XR

Despite the growing popularity of whale-watching, there remains a significant gap in public understanding of marine ecosystems and the importance of conservation. Traditional whale-watching experiences often fail to provide sufficient educational content, limiting participants' awareness of the threats facing marine life. This lack of marine literacy hampers efforts to promote conservation and responsible interaction with the environment and perpetuates misconceptions about whales. One of the key objectives of whale-watching tourism is to enhance marine literacy and raise awareness of conservation issues. XR has the potential to introduce non-experienced individuals to whale-watching, fostering greater appreciation and understanding of marine life. However, the extent to which XR can contribute to these outcomes in onshore settings has not been fully explored.

Conventional offshore approaches to whale-watching can be intrusive to marine life, leading to disturbances in natural behavior and misaligning with responsible tourism practices. The ecological impact includes behavioral disturbance, increased stress from engine noise and human activity, and collision risks that can cause injuries or fatalities. Many whale species are already endangered, and these practices can heighten threats, complicating protection efforts. Moreover, enforcement of protective regulations varies by region, leading to inconsistent practices that further endanger these animals. In contrast, whale-watching from onshore locations often yields low engagement, the experience can be passive and less immersive, reducing its impact on participants' understanding and appreciation of marine ecosystems and leaving some viewers feeling disconnected from the environment.

Given these limitations, achieving a meaningful emotional connection with great whales is also challenging. Traditional methods often fail to translate observation into felt connection, underscoring the potential of XR to create more immersive and emotionally resonant experiences. A critical aspect of wildlife tourism is fostering deeper emotional bonds that support conservation. It is essential to examine how different XR technologies shape emotional responses and motivate participation in marine conservation, particularly in the context of whale preservation.

Traditional whale-watching opportunities are restricted to specific coastal locations, making them inaccessible to many people. XR can overcome these geographical limitations by bringing whale-watching to individuals regardless of location. Furthermore, the high cost of tours limits participation, creating an economic barrier to engaging with marine life and conservation learning firsthand. XR offers a more affordable alternative: while high-end systems may have an initial cost, experiencing virtual whale-watching from home or a local facility can be more cost-effective than traditional tours, and accessibility is increasing as costs decline. However, XR accessibility varies across demographics, including economic factors, age, and physical abilities. High headset costs can be a barrier for economically disadvantaged groups, current system design may not be fully inclusive for older adults, and some features pose challenges for individuals with disabilities. To realize XR's potential for sustainable and inclusive whale-watching, these accessibility issues must be addressed so systems are affordable, usable, and accessible to all.

1.2.2 External Constraints and Underexplored Potential of XR in Marine Tourism

Despite the promise of XR technologies, they are subject to various external constraints, including environmental factors such as weather and lighting, as well as technological limitations like motion sickness and hardware comfort. These challenges can significantly impact usability, effectiveness, and overall visitor experience, particularly in onshore whale-watching settings. Understanding how AR, VR, and MR compare in terms of user experience and adoption in coastal scenarios is crucial for optimizing these technologies as a viable alternative.

Nevertheless, XR technologies offer innovative solutions to enhance whale-watching experiences and address the gap in marine literacy. However, their potential in marine tourism and coastal environments remains underexplored, including how XR can create immersive, educational experiences that foster a deeper connection with marine conservation. As XR evolves, there is a need to optimize comfort, usability, and overall visitor experience in onshore whale-watching without the ecological footprint of traditional boat tours, and to clarify pathways for future adoption by addressing current challenges.

1.3 Research Statement

To achieve the goals of the proposed dissertation, the research questions guided a comparative user study, allowing the apparatus to be tested in on-shore settings. Although whales remain distant in on-shore setting, interaction in such setting is currently passive, as whales may be seen solely using binoculars. This dissertation proposes a novel approach, augmenting such passive experiences with virtual great whales.

Dissertation studies several research questions:

- RQ1: How do AR, VR, and MR technologies compare in enhancing educational outcomes, in marine literacy and awareness of conservation issues in coastal whale-watching experiences?
- RQ2: How do AR, VR, and MR technologies compare in fostering user engagement, including enthusiasm and emotional connection with marine life, in coastal whale-watching experiences?
- RQ3: How do AR, VR, and MR technologies compare in terms of ease of use and adaptability to coastal whale-watching experiences?

By addressing these research questions, the dissertation aims to provide valuable insights into the application of XR technologies in marine environments, offering recommendations for future research and development in the field.

1.4 Contributions

This dissertation makes several contributions to the study of XR in marine tourism. A multi-modal XR artifact was developed for onshore whale-watching, comprising three complementary experiences: an AR smartphone application using custom 3D marine models and image-trigger interactions, a VR encounter optimized for mobile headsets, and a cardboard-based MR setup blending virtual whales with the coastal environment. Each modality presented three scenarios—"Whale and Divers," "Fishing Net with Whales," and "Whale Feeding Cycle"—designed to convey scale, highlight anthropogenic threats, and visualize ecological processes. The content pipeline, from modeling and animation to Unity integration, was implemented to support interactive and accessible learning flows. In addition, a comparative field study with 60 participants was conducted directly after whale-watching tours at Praça do Povo in Funchal. Using pre- and post-questionnaires, Likert-scale evaluations, and observational data, the study explored marine literacy, engagement, emotional connection, enthusiasm, and usability under real outdoor conditions. This field-based approach provided an opportunity to examine XR in a natural tourism context, where factors such as weather, sunlight, and headset comfort shaped the overall experience. The work generated preliminary insights into the comparative use of AR, VR, and MR in onshore whale-watching. The study suggested that AR may be particularly useful for supporting knowledge acquisition, MR appeared to encourage stronger emotional engagement and ease of use, and VR provided a sense of immersion but faced usability challenges in outdoor settings. These insights highlight how different XR technologies may contribute in distinct ways to learning, engagement, and user experience. A modest methodological contribution was also made by implementing pre-/post-questionnaires and Likert-scale instruments for outdoor fieldwork, demonstrating how XR usability and learning outcomes can be assessed in real-world tourism environments. Finally, the research suggested practical implications for marine tourism and conservation communication. XR may help mitigate geographical and economic barriers to whale-watching by offering more accessible alternatives, while also potentially reducing ecological impacts by simulating encounters without physical intrusion. At the same time, the findings pointed to the need for further technical refinements, particularly in relation to AR robustness in sunlight, MR visual clarity, and VR headset comfort, to improve deployment in outdoor settings. Overall, this dissertation provides a basis for future studies and applications of XR in marine tourism. Its system design, field evaluation, and preliminary findings may inform researchers, developers, and practitioners interested in advancing immersive, sustainable, and inclusive approaches to whale-watching and marine education.

1.5 Dissertation Structure

This dissertation is organized to progress from motivation to evidence and implications. Chapter 2, Related Work, establishes the scholarly context by reviewing whale-watching as a phenomenon with emphasis on Madeira, responsible practice and sustainability, and the role of XR in tourism and marine environments, while also examining psychological outcomes of immersive media, conservation communication potential, and the constraints of deploying XR outdoors; together, these strands motivate the research gap and frame the research questions. Chapter 3, Methodology, presents the overall research approach, connecting the related work to the study's objectives, outlining the high-level concept, and describing the system design and evaluation approach adopted to compare AR, VR, and MR in outdoor whale-watching contexts. Chapter

4, System Design, details the XR artifact developed for the study, including hardware and software choices, the content pipeline from modeling to animation, Unity integration, and the application architecture and user experience that enable the AR, VR, and MR implementations used in the field. Chapter 5, Evaluation Study, describes the field study with 60 participants, the interactive setup and location, recruitment, pre- and post-questionnaires, testing procedures for AR, VR, and MR, the evaluation and data collection approach, and the ethical considerations underpinning replicability and validity. Chapter 6, Results and Discussion, reports participant demographics, pre/post knowledge outcomes, participant evaluations, and the influence of environmental factors, and interprets these findings in relation to the research questions and prior work, including a comparative analysis of AR, VR, and MR and a discussion of limitations. Chapter 7, Conclusion and Future Works, synthesizes the main contributions, reflects on the suitability of each modality for onshore whale-watching, and outlines directions for improving realism, comfort, accessibility, and deployment of XR in marine tourism settings.

2 Related Work

2.1 Whale-Watching

In a study of Icelandic fishing communities, Einarsson [28] highlights that whale-watching is an internationally growing industry, while whaling is in decline, marking a shift from the historical reliance on whaling practices. The author also notes that small resource-dependent coastal settlements continue to cope with rapid social and ecological change, where traditional consumptive attitudes toward marine mammals persist. In these fishing villages, local inhabitants reconcile opposing views on whales, whaling, and the emerging cetacean tourism.
According to Oslund [85], there is a need to examine these two aspects of history in relation to each other, analyzing how the multiplicity and complexity of human–whale interactions worldwide impacted the environmental history of whales, both before and after the emergence of the "save the whales" campaigns of the 1970s. Cunningham et al. [23] compare whaling and whale-watching, noting that these divergent practices have different viability. Whale-watching is viewed as a fast-growing ecotourism activity that promotes local conservation and regeneration. It is a sustainable practice that is both ecological and profitable, with participation growing from 9 million tourists in 2001 to 13 million in 2008, and revenues rising from $1 billion to $2.1 billion annually over that period. Whaling, on the other hand, relies on economic and cultural rhetoric to support its viability, while depending on state and private subsidies. These differences suggest that whale-watching may offer a serious alternative economy for whaling communities, supported by both public opinion and global trends. Kalland [48] argues that whales have long held symbolic significance, being enormous and anomalous animals that are difficult to categorize. They live in salt water, which is often associated with purity, and possess qualities similar to those of humans. Increasingly, opposition to whaling has been framed on moral and ethical grounds. As seen in Figure 1, their majestic presence underwater evokes both awe and fascination. Whales came to hold a symbolic status in the animal kingdom by combining characteristics found in diverse whale species, and this symbolic significance underscores the broader shift in public perception and policy from exploitation to conservation.

Fig. 1: Live action shot by Lobosonda of a great whale underwater near Madeira Island, capturing the thrill and awe of the moment i [65].

In 2013, Orams [83] found through research in Vava'u, Tonga that whales had become the predominant attraction for visitors to these remote islands, based on data collected through self-administered questionnaires. Interviews with tour operators further confirmed the increasing influence of whale-based activities on overall tourism in the Vava'u area. For instance, Cisneros-Montemayor et al. [17] assessed the potential for whale-watching in maritime countries not yet involved in the industry in 2009, estimating that it could generate an additional 413 million USD in annual revenue and support approximately 5,700 jobs. Notably, Mustika et al. [77] observed that the number of cetacean-watching tourists in developing countries doubled between 2003 and 2013, often occurring without regard for regulations or informed research. The authors also noted that research into the human dimensions of the tourist experience and the design of sustainable marine wildlife tourism remains limited. Ávila-Foucat et al. [4] demonstrated through empirical research that perceived and reported crowding negatively affect the probability that tourists will return for a whale-watching trip. However, the authors also noted that well-designed coastal management policies can both protect whales and increase the likelihood of tourists returning to the site. These findings indicate that companies cannot simply increase boat trips to boost the industry, as doing so can be counterproductive. Krasovskaya [55] estimated the 2015 economic contribution of the whale-watching industry in Madeira at €4,186,354, based on data from 12 main operators. This substantial economic contribution emphasizes the viability of whale-watching, supported by both ecological benefits and economic incentives. In the Archipelago of

Madeira, around 35% of the world's marine mammal species can be observed. Whale-watching in Madeira became a fast-growing activity since its beginning in the 2000s. As seen in Figure 2, which features footage from Madeira Island, whale-watching activities often include pods of whales, emphasizing their scale and beauty, which further highlights the appeal of these experiences.

(a) Pod of whales near Madeira Island, emphasizing the scale and beauty of these creatures, video by Joen & Amalie [47].

(b) Aerial view of two whales swimming in deep blue waters, in proximity to Madeira Island, recorded by Lobosonda [64].

Fig. 2: Aerial view of a pod of whales swimming in the surrounding waters of Madeira Island.

Garrod and Fennell [39] present the results of a manifest content analysis of 58 whale-watching codes of conduct from around the world, revealing significant disparities among them, not least in terms of the detail of the various guidelines they contain. Whale-watching is often seen as a conservation-friendly alternative to whaling and has produced a large number of such codes of conduct. However, this variation is not considered conducive to the sustainable development of whale-watching.

Williams et al. [114] tested the relevance of a voluntary code of conduct requesting that boats not approach whales closer than 100 m, as shown in Figure 3, which highlights a catamaran maintaining an appropriate distance. Whales responded to experimental approaches by adopting a less predictable path than observed during the preceding no-boat period. Females responded by swimming faster and increasing the angle between successive dives, whereas males maintained their speed and chose a smoother but less direct path. Canonical correlations between whale behaviour and vessel proximity were consistent with these conclusions, suggesting that weakening whale-watching guidelines, or not enforcing them, would result in higher levels of disturbance. Additionally, Argüelles et al. [2] analyzed the short-term impact of whale-watching on the behavior of Southern right whales (Eubalaena australis) in Patagonia, Argentina. The researchers found that when boats approached appropriately, with engines off, whales reacted positively by approaching the vessel and seeking contact, whereas inappropriate approaches, with engines on, caused whales to react negatively by moving away and avoiding contact.

Fig. 3: Whale-watching tour near Madeira Island, highlighting the catamaran boat, video by Travel Awaits [2].

This concern is echoed by Au and Green [3], who measured the underwater acoustic noise of five representative whale-watching boats in West Maui to study the effects of boat noise on the auditory system of humpback whales. The findings suggest that it is unlikely that the sound levels produced by the boats would have any grave effects on the whales' auditory system. However, the authors noted that ongoing exposure might still mildly affect whale behavior, as this aspect was not tested. Moreover, Parks et al. [87] examined the impacts of increased ocean noise on right whales, showing that during periods of heightened noise the whales increased the amplitude of their calls. This response affects both the way whales use sound to communicate and the human ability to detect them with passive acoustic monitoring systems. Tkaczynski and Rundle-Thiele [106] segmented 727 whale-watching tourists into four groups and introduced sustainability as a new criterion. The largest segment, wealthy domestic families who were also the most educated and financially well-off, offered the best opportunity for maximizing economic gains while supporting environmental conservation. Building on this understanding of environmental impacts, Lopes and da Silva [66], in a book chapter on responsible nature tourism development, presented the case of the Azores as a compelling example of sustainable tourism. Recent shifts in leisure paradigms have led to an increase in informed, demanding visitors who prioritize the conservation of natural spaces. Whale-watching in the Azores, as seen in Figures 4a and 4b, is a key element of the region's nautical tourism and is highlighted as a sustainable practice. However, it also raises questions about the real impact of its implementation, prompting ongoing evaluations to ensure that this activity remains a model for responsible ecological conservation.

(a) Underwater view of whales swimming in clear blue waters near São Miguel, Azores Islands, showcasing their size and grace, video by Azores Whale Watching TERRA AZUL [112].

(b) Group of tourists engaged in whale-watching in the surrounding waters of São Miguel, Azores Islands, highlighting the popularity of eco-tourism, video by Azores Whale Watching TERRA AZUL [112].

Fig. 4: Azores sustainable whale-watching.

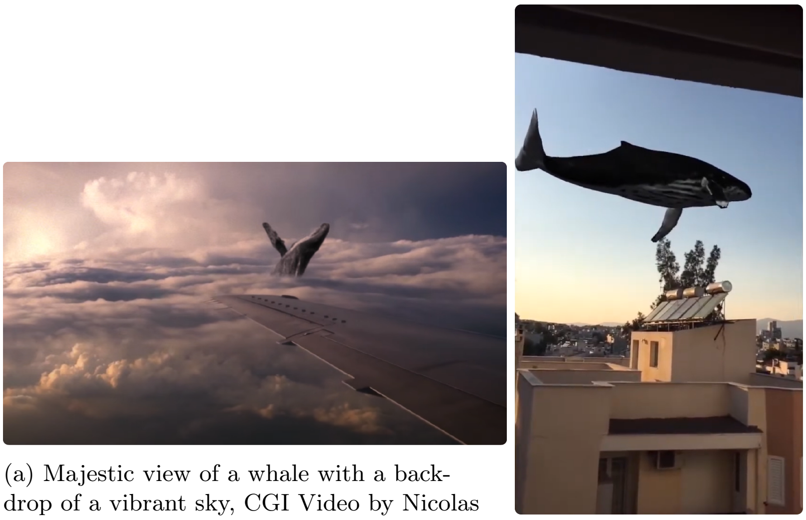
Building on the discussion of human impacts on marine mammals, Orams [84] reviewed historical accounts of human–wild dolphin interactions and showed that the 'new' dolphin-based tourism industry has developed from a long history of human–dolphin relationships. The review also revealed considerable risks, both for dolphins and for tourists, including harassment, stress, injury, and even death for dolphins, as well as injury for humans (see Figure 5). Further highlighting the need for careful management, Smith et al. [102] studied interactions between tourists and free-ranging bottlenose dolphins in an artificial feeding program at Monkey Mia, Australia. Their findings emphasized that long-term monitoring of tourism based on artificial feeding is essential to identify and rectify detrimental effects of provisioning on dolphins, ensure the safety and welfare of both dolphins and tourists, and maintain the sustainability of these interactions.

Fig. 5: Underwater view of whales swimming gracefully in Madeira Island's surrounding clear blue waters, video by Visit Madeira Official [110].

2.2 XR for Tourism

Fig. 6: A virtual whale breaching inside a gymnasium in front of a seated audience, blending reality with digital effects, video by Magic Leap [58].

Ryu [94] traced the evolution of visual effects in cinema from analog techniques such as rear projection to digital methods like CGI (see Figure 6), connecting this shift to broader cultural changes and using blockbusters as a case study to show how visual effects blend with cultural resistance. Similarly, Sawicki and Moody [96] reviewed the development of computer graphics from the advent of personal computing to the creation of hyper-realistic images, emphasizing the role of major corporate players and innovations in shaping the field. Their analysis highlights the technological foundations that have set the stage for Augmented Reality, with roots in computer-generated imagery and its transformative potential in digital interactions. Building on these technological advancements, Slater and Sanchez-Vives [100] noted that VR began to attract public attention about 50 years ago. Although the hardware at the time was very different, VR was hailed as the beginning of a new era before largely disappearing from public view. Research nonetheless continued in scientific, engineering, and industrial contexts, showing that VR is not intended to reproduce “reality” faithfully but to provide new and unexpected ways to achieve goals (see Figure 7a). Recently, Palestini and Basso [86] discussed increased investment in both hardware and software technologies for AR and VR, with a focus on creating real-time, explorable digital environments integrated with virtual stereoscopic headsets. Today, low-cost or freely licensed software often provides performance comparable to that of paid alternatives, enhancing accessibility to these technologies (see Figure 7b).

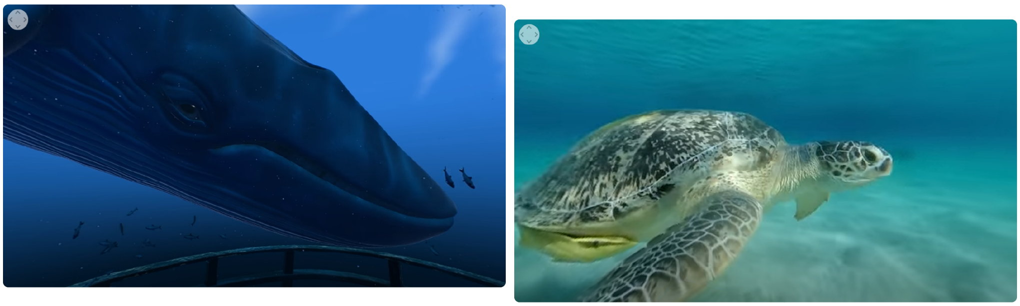


(a) Majestic view of a whale with a backdrop of a vibrant sky, CGI Video by Nicolas Meurs [73].

(b) Augmented reality depiction of a whale superimposed in an urban setting, merging nature with city life, video by eyeSphere [30].

Fig. 7: CGI and accessible Augmented Reality.

Egger and Neuburger [27] showed that VR, AR, and MR are opening a new paradigm, receiving increasing interest from both marketers and consumers. These technologies are not only creating opportunities by enhancing customer engagement through interactive experiences, but they are also paving the way for new marketing strategies that could revolutionize how tourists interact with travel destinations. Building on this foundation, Kim et al. [51] explored consumer behavior in VR tourism using an extended Stimulus-Organism-Response model. The results demonstrated that the intention to visit places shown in VR tourism was influenced by attachment to VR. Cognitive response had a stronger impact on the intention to visit a destination than affective response, shedding light on why potential tourists visit destinations presented in VR. Moreover, Tussyadiah et al. [108] confirmed that heightened feelings of presence in VR result in stronger liking and preference for the destination. Additionally, their study showed that positive attitude change leads to a higher level of visitation intention, providing empirical evidence of VR's effectiveness in shaping consumers' attitudes and behaviors. Various researchers argue that sustainability is considered among the most important topics within the tourism and information technology sectors. However, Cranmer et al. [22] noted that the use of AR technology to improve and increase tourism sustainability remains underexplored. This gap is particularly significant for cultural heritage tourism attractions, which rely heavily on preserving their natural environments as well as cultural and social traditions. Han et al. [41] noted that while AR has progressed beyond its hype stage, the technology is only on the verge of meaningful implementation in the tourism industry. However, for AR to be effective and attract tourists on a regular basis, it must be purposefully designed with user-specific functionalities, including multi-language support, ease of use, and personalization capabilities. Sanchez-Vives and Slater [95] explained the concept of 'presence' as the phenomenon of behaving and feeling as if one is in the virtual world created by computer displays. This feeling of presence is not only compelling for users but also critical for neuroscientists studying perception and consciousness, offering deeper insights into how virtual environments can simulate real-world experiences. The ability to feel present in the virtual world enhances the realism of interactions, which is particularly essential when simulating encounters with marine life (see Figure 8a). In parallel, Rubio-Tamayo et al. [92] reviewed the role of immersive virtual reality environments across scientific and educational fields. They emphasized that as these technologies evolve, they bring new interactive and immersive features that require novel narratives and user relationships. Their review underscored VR's role as a medium capable of conveying complex ideas and fostering new forms of interaction, making it an invaluable tool for environmental conservation (see Figure 8b).



(a) 360 experience focusing on underwater environments and whale interaction, providing users with a simulated dive into the ocean, from the Blu VR series, video by Wevr [113].

(b) Underwater 360 video capturing a serene turtle in its natural habitat, video by Airpano VR [111].

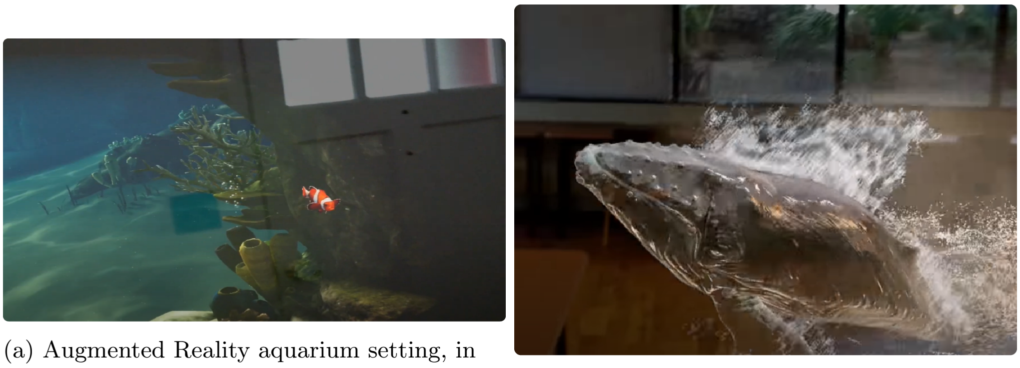
Fig. 8: 360 underwater experiences with marine life, simulation and video capture.

Fröschl [35] described the collaborative project NOISE AQUARIUM, in which XR visualizations of plankton species were created to present them at a scale that emphasizes their ecological importance. Similarly, Nassani et al. [78] reported on the Antarctica Marine AR project, which developed an augmented reality experience to highlight the significance of the Marine Protected Area of the Ross Sea, as illustrated in Figures 10a and 10b. Building on these themes, Chen et al. [15] introduced VV-Ocean, a virtual ocean simulation engine designed for high-fidelity representation of marine environments and life. The platform can be applied to a wide range of contexts, including demonstrating marine operations, communications, ocean games, reducing marine hazards, forecasting weather over oceans, and serving marine tourism. Relatedly, Jain et al. [46] developed a VR scuba simulation using sensors to capture buoyancy, drag, and temperature, with preliminary deployments showing strong potential to elicit a high sense of presence in VR. McMillan et al. [72] presented Infinite Scuba, a video game that enables players to explore the ocean virtually, including its recent VR adaptation, which has shown potential to support marine conservation awareness (see Figures 9a and 9b). Similarly, Calvi et al. [13] presented another VR diving game designed to increase player awareness of sustainable behavior underwater, though they noted it was not possible to confirm whether environmental awareness improved after gameplay.

(a) Illustrative VR game depicting marine life, enhancing, from Abzû video game, video by BandageGaming [37].

(b) Underwater exploration and adventure in VR, from Subnautica videogame, video by VR Game [38].

Fig. 9: Underwater exploration VR Games.



(a) Augmented Reality aquarium setting, in home, from Magic Leap's experience Undersea, video by ibrews [44].

(b) Whale simulation in augmented reality in home environment, from Magic Leap Magnopus Whale Demo, video by Engage VR [29].

Fig. 10: Home environment whale simulations.

In the context of in-field XR, Hugues et al. [43] integrated a vision system combining a thermal camera and a conventional camera into maritime navigation software based on a virtual environment. Their exploratory work presented AR applications for mobile use at sea, outlining potential functionalities, and was carried out under a CIFRE agreement with MaxSea Int. Benton et al. [6] explored how the close coupling of ocean and maritime models with augmented reality navigation systems can benefit both scientific understanding of the Arctic environment and safer, more affordable operations in Arctic waters. Liu et al. [61] presented BoatAR, a multi-user AR boat configuration system designed to address navigation issues. The prototype, implemented using HoloLens, was demonstrated to a group of boat dealers, providing an example of how such systems can support decision-making. Zhao et al. [116] simulated submarine motion in a virtual ocean environment using the Vega software package. Their results showed that underwater motion could be effectively represented and that the simulation system could be extended for virtual training. Oppermann et al. [82] developed AREEF, described as the world's first multi-player Underwater Augmented Reality (UWAR) experience, with the mission of bringing traditional computer games into the water using AR. Finally, Bellarbi et al. [5] proposed DOLPHYN, a device equipped with GPS, wireless connectivity, and a video camera to deliver AR content at the water surface and underwater by overlaying live footage with 3D animations. Similarly, Bruno et al. [11] developed UWAR technologies as part of the iMARECulture project to improve the experience of divers visiting the Baiae Underwater Archaeological Park in Naples (see Figure 11a). Their experiment showed that the proposed UWAR tools contributed to a better understanding of the underwater site and its archaeological remains by assisting divers in locating the work site, orientation, and position through a 3D virtual model. Lim [60] reported on Malaysia's first 5G AR marine life experience, where an AR showcase guided visitors on a virtual journey across the ocean floor, offering an immersive perspective on ocean conservation. Another study by Costa et al. [21] analyzed the effectiveness of different devices for underwater VR. By comparing rotation data, the researchers found that the magnetic tracking system implemented by the Razer Hydra was more accurate underwater compared to a phone-based IMU, suggesting that magnetic tracking systems should be further explored for underwater VR applications. As shown in Figure 11b, Costa [20] examined the feasibility of aquatic VR in a dissertation, noting that while aquatic VR is becoming more feasible and less expensive, it remains unclear how similar it is to non-aquatic VR. Results indicated that a phone IMU had several limitations leading to poor accuracy, while the Hydra demonstrated the least error in position. Vuforia performed slightly worse in slow movement and considerably worse during fast movement, though Hydra, Optitrack, and Vuforia all achieved high jump detection accuracy regardless of position and rotation accuracy.

(a) Underwater exploration with AR technology, showing detailed marine environments, video by HoloLux [68].

(b) Another scene of AR-enhanced underwater exploration, emphasizing technology's role in experiencing marine life, video by HoloLux [68].

Fig. 11: AR-enhanced Underwater exploration.

2.3 XR Effects

Revonsuo [91] described virtual ecosystems inhabited by artificial animals, each acting as an autonomous agent, and suggested that a networking solution could allow multiple remote users to control animals and interact within the virtual ecosystem. Lee and Choi [59] presented an application that superimposes 3D animal models in tideland environments whenever users create image targets in real time. The application included 3D models of ten tideland animals and a mobile interface for displaying them on smartphones.

Also, Zarzuela et al. [115] employed a virtually created zoo platform in an AR game for children and people with disabilities to present animal interactions. Morey and Crider [75] examined how Satoshi Tajiri, the creator of Pokémon, explored undeveloped areas as a child, engaging in bug-catching, analysis, and collection. They noted that this activity became the foundation of Pokémon as a game (see Figure 12).

Fig. 12: A playful augmented reality scene of a whale looking creature breaching the surface of the sea, from Pokémon Go videogame, video by Adiyen [89].

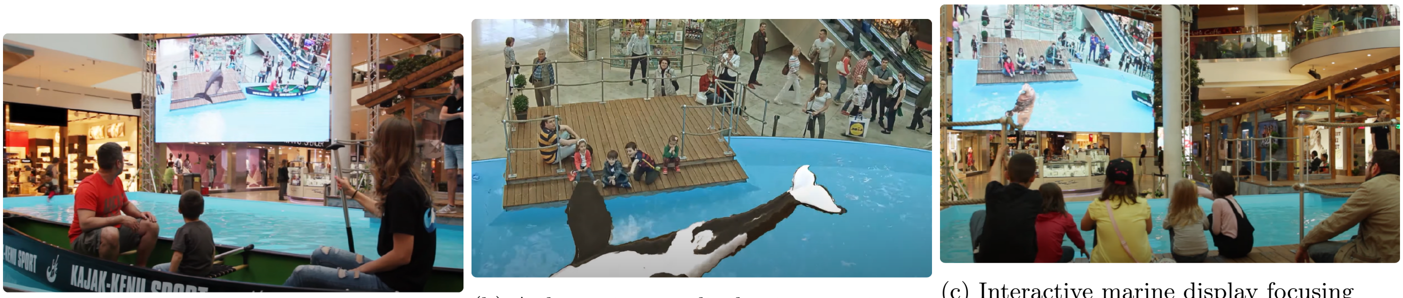
In a study of avatar embodiment in VR games, Krekhov et al. [56] investigated how virtual reality can strengthen the bond between players and their avatars, noting that the potential of nonhumanoid avatars remains underexplored. Their experiment revealed a correlation between virtual body ownership and game enjoyment, indicating that nonhumanoid creatures offer a meaningful design space for VR games worthy of further study. According to Ahn et al. [1], embodying animals in immersive virtual environments increases presence, embodiment, and inclusion of nature in self compared to video-based experiences. Building on this, Krekhov et al. [57] introduced five control methods for embodying three different animal forms within a VR environment, highlighting how virtual body ownership can support novel animal-centered game mechanics. Within the literature on tourism, Markwell [71] identifies the diverse relationships between animals and tourists, observing that species such as humpback whales, butterflies, and birds support tourism with significant returns, while others such as sharks, leeches, and flies may damage destination reputations. It is evident that animals intersect with tourists in multiple ways, inducing different emotional responses. Several authors, including Franklin et al. [34], emphasize the role of empathy in human-animal relations. Their study of neural responses to suffering noted that humans are predisposed to empathize with others as a means of maintaining social bonds. This capacity extends to nonhuman entities; however, people are more likely to empathize with creatures that share human-related qualities, responding instinctively rather than through semantic evaluation. According to Curtin [24], encounters with wildlife contribute to psychological well-being by provoking emotional responses such as awe, wonder, and privilege, which can lead to long-term health benefits, empathetic connections to animals, and ecological behavior. Participants often reported being absorbed in the spectacle of nature, with their thoughts concentrated on the moment. Similarly, Curtin and Kragh [25] emphasized that the psychological benefits and emotional responses of experiencing nature first-hand are valuable both for human health and for conservation. They noted that wildlife destinations are expected to attract increasing tourism from emerging economies, and argued that in a society largely disconnected from nature, this growth represents a potential awakening of ecological consciousness. Research by Bertella [7] found that the presence of animals reinforces an outdoor lifestyle. Influential elements included preconceptions of the animals, the possibility of human-animal interactions, and the presence of a guide. These findings highlight the potential of designing outdoor animal-based interactive experiences supported by storytelling and narrative. Whale-watching provides a clear example of these phenomena. Muloin [76] reported that visitors benefit from close encounters with whales, with satisfaction levels rising in relation to encounter intensity, proximity to vessels, and the length of surface intervals (see Figures 13a and 13b). DeMares [26] described how participants considered spontaneous encounters with cetaceans to be significant personal events that often led to peak experiences. They disclosed that reciprocity, connection, aliveness, and harmony culminated in emotional catharsis and healing.

(a) Segment of video capture of a whale breaching in whale-watching context, video by Newsflare [33].

(b) Dramatic video capture of a whale breaching, a powerful moment in whale-watching context, video by MaasaiSightings [69].

Fig. 13: Video captures of whale breaching.

Norouzi et al. [80] argued that augmented reality could offer potential for human–animal interaction in terms of mental and social health, and proposed several aspects of AR animals that warrant further research. Exploring the impact of VR on experiencing nature, Browning et al. [10] demonstrated that short exposures to 360-degree VR nature videos can significantly enhance physiological arousal and elevate mood levels, offering restorative effects compared to indoor settings without nature. They suggested that VR nature experiences could be particularly valuable in contexts where access to real environments is limited, such as marine education and conservation. Further research by Blum et al. [8] revealed that VR-based Heart Rate Variability Biofeedback in immersive natural settings decreases perceived stress, increases relaxation efficacy, reduces mind wandering, and enhances focus on the present moment. These benefits underscore VR's potential to promote well-being and concentration, highlighting its relevance for marine education and conservation by enabling deep, focused interactions without physical presence. In a study on computer-simulated pets, Tsai and Kaufman [107] found that participants built emotional bonds with their virtual pet dogs, with many believing that the dogs had their own interests and personalities. Participants often based desired activities on their perception of the pet's needs, demonstrating the capacity of virtual animals to foster empathy. Sierra Rativa et al. [98] investigated the effect of animal character appearance in games, showing that the realism of virtual animals significantly influenced user experience and empathy toward the characters. Prueitt et al. [90] developed *The Urban Whale*, a digital interactive experience focused on the North Atlantic right whale, designed to evoke empathy for the species and awareness of human actions hindering its recovery (see Figures 14a, 14b and 14c). The project was proposed as a template for future serious games centered on endangered species. Fuchs [36] distinguished between three forms of empathy: intercorporeal empathy, extended imaginative empathy, and fictional empathy. He argued that empathy in virtual contexts is not limited to direct contact but also becomes a medium for virtual relations, albeit with the risk of projecting fictional emotions. Finally, Liu [62] proposed a framework for applying VR to empathy across two dimensions—internal versus external worlds, and business innovation versus social innovation—offering a useful reference for promoting VR as a tool for empathy and innovation across diverse fields.



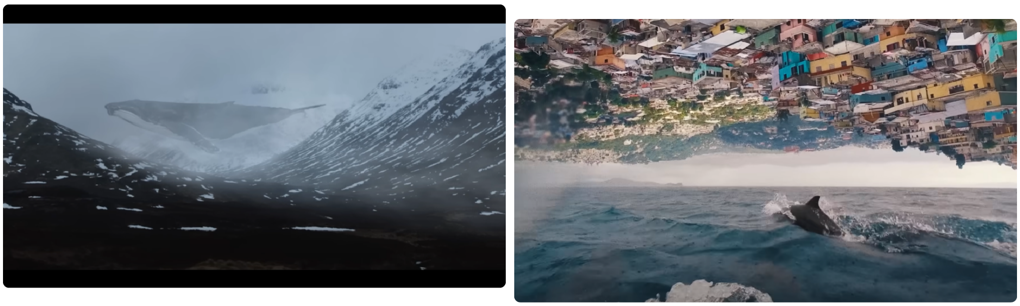
(a) Augmented Reality aquarium setting, in a marine park, from Orca in a Shopping Mall: Ocean Adventure by INDE at Allee Budapest, video by Indestry [45].

(b) A dynamic orca display in a marine park, engaging visitors with live educational showsfrom Orca in a Shopping Mall: Ocean Adventure by INDE at Allee Budapest, video by Indestry [45].

(c) Interactive marine display focusing on orcas, aimed at educating the public about these marine mammalsfrom Orca in a Shopping Mall: Ocean Adventure by INDE at Allee Budapest, video by Indestry [45].

Fig. 14: Interactive AR display in a marine park.

Chou and Hoisington [16] reported that VR integration can contribute to experiential immersion, student engagement, and authentic learning. Smink et al. [101] suggested, based on a dissertation analysis, that AR enhances perceived informativeness and enjoyment compared to non-AR presentations. In a similar vein, Bucher [12] concluded that VR provides a new form of spatially oriented entertainment, extending traditions found in theme parks and theater. Kool [54] emphasized that the realistic and empathy-generating nature of 360-degree VR journalism alters both the role and ethical responsibilities of journalists and viewers. Fauville et al. [31] highlighted VR's potential as a persuasive tool to promote climate change awareness. Similarly, Coen et al. [18] showed that AR devices designed with persuasive informational features improved awareness of environmental issues, demonstrating that AR can effectively encourage pro-environmental behavior (see Figures 15a and 15b). Fauville et al. [32] examined the use of VR in teaching about ocean acidification, identifying empowerment, perspective-taking, and visualization as three principal avenues for raising awareness of this largely unknown issue. Hsu et al. [42] demonstrated through an immersive VR game that exaggerated feedback can produce significant cognitive and behavioral gains in water-conservation intention, a particularly relevant finding in Taiwan, where water shortages are a persistent issue. Lu and Liu [67] proposed an AR-based program introducing Taiwan's marine ecology and water resources, which increased student confidence, improved knowledge acquisition, and helped low academic achievers. Midden et al. [74] reviewed broader efforts to promote sustainable behavior through persuasive technology, with particular attention to climate risk appraisal and interactive methods for reducing household energy consumption. Chang and Tien [14] developed AR and VR training systems for marine ecology education, finding that both technologies enhanced visitor experiences, activity involvement, and positive attitudes toward use. Finally, Vasiljević et al. [109] analyzed AR and VR applications in the maritime sector, offering examples of current and potential implementations. Overall, these studies suggest that AR and VR hold significant promise as educational and persuasive tools, particularly in environmental and marine contexts, by enhancing immersion, promoting empathy, and encouraging sustainable behavior.



(a) Abstract art representation of great whales, evoking a sense of the vast marine environment, from Pstereo videoclip, by Emilie Nicolas [79].

(b) Creative visual of a whale floating above the clouds, symbolizing freedom or dreams, from Up&Up videoclip, by Coldplay [19].

Fig. 15: Whale CGI used for immersive storytelling in videoclips.

Katsumata et al. [49] argued that achieving a deep depth of field for computer graphics over real scenes in compact, low-cost devices is difficult because laser projectors or complex optics are typically required. They proposed using the pinhole effect with polarizing plates to achieve deep DoF without reducing the field of view. Implemented in a prototype for smartphone-based OST-HMDs, the method confirmed that CGs could be clearly perceived at any focal point. Similarly, Koeijer et al. [53] compared cardboard headwear with a mobile handheld device in a museum setting. Results from visitor questionnaires showed a preference for cardboard AR, while observational data suggested that handheld AR might be easier and more intuitive to use. Schnädelbach et al. [97] developed the Augurscope, a mixed reality interface for outdoor use. Their analysis revealed problems with lighting, movement, and aligning virtual and physical viewpoints, highlighting how environmental factors and device form shape interaction. The authors suggested that careful design of both virtual and physical content could mitigate these challenges. Swan et al. [105] identified a fundamental problem in optical see-through AR regarding perception of spatial layout and depth. Comparing real objects, real objects viewed through AR, virtual objects, and combined real/virtual objects, they found that AR objects' egocentric depth was underestimated, though to a lesser degree than in many VR environments. Livingston et al. [63] explored indoor versus outdoor depth perception in mobile AR. Their results indicated a consistent underestimation of depth indoors, typical of AR and VR systems, but an overestimation of depth outdoors. To address such challenges, Stuerzlinger and Wingrave [104] proposed guidelines emphasizing the use of constraints, which have proven effective in improving interaction in complex 3D environments. Brigham [9] provided an overview of the concerns surrounding augmented, virtual, and mixed reality applications, describing how and where they are currently being used. Klinker et al. [52] emphasized that AR systems must balance the trade-off between striving for high-quality, physically accurate presentations and simplifying processes to achieve real-time responsiveness. Gruber et al. [40] extended this discussion by presenting a system for color harmonization in video-based AR, which re-colored virtual and real-world items to achieve more visually coherent results. Nuernberger et al. [81] proposed SnapToReality alignment techniques that allow users to position, rotate, and scale virtual objects relative to dynamically extracted real-world constraints. Their results showed that alignment was significantly faster with snapping assistance, and they highlighted its potential for enabling more expressive AR content creation. Keshavarz [50] explored methods to reduce visually induced motion sickness (VIMS), noting that symptoms include oculomotor issues, fatigue, disorientation, dizziness, and nausea. Pettijohn et al. [88] compared VR and AR conditions in terms of safety and effectiveness, finding that motion significantly impacted behavioral performance. While symptoms increased over time, they did not differ between headsets, and VR conditions produced higher accuracy and faster response times. Stevens and Butkiewicz [103] examined the use of visual compensation to reduce seasickness in marine VR. By moving the virtual environment to match vessel motion, their results suggested that VR systems aboard ships may provide visual cues that reduce motion sickness. Finally, Russell et al. [93] applied controlled diaphragmatic breathing to manage motion sickness in VR environments. Evidence indicated that activating the parasympathetic nervous system suppressed physiological responses and reduced motion sickness symptoms, while the breathing protocol increased parasympathetic tone and enhanced user comfort.

3 Methodology

3.1 Related Work Connection to Study

This study builds on three strands of related work, each directly tied to the research questions: the educational limitations of whale-watching, the affective potential of XR in tourism, and the usability challenges of immersive technologies in outdoor contexts. First, whale-watching encounters often evoke awe and conservation awareness, but remain constrained by short viewing times, ecological disturbance, and accessibility barriers [28, 24, 25, 23]. Research also shows that tours frequently lack sufficient educational content, leaving gaps in marine literacy [4, 77], while vessel proximity may disturb natural behavior, increase stress from noise, and pose collision risks [114, 3]. These limitations connect directly to RQ1, which examines whether XR can extend interpretation onshore to reinforce ecological understanding beyond the brief at-sea encounter [39, 66]. Second, XR in tourism has been shown to heighten immersion, presence, and empathy. VR can foster emotional engagement, reshape attitudes, and influence conservation-related intentions [108, 51], while AR and MR applications in cultural heritage and nature tourism strengthen storytelling and visitor engagement [27, 22]. This evidence underpins RQ2, which asks whether XR whale-watching can deepen affective responses and enthusiasm for marine life. Finally, evaluations of XR highlight both potential and limitations. Outdoor use introduces issues such as sunlight glare on AR displays, motion sickness in VR, headset discomfort, and reduced usability in uncontrolled environments [52, 41]. Studies note trade-offs between graphical fidelity and real-time responsiveness [52], while others explore improvements such as color harmonization in AR [40] and alignment or stability in MR [81, 31]. These findings frame RQ3, which investigates how AR, VR, and MR compare in usability and suitability for deployment in outdoor coastal whale-watching contexts.

3.2 System Design and Evaluation Approach

To address the research questions, this study involved the design and evaluation of a multi-modal XR system tailored to onshore whale-watching. The system integrated AR, VR, and MR, each designed to present the core content as similarly as possible across modalities so that differences in outcomes could be attributed to the technology itself rather than to changes in narrative or visuals. In this way, the system directly operationalized the research aims: enhancing marine literacy (RQ1), fostering emotional connection and engagement with whales (RQ2), and testing usability in outdoor tourism settings (RQ3). The XR system was conceived as a complementary layer to traditional VMT's whale-watching rather than a substitute. Sessions were deliberately kept brief and self-contained to reflect the practical constraints of public tourism contexts. Evaluation methods combined pre- and post-questionnaires, Likert-scale measures, and open feedback, balancing quantitative and qualitative insights while minimising disruption to leisure activities. The project was conducted in collaboration with VMT Madeira, a leading whale-watching operator located at Praça do Povo in Funchal. This partnership ensured ecological validity by embedding the research in the natural flow of tourism. VMT facilitated recruitment immediately after offshore trips, providing access to a sample of participants already primed by direct whale encounters. The study location, adjacent to VMT's boarding area, enabled a seamless transition from sea-based excursions to onshore XR interaction. By situating the evaluation in a real-world tourism environment rather than a laboratory, the methodology both addressed the research questions and served as an experimental prototype for applying immersive technologies as complementary interpretive tools within sustainable marine tourism.

3.3 High-Level Concept

The XR experiences were conceived as a sustainable and accessible complement to whale-watching, extending interpretation onshore without competing with the live encounter. The concept was that participants, immediately after returning from the VMT tour, would engage with a short immersive session. Each experience was designed to be concise and impactful, lasting approximately seven minutes from first contact to completion of the post-experience questionnaire. This compact format allowed integration into the flow of tourism activities while still encouraging reflection on ecological themes. All three technologies—AR, VR, and MR—were structured around the same three scenarios: "Whale and Divers," "Fishing Net with Whales," and "Whale Feeding Cycle." The storyboard developed during the design phase (Figure 42) illustrated the intended participant pathway: a seamless progression from recruitment after whale-watching, to onboarding, immersion in the XR content, and concluding with evaluation. These scenarios were deliberately selected to represent distinct dimensions—Information, threats, and contribution—while also varying in cognitive complexity. The first scene, Whale and Divers, was framed around the question: “How many scuba divers equal the length of a North Atlantic Right Whale?” As the most accessible of the three, it served primarily as an informational comparison, by aligning divers with the whale, the visualization translated abstract scale perception into a concrete comparison, sparking curiosity and awe supporting RQ2 Engagement and Emotional Connection by eliciting fascination and an immediate affective response to the whale’s magnitude. The second scene, Fishing Net with Whales, represented an intermediate level of complexity and answered the question: “How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime?” The visualization showed multiple whales entangled in ropes, symbolizing a widespread anthropogenic threat. Designed to be interpretable and emotionally salient rather than a literal capture event, it contributed to both RQ1 Marine Literacy and Learning and RQ2 Engagement and Emotional Connection by raising awareness of human impacts and provoking empathy and conservation concern. The third and most complex scene, Whale Feeding Cycle, was tied to the ecological question: “Who eats whom?” It animated the nutrient cycle in which whales contribute nutrients through feces, sustaining phytoplankton, which feed zooplankton, which in turn feed whales. By making this invisible process visible, the scene required greater cognitive effort but offered deeper ecological insight, directly addressing RQ1 Marine Literacy and Learning by highlighting interdependence and whales’ critical role in ecosystems. This design ensured systematic coverage of the study’s aims: RQ1 through ecological knowledge, RQ2 through emotional engagement and conservation concern, and RQ3 Ease of Use and Outdoor Adaptability through comparative evaluation of the three modalities in real outdoor conditions.

4 System Design

4.1 Used Hardware

4.1.1 Supported AR/MR/VR Smartphone

The software used to develop AR, MR, or VR experiences in this project is smartphone-based. For these technologies to function effectively, the hardware must support both AR and VR capabilities. While VR is widely supported across various devices, ARCore—Google's platform for building AR experiences—only supports certain smartphones that meet specific processing power and camera quality requirements. The complete list of compatible devices can be found online[2]. In iOS side, ARKit requires iOS 11.0 or later and an iOS device with an A9 or later processor. The smartphone utilized to test this project was the OnePlus 8T, which features an OLED display with a peak brightness of 802 cd/m^2. This brightness level ensures that the screen's image remains clear and vivid when viewed through Aryzon MR glass system. During testing, the app maintained a stable performance at around 60 frames per second (fps), which is crucial for delivering a smooth and consistent user experience. The ARCore-enabled OnePlus 8T played a key role throughout the development process, providing a reliable platform for testing and refining the AR application.

4.1.2 Mixed Reality Setup

For MR, Aryzon and ARCore/ARKit will be used which enables at an accessible cost the tremendous value of taking the first steps into merging the real and the virtual. Such MR Headset needs to be further paired with a smartphone with either ARCore (Android) or ARKit (iOS) support. Users will directly see through the headset and view the real world, while virtual objects will be projected and blended on top of it. Studies will verify if Augmented Reality using a MR headset does increase retention rates compared to 3D-content shown on 2D-interfaces such as smartphones, tablets and computers. This headset works similarly to Google Cardboard, which works by placing a smartphone into the headset, where the phone's screen is divided into two images that create a stereoscopic effect, allowing for 3D visuals (See Figure 16). But differently, this headset uses a reflective system, where the phone's screen is projected onto a transparent visor in front of the user's eyes. The visor reflects the 3D content into the user's field of view, blending the virtual content with the real-world environment. The headset relies on the smartphone's internal sensors, such as the gyroscope and accelerometer, to track head movements. This tracking allows the virtual content to remain anchored in the real world as the user moves their head, providing an immersive AR experience. The design of the Aryzon headset enhances the field of view compared to traditional AR on smartphones alone, offering a more immersive experience. It projects the augmented content over a larger area of the user's vision. Aryzon is lightweight, portable, and easy to set up. Users simply fold the cardboard viewer, insert the smartphone, and start the AR app. The device is designed to be user-friendly and accessible to a broad audience, making AR technology more affordable and widely available.

Fig. 16: Mixed Reality Cardboard Headset made by Aryzon

4.1.3 Virtual Reality Setup

For this particular case, VR will be used Google Cardboard. For VR Google Cardboard is choosen due to the same reason as Aryzon which is affordability and accessibility, as shown in Figure 17. Google Cardboard VR also needs to be paired

---

[2] `https://developers.google.com/ar/devices?hl=pt-br`

with a smartphone with Google Cardboard support. The tracking function is a lot less demanding and detailed, as the objective is a lot simpler, which is to track head position and angle, with no need to scan the real world environment. The smartphone is placed inside the viewer, and it runs VR apps that split the smartphone screen into two images, one for each eye, to create a stereoscopic 3D effect. The viewer has two lenses that magnify and adjust the images from the smartphone, providing the 3D depth and immersive experience. The lenses are positioned to align with the two images displayed on the smartphone screen, tricking the brain into perceiving depth and a sense of presence within the virtual environment. It also has an optional button mechanism, tipically made of conductive metal or foil, that when pressed, it makes contact with the smartphone screen, mimicking a finger tap. With Google Cardboard, the user will be totally immersed in the 3D Environment, with vibrant colors, detailed geometry, lighting, particles and animations. Giving them the possibility to forget about their current physical situation and surroundings. With the following user studies, VR will be compared against AR and MR conditions, assessing usability, user experience and emotional behaviour. The goal is to understand which technology is more adequate in on- and off- Shore real world situations. Main hypothesis of this research is to assess whether such experience will allow for users to better explore and recall the content and get a better insight of the great whales. It will also analyze how does the sensation of real-time influences their interaction. Lastly, it will provide a novel design and development a more memorable impact to the user and share knowledge in a joyful, appealing and intuitive way.

Fig. 17: Google Cardboard Headset made by ColorCross, which offers more support

4.2 Used Software

4.2.1 SDKs (Software Development Kits) - ARCore and ARKit

Since ARCore or ARKit is supported by a wide range of Android and iOS devices, the development of AR applications with this software ensures broader compatibility and accessibility for potential users. Augmented Reality makes use of ARCore (Android) or ARKit (iOS) software ability to perform a motion tracking function which uses the smartphone's camera and sensors to track the phone's position in relation to the world, changing perspectives to alter its own content (3D Model's) position. The ARCore/ARKit is also powered by the gyroscope and camera on smartphones, which together further detects flat surfaces such as tables or floors and use them as a reference to place digital objects in the physical world accurately. This feature is crucial for ensuring that virtual objects appear anchored and stable as you move the phone around, or even explore them by walking around them or approaching closer or going further, simulating the real physical objects.

4.2.2 Unity

Unity was chosen as the development software due to several compelling factors that make it particularly well-suited for creating AR, MR, and VR experiences. Firstly, Unity offers robust support for a wide range of software development kits (SDKs), including ARCore and ARKit, which are essential for integrating advanced features such as plane detection, image tracking, and environmental understanding into the applications. This strong SDK support ensures that the development process can fully leverage the capabilities of these technologies. Moreover, Unity is renowned for its ease of use, featuring a user-friendly interface and comprehensive documentation that cater to both beginners and experienced developers. Its visual editor facilitates rapid prototyping and iterative development, which is crucial for testing and refining interactive experiences. This ease of use is complemented by Unity's cross-platform capabilities, allowing developers to deploy applications across multiple platforms, such as Android, iOS, and Windows, without needing extensive rework for different devices. This flexibility ensures that the applications can reach a broader audience. Additionally, Unity's Asset Store provides a vast library of pre-made assets, scripts, and plugins, significantly reducing development time by allowing developers to integrate complex features or graphics without having to build everything from scratch. This resource is invaluable for speeding up the development process.

Performance optimization is another critical aspect where Unity excels, ensuring smooth user experiences, even in resource-intensive AR and VR environments. This is vital for maintaining the quality and consistency of the user interaction across a multitude of devices

Furthermore, Unity benefits from a large and active community of developers, providing ample support, tutorials, and forums, which are essential for troubleshooting and learning best practices. This community-driven support network is a significant advantage, especially when facing complex development challenges. Lastly, the cost-effectiveness of Unity cannot be overlooked. The software is free to use for individuals and small companies, making it an accessible option for projects with budget constraints. Even the Pro version, which includes additional features, remains competitively priced. These factors combined made Unity the ideal choice for developing the AR, MR, and VR applications, offering efficiency, flexibility, and the capability to produce high-quality outputs.

4.2.3 Blender

Blender was chosen as the primary software for creating the characters and elements, such as the whale, krill, and swimmers, for the AR/VR/MR app due to its robust and versatile features, tailored for 3D modeling, texturing, rigging, and animation, which are particularly suited for creating game-ready assets that need to be optimized for real-time applications. Firstly, Blender is an open-source and free software, making it accessible to developers without the financial burden associated with other high-end 3D tools. This is crucial for projects that need to manage costs effectively while still producing high-quality assets.

Blender's comprehensive 3D modeling tools allow for the creation of highly detailed and accurate models, which is vital for representing realistic marine life like whales and krill. Blender excels in low to medium poly modeling, the ability to sculpt, model, and refine characters with a variety of brushes and modifiers within the same software enable a higher control over the model, which is essential for crafting assets that maintain a balance between visual quality and performance efficiency. This is particularly important in game development, where models need to be lightweight enough to run smoothly on various platforms, including mobile devices, without compromising detail and realism. Blender enables the creation of game-ready textures directly within the software. Texturing and painting in Blender is streamlined, offering built-in tools to apply and adjust textures directly on the 3D models which is particularly beneficial for ensuring that textures fit perfectly with the model's topology. Blender's UV unwrapping and texturing tools allow for the creation of clean, efficient UV maps, maximizing texture detail without increasing polygon count. The texturing process within Blender is streamlined, enabling the creation of game-ready textures directly within the software.

Blender's rigging and animation capabilities are another significant advantage. The software provides a complete rigging system, allowing for the creation of complex skeletal structures and animations for characters, such as those as marine life. Moreover, Blender supports non-linear animation, enabling the layering of animations and fine-tuning of movements, which is crucial for creating lifelike behaviors. One of Blender's most significant strengths is its seamless export to Unity. Models, animations, and textures created in Blender can be easily exported to Unity in formats that retain all the necessary data, ensuring that there are no issues with compatibility or quality loss during the transfer. This smooth integration between Blender and Unity allows for a more efficient workflow, reducing the time and effort needed to bring the 3D assets into the app. Blender also boasts a wide and active community, providing an abundance of tutorials, plugins, and resources that can help overcome any challenges encountered during the development process. This community support is invaluable for troubleshooting, learning new techniques, and staying updated with the latest tools and trends in 3D modeling and animation. Lastly, Blender's ongoing development and frequent updates ensure that it keeps a future-proof choice for developing 3D content. These factors collectively make Blender an ideal choice for creating the dynamic 3D assets required for the AR/ VR/MR app, offering flexibility, quality, and efficiency in the development process.

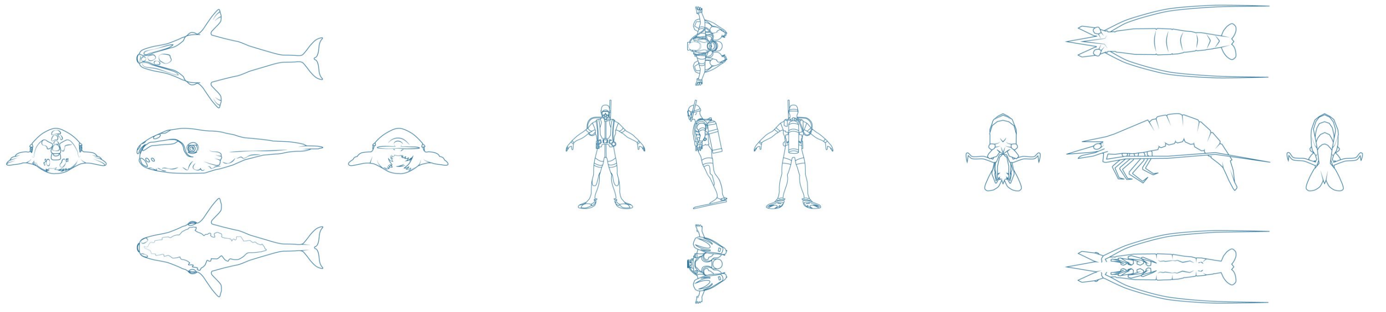
4.2.4 Adobe Photoshop CC

Blender provided the foundation for modeling and initial texturing, while Photoshop played an essential role in refining these textures to achieve realism in models like the whale, diver, and others. The process involved meticulous attention to detail, using tools to ensure depth, consistency, and quality across platforms. In terms of precision detailing, Photoshop allowed for intricate adjustments, such as color gradients and weathering effects, which added significant depth and realism to the textures. Layer management was crucial here; using layers enabled complex textures by blending different materials and details seamlessly, providing flexibility in design and allowing for more detailed work without sacrificing consistency. Photoshop's tools were also instrumental in creating seamless textures, ensuring they wrapped around models without visible seams and maintained a cohesive look across different sections. Additionally, Photoshop's compatibility with other software like Blender and Unity enabled seamless integration of textures and designs, ensuring visual elements retained their quality when moved across these platforms. In designing artwork for the app, Photoshop was also fundamental. It was used to create AR triggers and other interface elements that were functional and visually cohesive with the app's overall design. Custom artwork for AR triggers was crafted to be easily recognizable and visually aligned with the app's theme. Moreover, icons, buttons, and menus were also designed in Photoshop, maintaining visual consistency throughout the app's interface, enhancing the user experience and ensuring all elements worked together harmoniously.

4.3 Process, Design & Development

4.3.1 3D Modelling

The scenes were composed with the following elements to create an engaging narrative. In Scene 1, whales are depicted caught in a fishing net, highlighting the interaction between marine life and human activity. The models used for this scene include the fishing net and whale models. Scene 2 explores the scale of the whale, illustrating "how many divers long" it is by positioning a diver model alongside the whale model to provide a visual comparison. In Scene 3, the whale's feeding cycle is portrayed. Here, zooplankton consume phytoplankton, which in turn feeds on nutrients from whale feces, while the whale consumes zooplankton. This interconnected cycle showcases the ecological relationships sustained by the whale. First step involved drawing a reference image of the main elements: a whale, krill, a diver, from different angles (top, side, and front views) (See Figures 18a, 18c and 18c). These references provided a clear visual guide for ensuring accuracy in proportions and details. These images were added as background references in Blender by navigating to View > Background Images in the Properties panel. Since the scenes included more objects, such as the fishing net and various elements in the whale feeding cycle such as whale feces and phytoplankton, these additional elements also needed to be modeled. However, unlike the main models like the whale, diver, and zooplankton, these more simple objects did not require detailed reference images. Instead, they were modeled directly in Blender based on their functional and aesthetic requirements within the scenes.



(a) Orthographic view of the Whale illustration.

(b) Orthographic view of the Diver illustration

(c) Orthographic view of the Zooplankton illustration

Fig. 18: Orthognatic views to be used as references in Blender.

The modeling process for the whale began by blocking out its basic shape using Blender's primitive objects, accessible through the Add > Mesh menu. A sphere was used for the body, cylinders for the flippers, and a cube for the tail. Using the Scale (S) and Move (G) tools, these shapes were adjusted in size and position until they roughly matched the whale's overall proportions. Once positioned, the Join function (Ctrl + J) was used to merge these objects into a single mesh, forming a unified base for the whale model. To further refine the proportions, Edge Loops (Ctrl + R) were applied where necessary, particularly around the flippers and tail, while the Proportional Editing Tool (O) allowed for broad adjustments, enhancing the model without disrupting the whale's form.

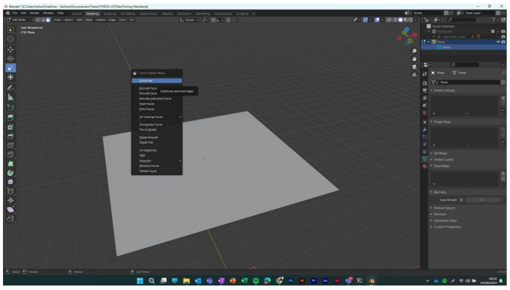
For the diver, Blender's human base mesh served as the starting point, ensuring accurate proportions from the outset. The Proportional Editing Tool was used to fine-tune areas like the shoulders, torso, and limbs, critical for depicting a person wearing a wetsuit. In Sculpt Mode, details were added to the wetsuit, focusing on wrinkles, seams, and overall fit, using the Grab and Inflate brushes to create a realistic surface that clings naturally to the body. Additional details, including zippers, straps, and other features, were modeled separately with the Extrude and Inset Faces tools, then positioned on the main mesh to enhance realism.

The zooplankton model drew from reference images of krill, starting with a simple cylinder mesh from the "Add" menu to represent the krill's main body. The Mirror Modifier ensured symmetry, automatically reflecting changes on one side to the other. The Proportional Editing tool (O) was used to taper the cylinder towards one end, and the "Loop Cut and Slide" tool (Ctrl + R) created evenly spaced cuts along the cylinder's length, shaping the segmented body of a krill.

For the phytoplankton scene, basic primitives like cubes and spheres were scaled down and positioned to capture the essential forms of plankton. The Grab Brush in Sculpt Mode was used for minor adjustments, giving each piece an organic, natural form. In Edit Mode, vertices were manipulated to elongate shapes to represent the structure of diatoms, while the Extrude tool extended parts of the geometry, forming characteristic spines and extensions. Simplicity was maintained, with minor use of the Subdivision modifier to smooth out the forms, emphasizing the plankton's overall silhouette.

To model the whale feces, a UV Sphere was used as the base mesh for the faeces cloud. In Sculpt Mode, the sphere was transformed into a cloud-like, amorphous shape using the Grab and Smooth brushes to create soft contours. The Inflate brush was applied to add volume and achieve an irregular, organic form, avoiding hard edges to maintain a natural, cloud-like appearance. The process of modeling the fishing net began by adding a simple plane mesh (Shift + A > Mesh > Plane) and scaling it to match the general size of the net. The plane was then subdivided using the W > Subdivide option, creating a finer grid. To simulate the net's structure, the Wireframe Modifier was applied. The plane was further subdivided multiple times (Right-click > Subdivide) to increase the mesh density (See Figure 19).

To refine the net's grid, the subdivisions were adjusted, and vertex positions were tweaked, ensuring uniformity and enhancing realism. Finally, the net's silhouette was given subtle irregularities using the Smooth Brush, adding a natural, organic look to the model.



Subdivide selected edges.

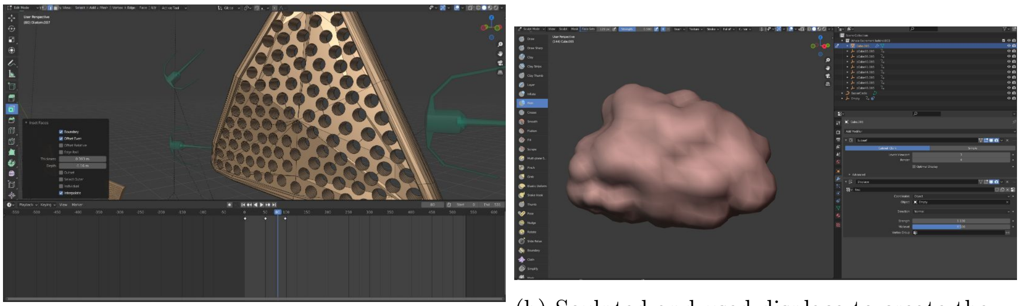
Fig. 19: Simple plane mesh subdivided to be used as the basic shape of the fishing net

With the basic shape of the whale in place, Edit Mode (Tab) was used to refine its proportions. Edge Loops (Ctrl + R) were added where needed to introduce additional geometry, ensuring enough vertices to accurately shape the model. For instance, loops were added around the flippers and tail to capture their natural curvature. The Proportional Editing Tool (O) proved particularly useful in making broader adjustments to the mesh, enabling refined modifications without compromising the whale's overall form.

The diver model underwent similar adjustments, with particular attention given to the limbs and head-to-body ratio, using the Scale and Grab tools in Edit Mode. In Blender's Sculpt Mode, further details were added to the wetsuit, such as wrinkles, seams, and the overall fit. The Grab and Inflate brushes helped achieve a realistic surface, capturing the way a real wetsuit clings to the body. For additional detail, features like zippers, straps, and other small elements were modeled separately using the Extrude and Inset Faces tools and carefully positioned on the main mesh, enhancing the wetsuit's realism.

In the zooplankton model, the Proportional Editing tool (O) was used to scale and taper the cylinder toward one end, simulating the natural tapering shape of a krill's body. To form the segmented body, the "Loop Cut and Slide" tool (Ctrl + R) was applied to create several evenly spaced cuts along the cylinder's length. Each segment was then slightly adjusted using the scaling tool to reflect the anatomical sections of a krill, achieving an accurate representation of the zooplankton's structure. For more detailed elements, like the intricate cell walls and pores of the diatom, the Inset Faces tool was employed to create the small holes and grooves, as illustrated in Figure 20a. The Subdivision Surface modifier was also utilized to smooth out the shapes and give them an organic look. This was crucial for achieving the delicate and detailed appearance of the diatom's frustule.To add finer details to the cloud, the Detail Size in the Dyntopo (Dynamic Topology) settings was adjusted, allowing for the sculpting of finer bumps and indentations on the surface. The Blob brush was applied lightly over the surface to simulate the uneven distribution of the cloud particles (See Figure 20b).

For the fishing net model, Edit Mode (Tab) was entered, and alternating faces of the subdivided plane grid were selected and then deleted (X > Faces) to create the net's openings. To give thickness to the net strands, a Solidify modifier was applied (Modifier Properties > Add Modifier > Solidify). This added depth to the flat net, enhancing its realism and giving it a more three-dimensional appearance.



(a) Used Inset Faces Tool to create holes in one of the phytoplankton models.

(b) Sculpted and used displace to create the basic shape of the faeces cloud.

Fig. 20: Final Adjustments

After refining the proportions of the whale, the base mesh was smoothed using a Subdivision Surface Modifier added via the Modifiers Tab. This helped to soften rough shapes and add fluidity to the model. Throughout this process, Edit Mode and Sculpt Mode were alternated to push and pull vertices, ensuring accurate anatomical flow and structure. For instance, the curvature of the whale's back and the tapering of its tail were fine-tuned during this phase to enhance realism

The diver model underwent a similar process, with the Subdivision Surface Modifier applied to the base mesh to ensure smooth transitions between body parts. To create the mask, a basic cube was initially used, then scaled and extruded to fit the diver's face. The snorkel was modeled from a cylinder, shaped, and curved with the Bend Modifier, allowing for a smooth transition from the mouthpiece to the rest of the equipment. The oxygen tank was created from a simple cylinder, with a few loop cuts applied to refine its shape. The regulator was modeled by extruding from the tank's valve area and connected to the diver's mouthpiece using a curved tube, shaped with the Curve Modifier. For the fins, a basic plane was used as the starting point, which was extruded and shaped to follow the natural curve of a diving fin. The fins were then attached to the diver's feet, with adjustments to scale and orientation to ensure they appeared natural and cohesive with the rest of the model. The krill's base mesh was developed by initially increasing geometry with the Subdivide tool, followed by the Extrude function to create legs and antennae. To achieve a more refined and natural shape, the Subdivision Surface Modifier was applied (See Figure 21). For the legs and antennae, faces on the lower side of the body were selected, and the "Extrude" function (E) was used to pull out geometry and shape these appendages. They were then scaled down and adjusted to the appropriate thinness using the "Scale" tool (S), resulting in a realistic representation of krill appendages

In Blender's Sculpt Mode, finer details were added to the phytoplankton models to represent ridges and textures typical of various species. Tools such as Clay Strips and Crease were particularly effective for creating the organic patterns on the surface of the plankton. To give the cloud a diffused, soft appearance rather than a solid one, the Smooth brush was used with a low strength setting to blend out harsher edges, resulting in a wispy, natural look.

To create a realistic faeces cloud, Blender's Array Modifier and Particle System were utilized. The Array Modifier was used to duplicate and position the phytoplankton models into clusters, while the Particle System scattered these clusters throughout the scene, simulating a natural distribution within a marine environment. Once the cloud shape was satisfactory, all modifiers were applied to finalize the mesh, making the deformations permanent and ensuring the phytoplankton cloud retained its shape during animation or other interactions. In Edit Mode, final tweaks to the mesh were made, adjusting vertices to prevent any unnatural overlaps or gaps that might appear during rendering. For the fishing net, a Lattice Modifier (Modifier Properties > Add Modifier > Lattice) was applied to the subdivided plane to deform it into a natural, curved shape resembling a real fishing net. The lattice points were adjusted to simulate the sagging and pulling effects typically seen in nets. Proportional Editing (O key) further refined the net's shape, ensuring it looked organic and flowed naturally as a suspended or cast net would. Additional detailing was added using the Draw Brush to introduce subtle variations in thickness and simulate wear and tear. To enhance realism, rope elements were added around the edges of the net by extruding its edges and applying a Bevel modifier to round them out, creating the appearance of ropes. In Sculpt Mode, slight surface imperfections and variations were applied to the net strands to mimic the wear and tear experienced by real nets in marine environments, adding an extra layer of authenticity to the model.

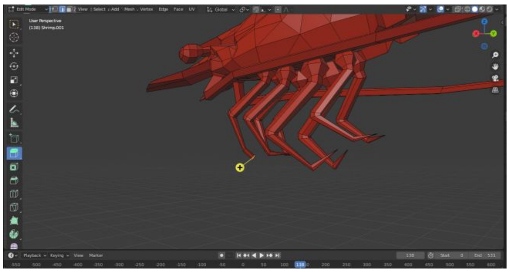


Fig. 21: Extruding the legs of the Krill model

Once the base meshes were complete, Sculpt Mode was fully utilized to begin detailing. The detailing began with the whale, utilizing the MultiRes Modifier to gradually add finer details while preserving the mesh's overall integrity. For the krill, plankton, diver, and fishing net, a lower subdivision level was applied to keep the models efficient, focusing on essential details that enhanced their realism. Once the base mesh was complete, Sculpt Mode was fully utilized to begin adding details. In this mode, lower subdivision levels were initially used with the MultiRes Modifier to block out larger forms, gradually increasing the subdivisions as finer details were required. The next step in modeling the whale involved refining its silhouette to ensure the outline appeared as realistic as possible. In Sculpt Mode, the Grab Brush was used to adjust the model's outline from different angles (See Figure 22), while the Smooth Brush helped even out any areas that needed a more uniform surface. The Clay Strips Brush was utilized to build up the whale's major muscle groups and define essential anatomical features like the head, flippers, and tail. To add detailed textures and anatomical accuracy, the Crease Brush was used to carve skin folds and other defining features of the whale's anatomy. Emphasis was placed on major details such as the head, flippers, and tail, where the Clay Strips and Crease Brushes highlighted muscle and bone structures. The Draw Sharp and Smooth Brushes were frequently alternated to carve out and then refine these features, enhancing the natural contours and depth of the model.

The diver's silhouette was refined using the Grab Brush to ensure anatomical accuracy and smooth transitions between the limbs and torso. Smooth Shading was applied to the entire model to create a more polished look, blending the surfaces together and giving the wetsuit and equipment a cohesive appearance. In Sculpt Mode, the Clay Strips Brush was revisited to add finer details, such as slight creases around the joints and additional surface imperfections found on the wetsuit and diving equipment, emphasizing realistic folds and gear placement. Once the model was complete, Blender's Pose Mode was used to position the diver in a natural swimming pose, adjusting the limbs and body to simulate underwater movement. A final review and optimization ensured all elements were aligned and that the model was optimized for use in VR/AR/MR environments. This process resulted in a diver model that is both visually appealing and functional, with attention to detail in the human form and diving equipment enhancing its effectiveness in immersive applications.

For the zooplankton, the krill's silhouette was refined using Sculpt Mode tools, with a particular focus on the segmented body to ensure smooth transitions between parts. To enhance the organic look, the Subdivision Surface Modifier was applied, smoothing out the model and adding more detailed curves. In Sculpt Mode, the Clay Strips and Smooth brushes were used to add subtle muscular details and refine the body and legs' shapes. The krill's segmented body, antennae, and legs were sculpted with the Clay Strips Brush to ensure each segment had appropriate texture and detail, while the Crease Brush was instrumental in defining fine segmentation, bringing realism to the krill model.

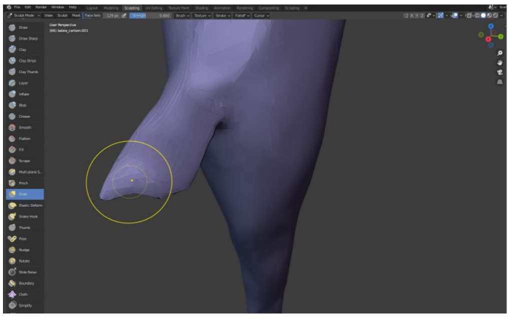


Fig. 22: Using the Grab Brush tool to fine-tune the model's outline.

The whale's eyes and mouth were sculpted with meticulous attention to detail. UV Spheres were used for the eyes, which were then integrated into the head using the Boolean Modifier to add and subtract shapes as needed, creating a natural fit. The Crease Brush was essential in defining the eyelids and surrounding skin, ensuring smooth transitions with the rest of the head. For facial details, the Crease Brush helped emphasize the contours around the eyes and mouth, bringing more realism to the model. To add skin texture, small wrinkles, and scars, higher subdivision levels were applied to the mesh. The Draw Sharp Brush was used to etch fine lines, while the Inflate Brush added subtle bulges and scars. Additionally, alphas were applied from the Texture menu in Brush Settings, stamping complex details like barnacles directly onto the model, enhancing the whale's realistic and weathered appearance.
The diver's mask and facial features were carefully sculpted to ensure a natural fit of the mask over the well-formed face beneath (See Figure 23). Using the Draw Sharp Brush, additional texture was added to the diver's suit, detailing folds and gear elements to enhance realism and provide a lifelike appearance to the model.
Two UV spheres were added for the krill's eyes (Shift + A > Mesh > UV Sphere) and positioned symmetrically on the head using the Mirror modifier, ensuring identical alignment for both eyes. Fine details, such as textures on the legs and antennae, were meticulously sculpted to give a realistic, segmented appearance. Once the primary modeling was completed, proportions were further refined using the Grab tool (G) in Sculpt Mode, maintaining a balance between realism and stylization for the krill. A final pass was conducted across all models—the whale, krill, and diver—making minor adjustments with the Smooth Brush to eliminate any rough areas. This step ensured each model was polished, consistent, and ready for the next stages of development.

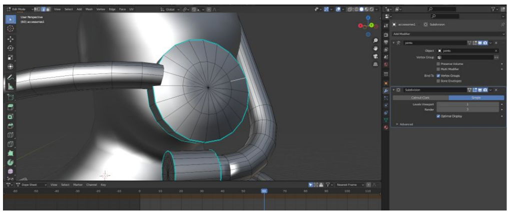


Fig. 23: Subdivision of the Mask basic shape to prepare for sculpting

4.3.2 Retopology and Low-Poly Optimization

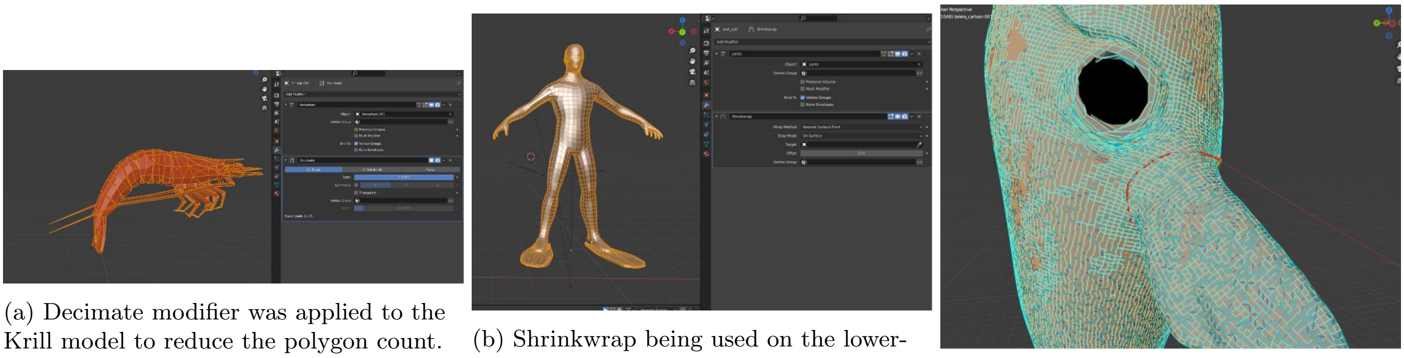
Retopology is an essential step in preparing a 3D model for animation or real-time applications like VR/AR experiences. It involves simplifying and optimizing the mesh to create a cleaner, more efficient geometry that maintains the necessary details while reducing the polygon count (See Figure 24a). This careful approach allowed the Whale, Diver and Zooplankton models to be animated and rendered smoothly in the final scenes. First, the high- poly models were duplicated to preserve the original detailed mesh. This is done by selecting the model in Object Mode, thenpressing 'Shift + D' to duplicate it. A 'Decimate' modifier was then applied to reduce the polygon count while preserving the overall shape. This can be found in the Modifiers panel under ‘Decimate‘. By adjusting the ‘Ratio‘ slider, the complexity of the models was reduced while maintaining key details.

The duplicated model was selected, and Edit Mode was entered by pressing ‘Tab‘. To facilitate retopology, a ‘Shrinkwrap‘ modifier was added from the Modifiers panel (located in the Properties window). This modifier allows the new topology to "stick" to the surface of the original high-poly model (See Figure 24b).

After decimating, with the high-poly model was used as a reference to begin creating the new topology using the ‘Bsurface‘ tool. The ‘Knife‘ tool (‘K‘) was used to cut precise lines where deformation is likely to occur during animation (See Figure 24c). In the Whale model it was used on areas like the fins and tail where more control over edge flow was necessary. In the Diver model, it was used cleaner edge loops around joints like elbows and knees.

For the Zooplankton, I also used ‘Edge Slide‘ (‘G‘ then ‘G‘ again) was used to control the edge flow, particularly around the joints and antennae. I carefully placed edge loops were carefully placed around areas that would require smooth bending and deformation, such as the tail base and around the mouth. This helps prevent issues during animation.

The ‘Snap to Face‘ option (‘Shift + Tab‘) was often used to ensure that new geometry adhered to the surface of the high-poly model. After laying down the basic topology, edge flow and vertex placement were adjusted to ensure a clean and animation-friendly topology. This involved reducing unnecessary vertices and optimizing the polygon flow around areas of high movement. Once the topology was complete, the Shrinkwrap modifier was reapplied, and the mesh was checked for any overlapping vertices or faces. These were then cleaned up using the Merge by Distance tool (M key in Edit Mode), ensuring a clean and optimized geometry free from any overlapping elements.



(a) Decimate modifier was applied to the Krill model to reduce the polygon count.

(b) Shrinkwrap being used on the lower-resolution Diver model for it to stick to the surface of the original model.

(c) Knife tool being used to cut precise lines in the whale model.

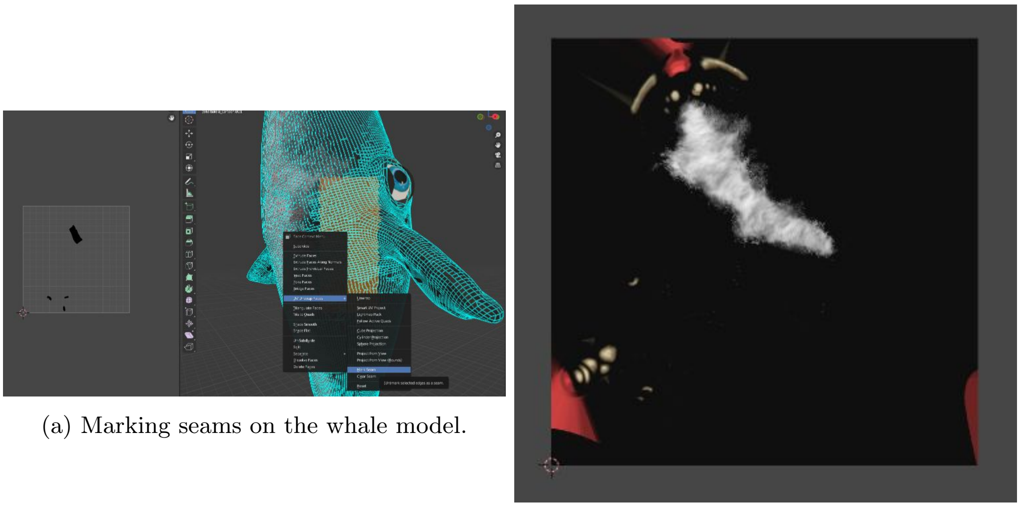
Fig. 24: Retopology steps: Decimate, Shrinkwrap, Knife tool.

4.3.3 UV Mapping

UV mapping is a critical process that involves unwrapping the 3D model’s surface into a 2D plane for texture application. This process ensures that textures align correctly and appear as intended on the models. In this project, UV mapping was performed on the Diver and Whale models, each with specific requirements to accommodate their distinct shapes and textures. The first step in UV mapping involved marking seams on each model, which act as "cut" lines to allow the 3D surface to unfold into a 2D plane. In Blender’s Edit Mode (Tab), these seams were strategically placed to minimize visibility when textures are applied. For the whale model, seams were placed along less visible areas, such as the underside and around the fins and tail, to keep seams hidden on prominent parts of the model (See Figure 25a).

Similarly, for the diver model, seams were marked along natural boundaries, like the sides of the suit, around the arms and legs, and along the edges of the fins and mask. This approach helped create UV islands that aligned with the natural segmentation of the diver’s suit and equipment. To mark seams, the required edges were selected, then "Ctrl + E" was pressed to open the Edge menu, where "Mark Seam" was chosen, ensuring effective UV mapping for both models.

Once the seams were marked, the model was unwrapped to create the UV map. This was done by selecting all faces (‘A‘), pressing ‘U‘ to open the UV Mapping menu, and then choosing "Unwrap." Blender automatically laid out the UV map based on the seams (See Figure 25b).


(a) Marking seams on the whale model.

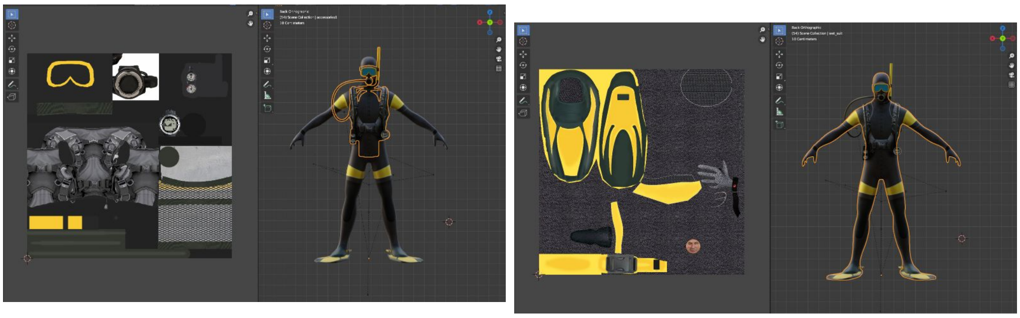
(b) UV Unwrapping of the Whale model.

Fig. 25: Marking Seams and Unwrapping the Model of the whale

Once the UV islands were laid out, the UV menu was used to select "Pack Islands" (Ctrl + P) to automatically arrange the islands within the UV space, ensuring there was no overlap and that space was utilized efficiently. Once the UV islands were laid out, the UV menu was used to select "Pack Islands" (Ctrl + P) to automatically arrange the islands within the UV space, ensuring there was no overlap and that space was utilized efficiently. After unwrapping, each UV island was fine-tuned in the UV Editor. This involved moving (G), scaling (S), and rotating (R) the islands to ensure optimal positioning and efficient use of the available UV space. For the whale model, a large, continuous UV map was created for the main body, with smaller islands for the fins and tail. This layout was adjusted to prevent texture stretching and to ensure the whale's skin texture appeared smooth and realistic.

For the diver model, the unwrapping process resulted in several UV islands representing different parts of the suit and equipment. Each island was adjusted in the UV Editor to maximize space and maintain proportionality, which helped achieve accurate texture details, including seams and logos on the suit. This careful arrangement ensured that textures would map precisely to both models (See Figure 26a).

Finally, potential texture stretching was checked by enabling the "Stretch" display in the UV Editor (‘N‘ for the side panel, then under the ‘Display‘ tab, check ‘Stretch‘) (See Figure 26b). Any problematic areas were adjusted by moving or scaling the UV islands as needed.

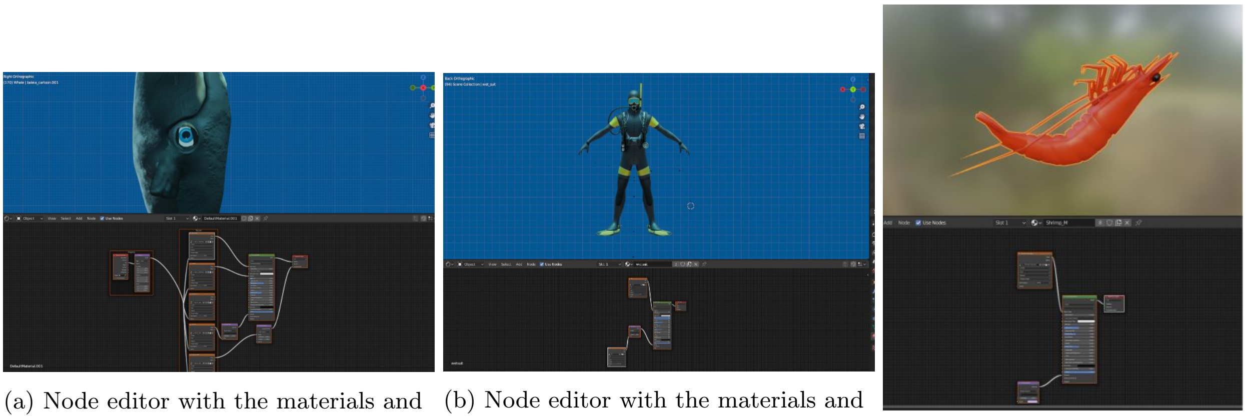

(a) Shrinkwrap being used on the lower-resolution Diver model for it to stick to the surface of the original model.

(b) Checking for stretching on the Diver UV map.

Fig. 26: Adjusting the UV Layout.

4.3.4 Painting and Texturing

In the process of assigning base materials, a new material was created for each model within the Materials tab in the Properties panel. For the whale, a base material with a dark, slightly reflective surface was applied to simulate the texture of whale skin. In the case of the diver, multiple materials were created to represent different parts of the suit, including the wetsuit, fins, and mask. Each material was assigned by selecting the relevant faces in Edit Mode (Tab) and clicking "Assign" in the Materials tab. The krill model was given a simple orange material with a slight specular highlight to mimic the shiny quality of its exoskeleton, while the eyes were assigned a black, high-gloss material for realism. For the phytoplankton and feces models, basic colored materials were used, and transparency was applied where needed to achieve a realistic appearance. After applying the base materials, adjustments were made in the Shader Editor to refine the properties such as Base Color, Roughness, and Specular. The whale's skin was given slight roughness to prevent an overly shiny appearance. For the diver, the wetsuit material was adjusted to be matte with minimal reflectivity, ensuring each model had a realistic and cohesive look.



(a) Node editor with the materials and textures of the Whale model selected.

(b) Node editor with the materials and textures of the Diver model selected.

(c) Node editor with the materials and textures of the Zooplankton model selected.

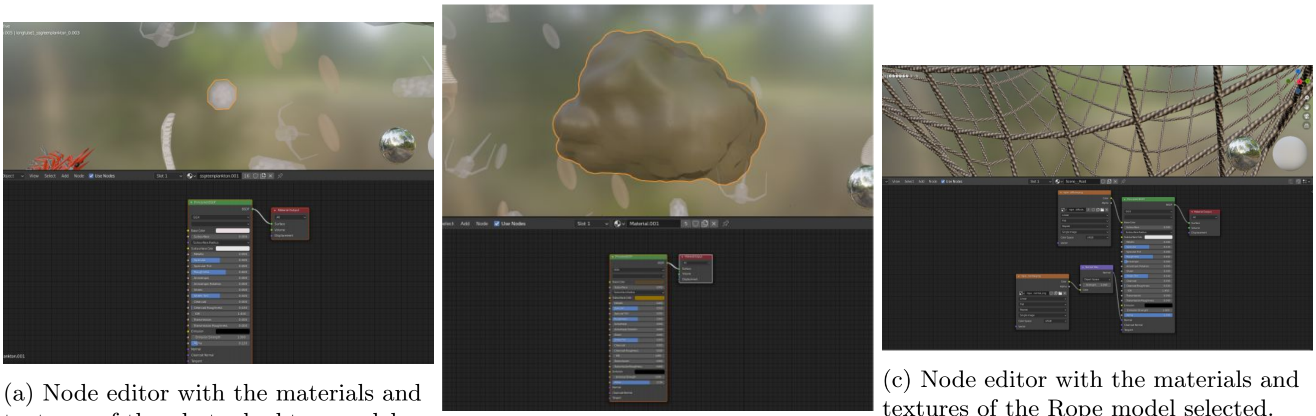
Fig. 27: Node editor screenshots with the materials and textures of the Whale and Diver models.

In this section, the painting, coloring, and texturing processes applied to various models within the project will be described. These processes involved both Blender and Photoshop, depending on the model's requirements. The process of painting and texturing the whale model began with the application of a base color directly in Blender. Switching from Object Mode to Texture Paint mode in the 3D Viewport, a basic grey-blue base color was applied to the entire model using the Draw brush. This base color served as the foundation for the more detailed textures added later. Next, finer details were incorporated using the Texture Paint tools in Blender. Color variations were painted around key areas such as the whale's belly, eyes, and fin edges. Brushes with different textures helped simulate the roughness of the whale's skin, and the Stencil tool was particularly useful for applying pre-prepared texture stencils to specific areas, giving the skin a realistic, varied appearance. Once the basic texture was painted in Blender, the UV map, along with the texture, was exported via the Image menu in the UV Editor by selecting "Save As." This texture file was then opened in Photoshop for further refinement. In Photoshop, additional details, such as subtle scars, enhanced texture depth, and color variations, were added using the Brush and Smudge tools. Layer blending modes, such as Overlay and Multiply, enriched the colors and created realistic shading effects. After completing these refinements in Photoshop, the texture was saved and reimported into Blender, where it was applied to the whale model for the final, polished look (See Figure 27a). The diver model's painting and texturing process began with the application of a base color in Blender. Using Texture Paint mode, the wetsuit was painted black, while equipment like the flippers, mask, and other accessories were given bright, contrasting colors, such as yellow, to ensure underwater visibility. The Draw brush was employed for broad color application, with the Fill tool helping to quickly cover large sections. For detailing and refinement, additional elements such as fabric textures, logos, and seams were painted using Texture Paint tools. Custom brushes were created to replicate the neoprene texture of the wetsuit, enhancing the model's realism. The UV map, along with the texture, was then exported to Photoshop for further refinement. In Photoshop, details such as zippers, water reflections on the suit, and wear marks on the flippers were added for a more authentic look. Finally, the refined texture from Photoshop was re-imported into Blender and applied to the diver model (See Figure 27b). Adjustments were made in Blender to ensure the textures aligned properly and maintained a realistic appearance when the model was animated.

The painting and texturing process for the Zooplankton model focused on simplicity. Using the Material Properties tab in Blender, an orange material was assigned to the body, while the eyes were given a black material to create contrast. The Principled BSDF shader was used to control key material properties, including roughness and subsurface scattering, to give the body a slightly translucent look, characteristic of small marine creatures. This subtle translucency enhanced the realism of the zooplankton's appearance (See Figure 27c).

The coloring process for the phytoplankton and whale feces models involved assigning basic materials in Blender. For the plankton, different shades of green and brown were applied to their bodies to simulate natural colors, while the feces were given a brownish, semi-transparent material to create a realistic underwater appearance (See Figure 28a and 28b). To achieve a translucent effect, transparency was adjusted for both the phytoplankton and feces materials using the Alpha setting in the Principled BSDF shader. This adjustment helped replicate the translucent quality often seen in microscopic marine organisms and particulate matter, enhancing the realism of the models.

For the rope model, a detailed texture was designed in Photoshop to replicate the rough, fibrous appearance of real rope (See Figure 28c). Starting with a base pattern, additional details like fraying fibers and color variations were added to enhance realism. This texture was then imported into Blender and applied to the rope model as a UV texture. After unwrapping the UVs of the rope model, the imported texture was assigned in the Shader Editor by using an Image Texture node connected to the Base Color input of the Principled BSDF shader. This setup ensured the rope's appearance was both authentic and visually consistent within the scene.



(a) Node editor with the materials and textures of the phytoplankton model selected.

(b) Node editor with the materials and textures of the Feces model selected.

(c) Node editor with the materials and textures of the Rope model selected.

Fig. 28: Node editor for basic Phytoplankton, Rope and Faeces coloring.

4.3.5 Rigging

The rigging process for the Whale, Diver, and Krill models involved creating a skeletal structure, known as an armature, which defines how each model moves and deforms during animation. This essential step in 3D modeling allows for dynamic and realistic movement, making the models suitable for interaction within AR/VR/MR environments. The skeletal framework was carefully tailored to each model, ensuring that the whale's large, flowing movements, the diver's human-like motions, and the zooplankton's subtle, segmented articulation could be effectively animated, bringing each model to life in immersive environments.

The rigging process began with adding an armature for each model. This was done by selecting the model in Object Mode, pressing Shift + A, and choosing Armature > Single Bone. The armature serves as the skeleton that controls the movement of the model. In Edit Mode (Tab) with the armature selected, the initial bone was positioned to align with the model's main body axis. For the whale, this involved placing the bone along the spine, while for the diver, the bone was positioned along the body center, extending from the head to the hips. Additional bones were then extruded (E key) to complete the skeletal structure. For the whale, bones were created for the tail, fins, and jaw, with each bone carefully aligned to its corresponding body part. The diver's rigging involved extruding bones for the arms, legs, and head, with particular focus on joint areas like the elbows and knees to ensure smooth deformation during movement. The zooplankton's skeleton was simpler, consisting of a main bone for the body and additional small bones for the legs and antennae. Once the armature was fully constructed, the mesh was parented to the armature by selecting the model, then the armature, and pressing Ctrl + P. In the popup menu, "With Automatic Weights" was selected, automatically assigning the model's vertices to the nearest bones and creating an initial skinning (See Figure 29a). To fine-tune the deformation, Blender's Weight Painting tool was used. By selecting the model and switching to Weight Paint mode, the influence of each bone on the surrounding mesh was adjusted. For the whale, extra attention was given to areas like the tail and fins, where smooth, fluid movements were essential. The weights were adjusted to ensure the tail and fins moved naturally without distorting the surrounding geometry. In the diver model, weight painting focused on the joints, such as elbows, knees, and shoulders, to prevent unnatural bending and ensure realistic limb movement. For the zooplankton, weight painting was simpler, focusing on the antennae and legs to ensure these smaller, delicate parts moved correctly with the main body.

For more complex animations, such as the diver's walking or swimming motions, Inverse Kinematics (IK) was set up (See Figure 29b). This allows for more intuitive control of the limbs by automatically calculating the rotations of the bones based on the position of a target bone. In the Diver model, IK was added to the legs and arms by selecting the end bone (e.g., the ankle for the leg) and adding an IK constraint from the Bone Constraints tab. The target for the IK was then set to an empty object, which was placed where the limb was intended to reach. For the Whale model, IK was not necessary due to the simplicity of the whale's movements, which mostly involved smooth, flowing motions rather than complex jointed movements.

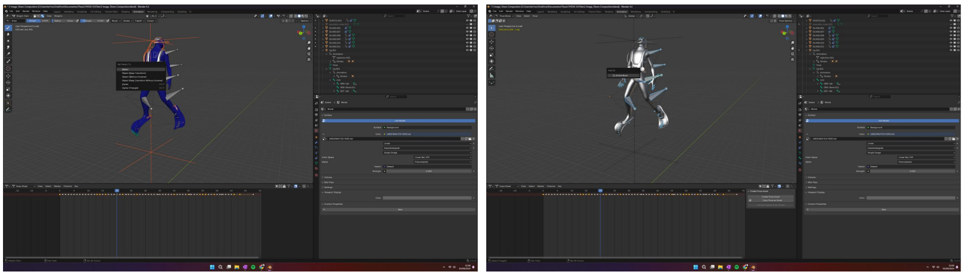

(a) Skinning the Diver Model to the Armature.
(b) Adding Inverse Kinematics to the Diver model.

Fig. 29: Skinning and Adding Inverse Kinematics.

After the rigging process was completed, Pose Mode (Ctrl + Tab) was activated to test the rig by moving the bones and checking the deformations. Various poses were tested to ensure that the mesh deformed correctly, with further adjustments made to the weight painting and bone placement as necessary. For the whale, movements such as tail swishing, fin flapping, and jaw opening were tested to verify that the rig responded well to the intended animations (See Figure 30c). The diver model was tested with swimming and walking animations, ensuring that the arms and legs moved naturally without any mesh distortions. The zooplankton's simple movements, like leg and antennae twitching, were tested to confirm that these small parts deformed accurately (See Figures 30a and 30b).

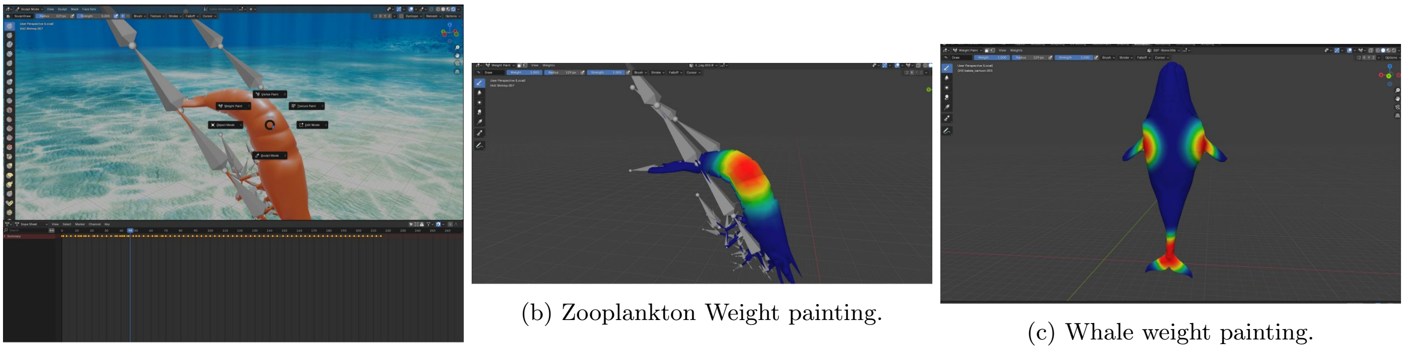
In the final rig optimization, unnecessary bones were removed, and the bone hierarchy was cleaned up to maintain an efficient and organized rig. Constraints were reviewed, and any final adjustments to the weight painting were made to ensure optimal deformation during animation.

4.3.6 Animation

Animation is the process of bringing static models to life by defining their movements over time. In this project, various animations were applied to the Whale, Diver, Zooplankton, Plankton, and Whale Feces to simulate natural behaviors within the AR/VR/MR scenes. Here's how each element was animated using Blender, with detailed steps and relevant shortcuts.

To begin animating, the Animation workspace in Blender was accessed from the workspace tabs at the top or by pressing Shift + F2. This workspace organizes essential panels for animation, such as the Timeline, Dope Sheet, and Graph Editor, making the process more streamlined.

The frame range for each animation was set based on its complexity. For example, the whale's swimming animation was assigned a longer frame range (e.g., 250 frames) to capture fluid motion, while simpler animations, like the plankton's rotation, were set to shorter ranges (e.g., 100 frames) to suit the straightforward movement.

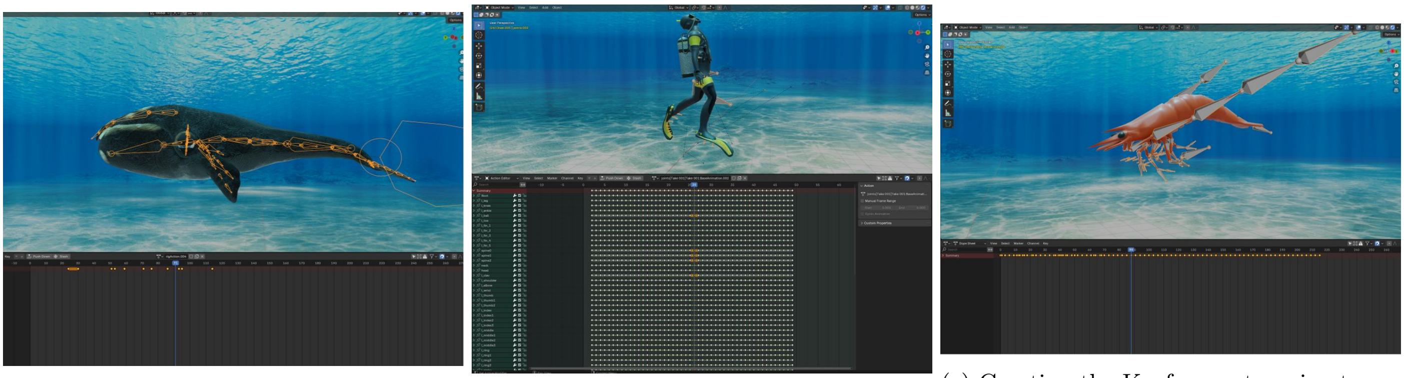


(a) Entering Zooplankton weight painting.

(b) Zooplankton Weight painting.

(c) Whale weight painting.

Fig. 30: Final Adjustments



(a) Creating the Keyframes to animate the whale model.

(b) Creating the Keyframes to animate the diver model.

(c) Creating the Keyframes to animate the zooplankton model.

Fig. 31: Creating the keyframes to animate the whale, diver and zooplankton model.

To animate the whale's natural swimming motion, Pose Mode (Ctrl + Tab) was entered with the whale model selected. Tail and fin movements were animated by selecting the corresponding bones and applying slight rotations at various points along the timeline. Keyframes were set by pressing I and selecting Rotation to capture changes at specific frames, such as 1, 125, and 250. Subtle rotations were then applied to the torso to mimic the undulating motion of a swimming whale, with these movements keyframed similarly. For the mouth animation, the jaw bone was rotated at different intervals, and keyframes were set to capture the slow, deliberate opening and closing, with spacing to ensure smooth motion See Figure 31a).

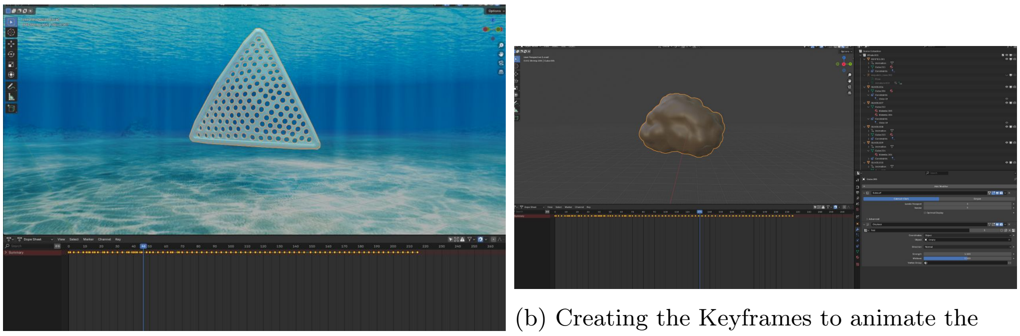
To animate eye blinking, the eyelid bones (modeled separately) were rotated and keyframed at intervals, approximately every 50 frames, to create a natural blinking effect. In animating the diver's legs and torso, Pose Mode was used to simulate a swimming motion. The leg bones were rotated at alternating intervals, such as raising the left leg at frame 1 and the right leg at frame 10, with keyframes set using the I key to capture these movements. A slight rotation was applied to the torso to mimic the natural sway of swimming, with keyframes set at regular intervals for a gentle, rhythmic motion. The arms were positioned to remain mostly static, slightly raised as if the diver was guiding themselves through the water. To complement the torso's motion, slight up-and-down movements were synchronized with the torso's gentle sway, with keyframes set to maintain a natural rhythm throughout the swim (See Figure 31b).

In animating the zooplankton's swimming motion, Pose Mode was used to create a gentle side-to-side movement by rotating the main body bone slightly and setting keyframes to simulate natural swimming. The antennae and legs were animated with subtle movements, with bones angled slightly and keyframes set to create a realistic, gentle locomotion.

The antennae were given a slight wave motion by rotating the bones at regular intervals, approximately every 20 frames, to maintain a smooth and rhythmic appearance throughout the animation (See Figure 31c).

The phytoplankton animation, being straightforward, was handled directly in Object Mode. With the phytoplankton model selected, rotation keyframes were set by pressing I and choosing Rotation. Keyframes were placed at the beginning and end of the timeline with varying rotation values, creating a slow, continuous spin that simulates the plankton's natural floating motion in water (See Figure 32a).

To create a cloudy, bubbly deformation effect for the whale feces, Shape Keys were used to add a dynamic, deforming motion. Shape keys were added by accessing the Object Data Properties tab (green triangle icon) and clicking "+" under the Shape Keys section. With the first shape key selected, the mesh was deformed slightly using the Grab tool (G), and keyframes were set to animate these deformations over time. The influence of the shape keys was adjusted in the Timeline to create a bubbling effect, with keyframed changes simulating the natural dispersal of the cloud (See Figure 32b).



(a) Creating the Keyframes to animate the phytoplankton model.

(b) Creating the Keyframes to animate the feces model.

Fig. 32: Creating keyframes to animate the phytoplankton and feces models.

The Dope Sheet was utilized to ensure that all keyframes were correctly aligned, allowing the Whale, Diver, and zooplankton models to have smooth and realistic swimming cycles. In the Graph Editor, Bezier curves were adjusted to refine the animations, providing natural acceleration and deceleration in movements and preventing abrupt transitions. To achieve a seamless loop, the starting keyframes were copied and pasted at the end of the timeline, allowing the models' motions to repeat continuously. This step was essential for maintaining consistent swimming motions across the main models.

In conclusion, by carefully keyframing and refining the animations using Blender's tools such as Pose Mode, Dope Sheet, and Graph Editor, each model was brought to life with realistic and natural motions. The animations were tailored to match the behavior of each element, from the Whale's fluid swimming to the subtle movements of the Zooplankton and Plankton, enhancing the overall immersion of the scenes within the AR/VR/MR environment.

4.3.7 Scene Composition

To arrange and compose the models for exporting to Unity for AR/VR/MR, a systematic process was followed for each scene. In Scene 1, "Whales in Fishing Net," the necessary models, including the whales and fishing net, were imported into Blender via File > Append, selecting objects from their respective .blend files. The whale models were positioned within the fishing net using the G key for moving and R for rotating. The aim was to create a realistic entangled effect, so the whales were carefully rotated and positioned at various angles to appear caught in the net. For precise alignment, Snap to Grid (Shift + Tab) was used to ensure the models fit properly within the net's geometry. To enhance the realism, the fishing net was adjusted by selecting vertices in Edit Mode (Tab) and using proportional editing (O key) to move sections of the net, making it wrap naturally around the whales. Final composition adjustments involved zooming in (Ctrl + middle mouse button) to check for any overlapping geometry or unnatural intersections. The Alt + Z toggle was used to switch to X-ray mode, allowing thorough inspection to confirm that all elements were accurately placed and visually cohesive.

In Scene 2, "How Many Divers Long is a Whale?," the diver and whale models were imported into Blender, with the scale checked to ensure an accurate visual comparison of their lengths. The S key was used to scale the divers if necessary. Divers were arranged vertically, stacking them head-to-toe beside the whale by duplicating the diver model with Shift + D and positioning with the G key. Precise adjustments were made using R for rotation and G for positioning, with alignment verified in various views (Numpad 1, 3, 7) to ensure consistency.

In Scene 3, "Whale Feeding Cycle," the models of whales, zooplankton, plankton, and feces were imported and distributed across the scene to represent the feeding cycle. Using G and R, the zooplankton were arranged around the whales, the phytoplankton positioned above the feces, and all elements aligned to create a natural feeding cycle layout.

This methodical approach ensured that each scene was composed accurately, with all elements correctly positioned and ready for integration into Unity for AR/VR/MR experiences (See Figure 33).

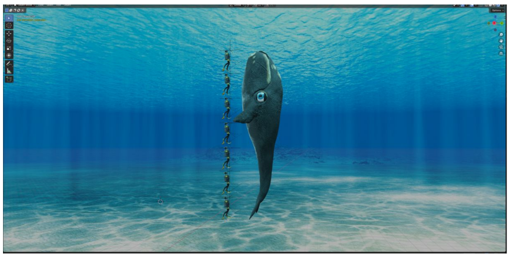


Fig. 33: Duplicating and repositioning the models for the Diver Scene Composition

4.3.8 Export to Unity

After completing the modeling, texturing, rigging, and animation of the elements in Blender, the next crucial step was exporting the scene compositions to Unity. This process was essential to ensure that all assets were accurately transferred, allowing them to be seamlessly integrated into the Unity environment for further development and final deployment in the AR/VR/MR application. Before exporting to Unity, several preparatory steps were completed to ensure the models and animations were ready for seamless integration. First, all necessary modifiers were applied by selecting each model, navigating to the Modifiers tab (wrench icon), and clicking "Apply" on each modifier, such as Subdivision Surface and Shrinkwrap, to finalize the geometry for export. Next, the scale and rotation of each object were checked for Unity compatibility. This was done by selecting each object in Object Mode, pressing Ctrl + A, and choosing "Rotation and Scale" to reset the transforms and ensure predictable behavior in Unity.

Finally, the models and animations were organized into collections in Blender's Outliner. For instance, all Whale-related elements—including the mesh, rig, and animations—were grouped into a single collection. This organization aids in exporting and importing, keeping related assets together for an efficient workflow in Unity. To export the models and animations, the selected elements were exported by navigating to File > Export > FBX (.fbx). In the export options, several key settings were chosen to ensure compatibility and functionality in Unity. "Limit to Selected Objects" was checked to export only the selected models, and "Apply Transform" was enabled to maintain the models' orientation and scale. The export options included "Mesh" to transfer the geometry, "Armature" to export the rig, and "Animations" to ensure the animations were included along with the model. These settings collectively ensured a smooth transition of assets from Blender to Unity.

The export path was chosen to align with the Unity project structure, and consistent naming conventions were applied, such as (whale anim.fbx, diver rig.fbx) This organization aids in easily locating and identifying files within Unity, ensuring an efficient workflow as assets are imported and managed.

Each element, including the Whale, Diver, and Zooplankton, was exported separately to maintain organization and clarity in Unity. For instance, the whale was exported with its animations and rig as "whale anim.fbx," the diver as "diver rig.fbx" with its animations, and the zooplankton as "krill anim.fbx," also including its rig and animations. This approach streamlined the process, allowing each asset to be individually managed and correctly imported into Unity.

4.4 Unity Development

4.4.1 Unity Setup & Import

(a) The navigation was made to Window > Package Manager and selected the Unity Registry.

(b) The AR Foundation package was searched for.

(c) The AR Core package was searched for.

Fig. 34: Importing packages in Unity's Package Manager.

To integrate AR Foundation and the ARCore SDK into the Unity project for the thesis, a structured approach was taken to enable smooth deployment of augmented reality (AR) experiences on Android devices.

First, the Unity environment was set up to support AR development. Unity version 2020.3 LTS was selected to ensure long-term support and stability, as versions from 2019.4.3f1 onward are compatible with AR Foundation and provide access to essential features. A new 3D project was then created in Unity, which is necessary for AR Foundation compatibility. Both the Built-in Render Pipeline and Universal Render Pipeline (URP) are supported by AR Foundation, but the Built-in Render Pipeline was chosen for simplicity and compatibility within this project.

To enable AR functionality, the necessary Unity packages were installed. The AR Foundation package was added, which provides the framework for building AR applications in Unity, along with the ARCore XR Plugin, allowing the project to run AR experiences on Android devices.

I navigated to Window > Package Manager and selected the Unity Registry to search for the AR Foundation package (See Figure 34a and 34b). After finding AR Foundation, it was installed to the project, provided the necessary framework for developing cross-platform AR experiences (See Figure 34c).

The ARCore XR Plugin was installed through the Package Manager, as it is essential for deploying AR applications on Android devices. After installation, the ARCore plugin was enabled by going to Edit > Project Settings > XR Plug-in Management, selecting the Android tab, and checking the box for ARCore.

To set up the AR experience in Unity, the default Main Camera in the scene was deleted, as AR Foundation requires a specific AR Camera included in the AR Session Origin object. This setup ensures that the AR session functions properly and that spatial coordinates are accurately handled in Unity's environment.

An AR Session and an AR Session Origin were added to the scene by right-clicking in the Hierarchy pane, selecting XR, and choosing the respective options. The AR Session Origin object includes the AR Camera, which automatically converts AR coordinates into Unity's world coordinates, enabling accurate spatial positioning.

Before deploying the project to an Android device, the player settings were configured to ensure proper AR functionality. This configuration step was essential for preparing the application for AR deployment on Android (See Figure 35).

To adjust the player settings, File > Build Settings was opened, the platform was switched to Android, and Player Settings was accessed. In the Rendering section, Auto Graphics API was unchecked, and Vulkan was removed from the Graphics APIs list, as Vulkan is not supported by ARCore. The Minimum API Level was set to Android 7.0 (API Level 24), which is a requirement for ARCore applications. These adjustments ensured compatibility and optimized performance for AR deployment on Android devices.

The Scripting Backend was changed to IL2CPP, and ARM64 was enabled under Target Architectures to comply with Google Play Store's 64-bit requirement.

With AR Foundation configured, AR functionalities were integrated into the scenes, ensuring that the application could fully utilize AR features within Unity and meet all platform requirements.

An ARPlaneManager component was added to a new GameObject in the scene, enabling the app to detect horizontal planes in the real world. This feature was essential for anchoring virtual objects, such as the whale or diver, onto real-world surfaces, providing a stable and realistic AR experience.

An ARRaycastManager component was added to the scene to manage touch input and enable interactions with detected planes. Combined with the ARPlaneManager, this allowed the app to detect horizontal planes and let users interact with them, anchoring virtual objects like the whale or diver onto real-world surfaces for an engaging AR experience.

To enhance realism, ARCore's Lighting Estimation was enabled by configuring the AR Camera within the AR Session Origin to adapt to real-world lighting conditions, allowing virtual objects to blend naturally into the environment. Finally, after configuring and testing the AR functionalities within Unity, the app was ready for deployment to an Android device.

To build and run the app, an ARCore-supported Android device was connected via USB, with Developer options and USB debugging enabled on the device. In Unity, File > Build and Run was selected to compile the project and deploy it directly to the device. The app was then tested in real-world conditions to confirm that all AR components functioned as expected, ensuring a seamless and realistic AR experience.

Concluding, integrating AR Foundation and ARCore into Unity was a meticulous process that required careful setup and configuration. By following these steps, it was ensured that the AR experiences developed for this project were both functional and immersive on Android devices. This process allowed the seamless transition of 3D models from Blender to Unity, enhancing the overall user experience with interactive AR elements.

☐ Gradle Installed with Unity (recommended)

Gradle /<somepath>/gradle-5.6.4

You are not using the recommended Gradle, other versions are not officially supported.

Fig. 35: Gradle Settings

As mentioned before, a new Unity project was set up ensuring that the project settings were configured for AR/VR/MR, including the installation of necessary XR plugins. This setup was crucial for preparing the environment where each scene from Blender would be placed individually. For each scene created in Blender, the relevant models (along with their animations and materials) were exported as separate FBX files. This was done to maintain organization and ensure that each Unity scene contained only the models needed for that specific scene. Unity, the Assets folder was navigated to, and by right-clicked to select Import New Asset, and imported the FBX files for Scene 1 (Fishing Net with Whales), Scene 2 (Whale and Divers), and Scene 3 (Whale Feeding Cycle) individually. After importing each FBX file, they were selected in the Project window and using the Inspector, the import settings were checked. In the Model Tab, it was ensured that the scale was appropriate and that Normals and Tangents were set correctly to match the shading and lighting required for each scene. In the Rig Tab, it was verified the rig type for each model—whether Humanoid or Generic—and confirmed that the avatar configurations were correct, particularly for the diver and whale models. And in the Animation Tab, it was checked that the animations for each scene (such as the whale's swimming or the zooplankton's movements) were properly imported and configured to loop where necessary.

For the Fishing Net with Whales composition, a new scene was created in Unity, the corresponding FBX file was imported, and arranged the whales were arranged within the net as per the original Blender composition (See Figure 36a).

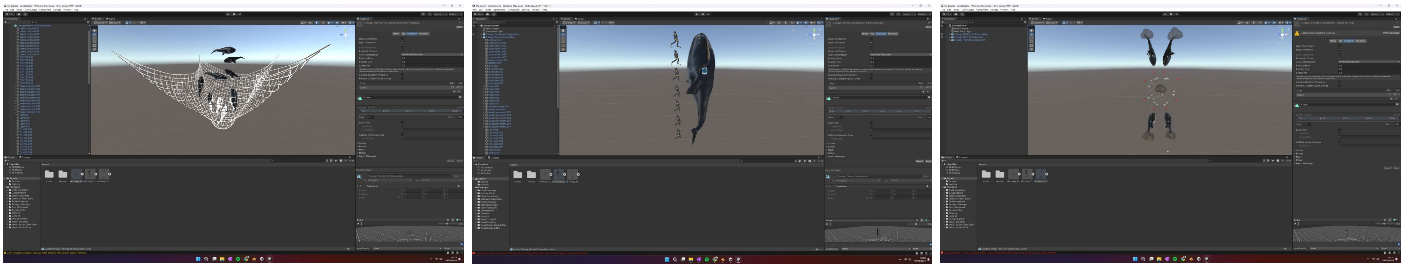
In a separate Unity scene, the Whale and Divers composition's FBX file was imported and the whale model was positioned alongside the divers, scaling and arranging them to match the setup from Blender (See Figure 36b) .

Another new scene was also created for the Whale Feeding Cycle composition, in this scene, the respective FBX file was imported and set up the whales, zooplankton, plankton, and feces in the correct positions to illustrate the feeding cycle, using the original Blender scene as a reference (See Figure 36c).

After placing the models in each Unity scene, materials were reassigned and textures were applied to ensure consistency with the Blender designs. Lighting and camera angles were adjusted to enhance the visual presentation, ensuring each scene was ready for the intended AR/VR/MR experience.

By carefully preparing each scene in Blender and exporting them individually as FBX files, the models, rigs, and animations were successfully transferred and set up in separate Unity scenes. This method ensured that each scene maintained its integrity and functionality, allowing for a smooth transition from Blender to Unity and ultimately providing an immersive experience in the AR/VR/MR environment.

After importing the model scenes into Unity, the next phase of development involved coding the app interactions and designing the information architecture to guide the user experience. The components were connected to the server to enable dynamic content delivery and interaction based on user actions. XR functionalities were integrated with the imported 3D



(a) Fishing Net Composition as per the the original Blender file.

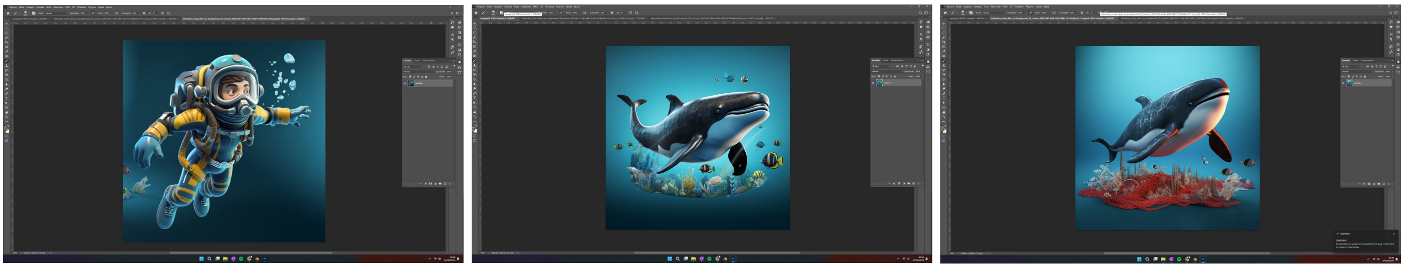
(b) Divers Composition as per the the original Blender file.

(c) Feeding Cylcle Composition as per the the original Blender file.

Fig. 36: Setting up eacch Unity scenes.

models to create a seamless connection between virtual elements and the real-world interface. Logic was developed for how and where each XR scene would appear, ensuring intuitive, natural, and immersive interactions. Scripts were implemented to make AR Foundation and the ARCore SDK work harmoniously with the models. This ensured smooth functionality and a coherent, engaging user experience, blending digital and physical worlds in an innovative and accessible way. The result was a technically robust, logically structured, and user-friendly product. In Unity AR Foundation, trigger images are used to recognize and track specific images in the real world, which then activate or "trigger" certain AR experiences. The trigger images were designed to be simple, easily recognized, and directly connected to the content of each scene. The feeding cycle image (See Figure 37b) shows a clear whale silhouette with hints of its surrounding environment. This choice keeps the whale as the main focus while still suggesting its ecological role, making the image immediately understandable. The diver image (See Figure 37a) presents a single, cartoon-like diver. This minimal design was chosen because the diver alone is enough to clearly differentiate it from the others, where no human figure is present. Its distinctiveness makes the trigger unambiguous and easy to connect to the intended scenario. The fishing net image (See Figure 37c) depicts only the net structure placed on the seafloor. Showing a whale entangled was avoided, as it would be technically visually confusing and difficult to perceive as a trigger. By keeping the whale and net as separate elements, the trigger remains clear while still conveying the idea of entanglement and human threats in a simple, recognizable way. Together, these images provide clarity and meaning, ensuring that each trigger not only activates the AR system but also prepares the viewer for the ecological story it introduces. To create the AR trigger images, Adobe Photoshop was used to craft visually distinctive and easily recognizable designs. The process began by sketching base visuals with strong, distinct characteristics such as high contrast, sharp edges, and complex patterns, which are crucial for effective AR marker recognition. The layering and blending system was employed to combine multiple elements into unique compositions. Layers were arranged to create depth, and various blending modes were applied to merge components seamlessly, resulting in a cohesive design. After establishing the basic composition, the images were refined by adjusting colors, enhancing contrast with tools like Curves and Levels, and using the Brush and Clone Stamp tools to add or remove details. This step was critical for ensuring the images had the necessary visual clarity and distinct features for AR recognition.

To enhance realism and visual appeal, textures were applied by overlaying them onto the images and using blending modes to integrate them seamlessly. Finally, the images were tested within the AR software to ensure they were easily recognized. If recognition issues arose, adjustments were made in Photoshop to make necessary adjustments, such as increasing contrast or simplifying the design (See Figures 37a, 37b and 37c).



(a) Creating the Divers scene trigger illustration on Photoshop.

(b) Creating the Feeding Cicle Scene trigger illustration on Photoshop.

(c) Creating the Fishing Net trigger illustration on Photoshop.

Fig. 37: Creating the scene triggers illustraion on Photoshop

In Unity AR Foundation, trigger recognition is achieved through image tracking by importing reference images into the Unity project and adding them to an XRReferenceImageLibrary. This setup allows the AR system to recognize and track specific images in the real world, which then triggers corresponding AR content or interactions within the application. Once the images are uploaded, they can be recognized by the AR application when viewed through the device's camera. During runtime, the AR Foundation continuously scans the environment for the trigger images. When a trigger image is recognized, the app can instantiate AR content, such as a 3D model or animation, overlaid on top of the real-world image. The image recognition process relies on comparing the live camera feed with the reference images stored in the XRReferenceImageLibrary.

For an image to function effectively as a trigger in AR, it should possess certain qualities such as high contrast and detail. Images with distinct features, high contrast, and a lot of details (such as varied colors, sharp edges, and distinct patterns) are easier for the AR system to recognize.

Using images with repetitive patterns should be avoided, as they can confuse the recognition system. Unique features in different parts of the image help the AR software to identify the image more reliably.

The image should perform well under different lighting conditions. Testing the image under various lighting scenarios can help ensure consistent recognition.The trigger image should also be large enough to be easily recognized but not so large that it becomes unwieldy. Maintaining a consistent aspect ratio is also crucial to prevent distortion. To check the efficiency of trigger images, online tools like Vuforia's Target Manager or ArToolKit provide insights into how easily images can be recognized.The images provided (e.g., the whale, diver, and underwater scenes) fit well within the criteria of this tools. Each image has unique, high-contrast elements like the whale's detailed body, the diver's bright colors, and the marine elements, making them highly recognizable. The absence of repetitive patterns and the presence of fine details help ensure that these images can be reliably tracked by the AR software. These characteristics make the images strong candidates for AR triggers, ensuring smooth and accurate performance within the AR Foundation framework. In addition to ensuring that the trigger images possess high contrast, unique features, and non-repetitive patterns, another important consideration was the lighting conditions under which these images would be scanned. Specifically, since the AR application might be used outdoors, where sunlight can be intense, the images were deliberately designed with darker tones. Bright sunlight can cause glare and reflections on white or very light-colored paper, making it difficult for the camera to accurately detect and recognize the images. The darker tones help reduce the chances of reflection and glare, thereby improving the reliability of the scanning process. This ensures that even in challenging lighting conditions, the AR triggers function correctly and the intended AR content is displayed without issues.

4.4.2 App Export, Testing & Calibration

Firstly, the project was exported to an Android build, making sure that all settings aligned with the requirements for ARCore and the AR Foundation setup (See Figure 38). This involved ensuring that the appropriate player settings were configured, such as disabling the Vulkan graphics API, setting the correct minimum API levels, and enabling ARM64 support. Each build was carefully prepared to reflect the most recent updates and configurations.

Once the builds were exported, a thorough testing process was initiated with a primary focus on verifying several key aspects of the application. This included ensuring that AR functionalities, model placements, animations, and trigger recognition operated as expected, providing a smooth and immersive user experience.

Next, the quiz feature was tested to ensure that all questions were working correctly, that the logic for displaying answers was accurate, and that the feedback system operated as intended.

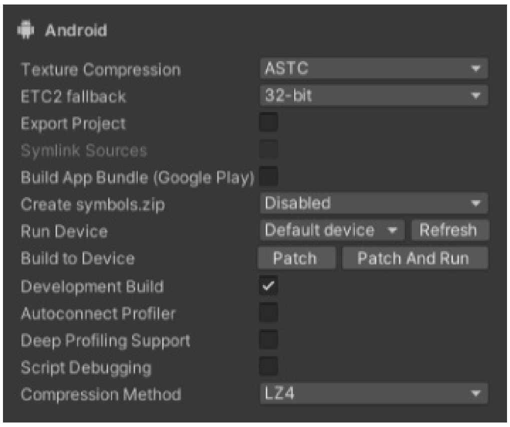
Since accurate placement of the 3D models was crucial, the AR floor detection was tested across various environments to ensure consistency. The goal was to confirm that the models anchored properly to real-world surfaces and that the floor detection algorithms provided stable and reliable results.

A significant part of the testing was dedicated to the AR triggers. It was evaluated whether the triggers were correctly detected under different lighting conditions and at various angles and distances. This step was essential for ensuring that the user's experience would be seamless and that the AR content would activate as expected when the triggers were scanned.

Throughout testing, issues were encountered where the models appeared either too large or oddly rotated within the AR environment. These anomalies needed careful adjustment in Unity, tweaking the scale, position, and rotation parameters to match the intended design. Each iteration was tested until the models appeared correctly in the AR space, maintaining the correct proportions relative to the real world.

Another critical aspect was the testing of animations. It was ensured that all animations played correctly and smoothly when triggered. This included verifying that the whale's swimming motion, the diver's movements, and the krill's animations were functioning without glitches. Sometimes, animations would fail to play or would loop incorrectly, requiring us to revisit the animation settings in Unity and adjust them before re-exporting.

Through the iterative testing process, various bugs and issues were identified and addressed, including problems with trigger recognition, model scale adjustments, animation trigger refinements, and ensuring all interactive elements worked seamlessly together. Each fix was followed by another round of testing to confirm that the issues were resolved without introducing new ones, leading to a polished and stable AR experience. This rigorous approach to export and version testing was essential in minimizing bugs and ensuring that the final application was both functional and polished, providing a smooth and immersive user experience.

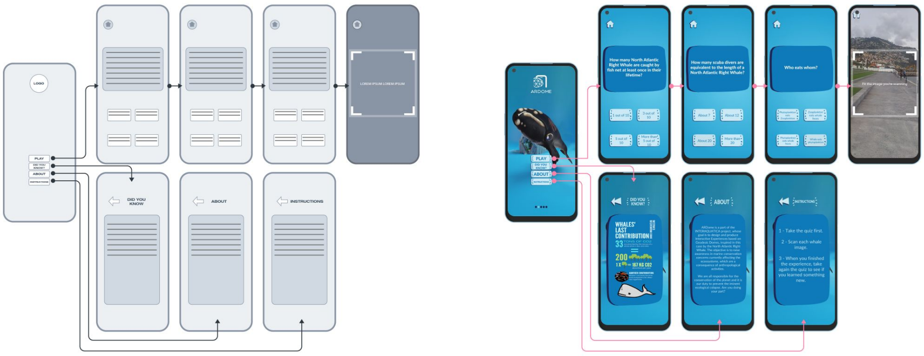


Android

Texture Compression	ASTC
ETC2 fallback	32-bit
Export Project	☐
Symlink Sources	☐
Build App Bundle (Google Play)	☐
Create symbols.zip	Disabled
Run Device	Default device · Refresh
Build to Device	Patch · Patch And Run
Development Build	☑
Autoconnect Profiler	☐
Deep Profiling Support	☐
Script Debugging	☐
Compression Method	LZ4

Fig. 38: Building settings for Android

4.5 Application Architecture & User Experience



(a) Low-Fidelity Wireframe of the app interface, illustrating the main navigation flow and layout. The interface includes sections for playing the experience, viewing educational content ('Did You Know?'), app information ('About'), and usage instructions.

(b) High-Fidelity Wireframe of the ARDome App: An overview of the ARDome application interface, showcasing the user journey from engaging with quiz questions related to whale conservation, to scanning augmented reality images and viewing educational content.

Fig. 39: Low Fidelity and High Fidelity App Wireframes.

4.5.1 Step-by-Step Guide

The user is welcomed with the start screen featuring the app's logo and a visually captivating image of a whale, which immediately sets the marine-themed context. From here, users can choose from three primary options: "Play," "Did You

Know?" and "About," with an additional "Instructions" option at the bottom. The interface is designed for easy navigation, guiding users smoothly into the app's core experiences (See Figures 39a and 39b).

Upon selecting "Play," the user is presented with the first quiz question: "How many North Atlantic Right Whales are caught by fish nets at least once in their lifetime?" This interactive feature engages the user right from the start, encouraging them to think and learn about marine life through multiple-choice questions. The design remains clean and straightforward, allowing users to focus entirely on the educational content.

The quiz progresses with more questions, such as "How many scuba divers are equivalent to the length of a North Atlantic Right Whale?" The consistent layout ensures that users can easily interact with the app, making the learning experience seamless and engaging. The questions are designed to prepare users for the AR scenes they will soon explore.

After completing the quiz, users are prompted to scan the AR trigger images. Each trigger corresponds to a specific scene: the first for the divers next to the whale for size comparison, the second for whales trapped in a fishing net, and the third for the whale's ecological role in the food cycle. The scanning process is straightforward, with clear instructions provided to ensure users can effectively trigger the AR content.

When the first trigger is scanned, the AR scene of the whale alongside divers appears. This visual comparison directly answers the quiz question about the whale's size relative to divers, providing a memorable, interactive learning experience. The simplicity of the design ensures users can easily appreciate the scale of the whale in comparison to humans.

Scanning the second trigger displays a scene where whales are trapped in a fishing net. This scene is crucial for visualizing the earlier quiz question about the dangers whales face, enhancing the user's emotional connection and understanding of the issue. The interface remains clean, focusing the user's attention on the critical conservation message.

The third trigger brings up a scene illustrating the whale's role in the marine food cycle, including plankton, zooplankton, and whale feces. This scene reinforces the educational content by visually explaining the whale's ecological importance, making the learning process immersive and impactful.

Going back to the Menu, the "About" section offers users additional context about the app's purpose, explaining its role in a broader marine conservation project. This section provides necessary background information, ensuring users understand the significance of their interaction with the app.

The "Instructions" screen provides a brief guide on how to use the app, ensuring that users are well-informed on how to engage with all the app's features. The instructions are concise, making it easy for users to get started without any confusion.

4.5.2 Visual and UX Design Goals

The app's design is anchored in three core principles, which are simplicity, accessibility, and engagement with the marine environment. The app is designed to be intuitively navigable, with clear menus and straightforward interactions. This ensures that users of all ages and technological proficiency can engage with the content without unnecessary complications. The app ensures that all users can easily interact with the content, regardless of their device or environment. The AR triggers were designed to be recognizable even in various lighting conditions, and the app's interface supports easy readability and interaction. By integrating interactive elements like quizzes and AR scenes, the app fosters a deeper connection between users and marine life. The immersive experiences are designed to not only inform but also emotionally engage users, encouraging a lasting interest in marine conservation.

Every aspect of the app, from the layout of the screens to the clear instructions, is designed to be user-friendly. This ensures that users can focus on learning without being hindered by technical issues or confusing interfaces.

The use of AR technology offers an immersive experience, allowing users to visualize and interact with marine life in a way that traditional learning methods cannot achieve. This immersive approach helps users retain information better and encourages repeated engagement with the app.

The combination of quizzes, AR scenes, and educational content creates a comprehensive learning experience. Users are actively involved in the learning process, which helps reinforce the information and makes the educational content more impactful. The app's thoughtful design and functionality effectively achieve the goals of simplicity, accessibility, and engagement. The careful integration of AR technology with educational content ensures that users not only learn but also develop a deeper connection to the marine environment. These design choices contribute to the overall success of the project, making the app a valuable tool for promoting awareness and understanding of marine conservation.

4.6 Demonstration Video

A demonstration video [99] was created to showcase the developed applications. The video presents one representative scene for each technology: "the Whale Feeding Cycle scene" for AR, the "How Many Divers Long is a Whale?" scene for VR, and the "Whales in Fishing Net" scene for MR. These examples allow viewers to see how each technology differs in appearance and mode of use. The video also incorporates a volunteer participant, who granted permission to be recorded, interacting with the system across AR, VR, and MR. This provides both the perspective of the user and the external appearance of the technologies during operation. In addition, the recording includes a screen-captured preview of the animated 3D model scenes, offering a clear representation of the visual content created for the applications. Finally, the video documents the physical setting of Praça do Povo in Funchal, adjacent to VMT Madeira and the boarding area for its clients, situating the applications within the intended deployment environment. The footage reflects the typical outdoor conditions of this location, particularly the strong sunlight, which limited the visibility of recordings inside the headsets. For this reason, the “in-headset” perspectives were captured in the nearest available indoor space to ensure clarity of the virtual content.

The complete demonstration video can be accessed at: `https://www.youtube.com/watch?v=bcPOYK5yMX0`.

5 Evaluation Study

Conducting this evaluation study in the context of onshore whale-watching presented both distinctive opportunities and unavoidable limitations. Unlike controlled laboratory settings, the research was carried out in a dynamic public environment immediately after participants had completed whale-watching tours. The novelty of this setting, combined with the practical realities of fieldwork, required several compromises that directly shaped the study design, the instruments employed, and the overall execution of the evaluation. Time constraints were particularly significant, as participants were often eager to rest, have lunch, or continue their touristic activities after whale-watching. The location of the study, Praça do Povo in Funchal, also introduced challenges. As an outdoor and highly frequented public space, it reduced experimental control compared to a laboratory and occasionally created hesitation among participants who felt self-conscious about participating in public view. The reliance on VMT Madeira clients further required sensitivity to avoid interfering with the original tourism experience, while weather conditions such as strong sunlight, heat, or light rain occasionally affected participant eagerness to participate. Ethical considerations restricted the collection of signed consent forms, photographs, or videos; instead, verbal agreement was obtained to minimise disruption and protect participant privacy. The absence of dedicated testing booths required mobile-friendly configurations, while the study was facilitated by a single researcher responsible for equipment setup, briefing, observation, and data collection simultaneously in the field. Taken together, these contextual factors meant that participants' limited willingness to engage with lengthy instruments required the use of concise questionnaires and a streamlined testing process. The questionnaires were therefore restricted to the most essential measures of engagement, learning, and user perception, allowing data to be collected efficiently without imposing excessive demands on participants, ensuring that participation remained feasible within the constraints of the setting. In light of these conditions, the present work does not constitute a formal experimental evaluation but rather a usability-oriented study focused on participants' experiences of XR systems in a real-world tourism setting. The central research questions are addressed not only through user responses but also through the researcher's experiential insights gained during the design, prototyping, and deployment of the system. This combined perspective captures both user perceptions and the practical realities of implementing XR for onshore whale-watching. In this section, several experimental conditions are depicted, comparing different usage of virtual technologies across on- shore settings. In Figure 40, it is possible to see the diverse experimental setup in reality/virtuality spectrum allowing benchmarking of proposed technologies. Below, we refer to some basic characteristics of each and how they will be used throughout experiments. **Augmented reality** brings the virtual content and overlays it on top of the real world without covering it completely. Dissertation will assess its potential when the user is within the proper environment and with other people in the same physical space. This feature makes AR the most suitable medium for science communication and public outreach (see Figure 41a). **Mixed Reality** as the name conveys, mixes some of the positives and negatives of each. In MR, the viewer is immersed in the content, with also a headset that can display 3D Models and detect its position and rotation, but this content such as the likes of AR is only presented in an overlay on top of the real world. It is possible to suspect it to be a middle ground between the two. While being superior to the AR in the correct light conditions, it may sometimes not be as clear. And also, if the real world environment does not fit the visual representation, the VR is expected to achieve better results (see Figure 41b). **Virtual Reality** is an alternative medium for communicating science where the viewer is completely immersed through virtual content. The headset can display 3D capture or reconstruction of the remote environment. In VR, the user can change their position i.e., move forward or back, in addition to rotation i.e., looking around. This provides a greater sense of presence and immersion to the viewer, and therefore more engagement with the content (see Figure 41c).

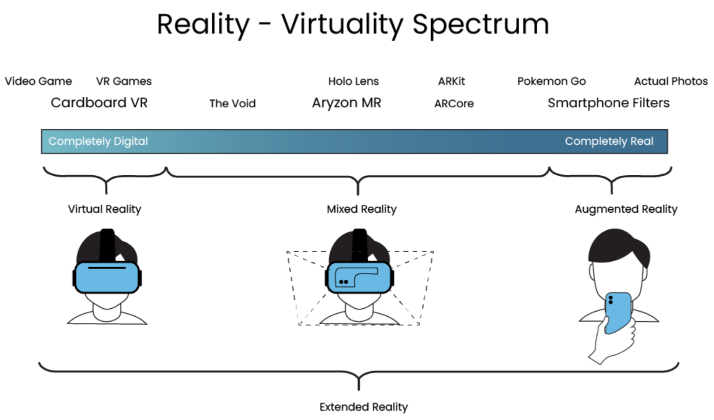
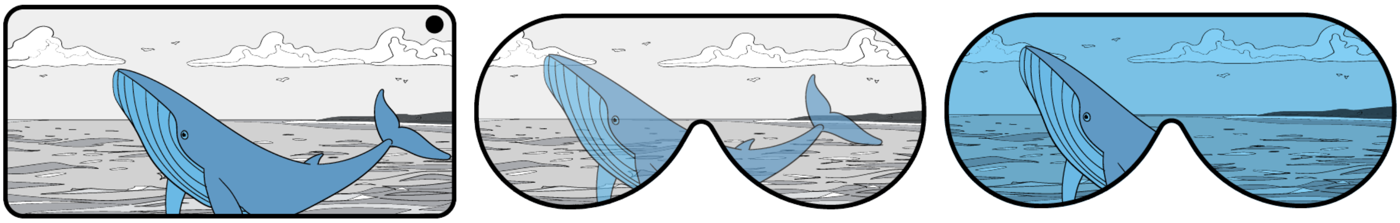


Fig. 40: Experiment 2 - Virtual Reality in On Shore Settings.



(a) Experiment 4 - Augmented Reality in On Shore Settings.

(b) Experiment 6 - Mixed Reality in On Shore Settings.

(c) Experiment 2 - Virtual Reality in On Shore Settings.

Fig. 41: Final Adjustments

5.1 Evaluation Study Overview

This section provides a structured overview of the research approach undertaken to evaluate the effectiveness of AR, MR, and VR in enhancing user engagement and learning in marine science communication. The primary goal of this section is to outline the experimental procedures, participant interactions, and data collection methods that were used to achieve the study's objectives.

The evaluation study is crucial for achieving the research objectives as it ensures a systematic approach to testing the hypotheses regarding the comparative effectiveness of AR, MR, and VR. By detailing each step of the experimental design, this section ensures that the study can be replicated and validated, providing reliable insights into how different immersive technologies can be used in public outreach and education.

The overall test was designed as an experimental study with a comparative analysis framework. Participants were divided into groups to experience the same content through different mediums: AR, VR, and MR. This experimental design allowed for a direct comparison of user experiences across the three technologies, focusing on their impact on engagement, knowledge retention, and perception of marine conservation issues. Through this structured approach, the study aimed to identify the most effective medium for communicating complex scientific concepts to a diverse audience.

5.2 Storyboard and User journey

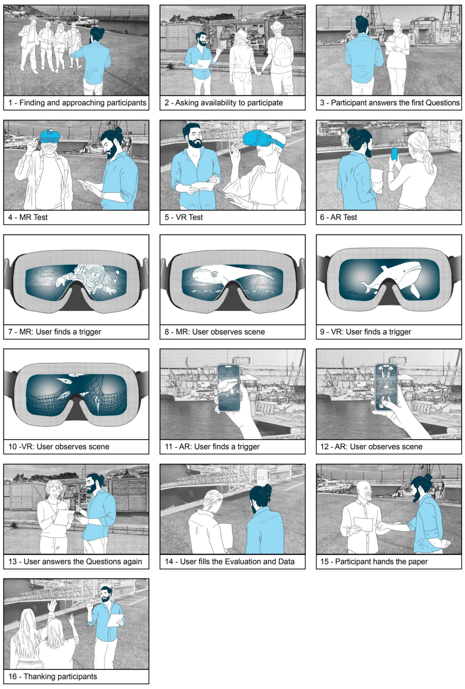


Fig. 42: This storyboard illustrates the process of testing XR technologies with participants. It begins with recruiting and explaining the study, followed by the individual AR, VR, and MR testing sessions. Participants provide feedback on their experiences. The process concludes with data collection and participant evaluation

5.3 Participants

The study involved a carefully selected sample of 60 participants, divided equally into three groups of 20: one group experienced the content through AR, another through VR, and the third through MR. This division was crucial for comparing the effectiveness of each medium in communicating marine science and engaging the participants.

Participants were primarily recruited from clients of VMT Madeira, a marine tourism company known for its whale-watching tours. This company operates in a popular onshore location that is frequently visited by tourists and locals alike due to its proximity to marine life. However, participation was not restricted to tourists; Portuguese nationals who met the criteria were also included. The key criterion for selection was that participants must have recently interacted with whales or cetaceans through VMT Madeira's tours. This recent experience with real marine life provides a relevant real-world context for assessing the effectiveness of AR, VR, and MR in enhancing their understanding and engagement with marine conservation content. Selecting participants who had just engaged in whale-watching or cetacean interactions establishes a baseline that could be compared with future studies involving participants who are far removed from such experiences, both geographically and in terms of time. This approach allows for a deeper understanding of how proximity to real-life marine experiences influences the effectiveness of immersive technologies in science communication.

Demographic data collected from the participants included age, gender, and nationality. This information will be further analyzed and discussed in the results and discussion section to explore any correlations between these demographic factors and the effectiveness of the different immersive technologies. Understanding the demographic makeup of the participants will provide insights into how various groups engage with AR, VR, and MR in the context of marine science, helping to identify any patterns or preferences that could inform future studies and applications.

Fig. 43: Most recent photo of the VMT Team, photo by VMT Madeira [70].

5.4 Location

As seen in Figure 44 The testing location for this study was Funchal Praça do Povo, a strategically chosen onshore area in Madeira. This site is situated near both the VMT Madeira Balcony store and the catamarans used for whale-watching tours, (see Figure 45a) where the participants had recently disembarked.

Funchal Praça do Povo is a vibrant public space located along the waterfront in Funchal, Madeira. The area is known for its proximity to the Atlantic Ocean and serves as a central point for various marine activities, including whale-watching tours offered by VMT Madeira. The location is bustling with tourists and locals, especially those who have just returned from marine excursions, making it an ideal spot for engaging with participants who have fresh memories of their interactions with marine life (see Figure 45b).

Fig. 44: Sattelite view of study location in Funchal, Praça do Povo, from Google Maps

This location was selected for several key reasons. Firstly, its close proximity to the VMT Madeira Balcony store and the catamarans ensures that participants are readily available after their whale-watching tours, providing a unique opportunity to capture their immediate reactions and insights. Secondly, being onshore and near the sea allows for an environment that closely resembles the natural setting of the participants' recent experiences, which is crucial for the AR, VR, and MR testing. This alignment between the test environment and the participants' real-life experiences enhances the validity of the study by ensuring that the immersive technologies are tested in a contextually relevant setting.

Overall, the choice of Funchal Praça do Povo as the testing location was driven by its strategic relevance to the study's objectives, ensuring that the participants were in the right frame of mind and environment to engage meaningfully with the immersive technologies being evaluated.

(a) Current balcony of VMT.
(b) Marina where VMT docks its boats.

Fig. 45: Eye-level view of study location.

5.5 Pre-Questionnaire

Individuals who had just completed their whale-watching experience, were approached near the VMT Madeira Balcony store, strategically located in Funchal's Praça do Povo. The purpose of the study was explained, and participants were available to participate by answering some questions about marine life sustainability (See Figure 42).

Before engaging with the immersive AR, VR, or MR content, participants were asked to complete a pre-questionnaire. This pre-questionnaire was identical to the post-questionnaire administered after the testing phase, allowing for direct comparison of responses before and after exposure to the immersive content. The primary purpose of the pre-questionnaire was to establish a baseline level of marine literacy among participants. By assessing their initial knowledge on topics related to marine conservation, the food chain, and the scale of marine animals, the pre-questionnaire provided a reference point against which post-test results could be compared. This comparison was essential for determining the educational effectiveness of the AR, VR, and MR experiences.

The pre-questionnaire aimed to gauge the participants' understanding before they were influenced by the immersive content. This allowed the research to measure any shifts in knowledge or awareness directly attributable to the educational interventions provided through the various immersive technologies. Additionally, understanding the participants' initial knowledge level helped in identifying areas where they might have had misconceptions or gaps in understanding, which the AR, VR, and MR content could potentially address. The questions in the pre-questionnaire were as follows:

"How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime?"
Options: A) 1 in 10. B) 3 in 10. C) 5 in 10. D) More than 5 in 10.

"Who eats whom?"
Options: A) Phytoplankton eats zooplankton. B) Zooplankton eats whale feces. C) Phytoplankton eats whale feces. D) Whale eats phytoplankton.

"How many scuba divers are equivalent to the length of a North Atlantic Right Whale?"
Options: A) Around 7. B) Around 12. C) Around 20. D) More than 20.

5.6 Testing Procedure

The testing procedure was designed to evaluate the effectiveness of AR, VR, and MR technologies in enhancing participants' understanding and engagement with marine conservation content. Participants were divided into three groups, each interacting with the app using a different immersive technology: AR, VR, or MR. The process involved several steps to ensure a consistent and comprehensive evaluation across all participants.

The testing process across all three technologies was designed to be intuitive and engaging, with minimal required interaction to trigger the content. Whether using a mobile phone for AR, a VR headset, or an MR device, participants were able to explore detailed 3D models of marine life and conservation scenarios. This hands-on, immersive approach was essential for evaluating how well each technology could convey scientific information and engage participants in marine conservation efforts. By maintaining consistent testing conditions and instructions across all groups, the study aimed to draw reliable comparisons between the different immersive technologies, ultimately contributing to a better understanding of their respective strengths and weaknesses in educational and outreach contexts.

Augmented Reality Testing

Setup involved providing participants in the AR group with a mobile phone pre-installed with the AR app. The testing environment included various AR triggers placed strategically on the ground or, when weather conditions were less favorable, on the balcony of the VMT Madeira store.

Interaction entailed participants pointing their mobile devices at the AR triggers, which were designed to initiate the respective 3D scene when detected by the app. Once the trigger activated the scene, participants panned their phones around the area to explore the 3D models that appeared on their screens. The models, representing different aspects of marine life and conservation, were interactive and could be viewed from multiple angles by moving the mobile device.

Virtual Reality Testing

Setup involved participants in the VR group with VR headsets for a fully immersive experience. The headsets were preloaded with the VR version of the app, designed to create a virtual environment that mirrored the real world while overlaying digital marine life models.

Interaction began as participants donned the VR headset, finding themselves in a virtual representation of the marine environment. They were instructed to look around the virtual space to locate digital triggers embedded within the environment. When a participant gazed at a trigger for a few seconds, the associated 3D scene was activated. Participants could then explore the digital models by rotating their heads or moving slightly within the virtual space, simulating a walk around the environment.

Mixed Reality Testing

Setup involved equipping participants in the MR group with MR headsets, allowing them to see both the real world and digital overlays. The MR experience combined elements of both AR and VR, with digital triggers integrated into the participant's real-world view.

Interaction began as participants donned the MR headsets, experiencing an enhanced view of their surroundings with digital marine models overlaid on the real environment. Similar to the VR experience, participants located digital triggers by looking around. Upon focusing on a trigger for a few seconds, the 3D scene was activated, allowing participants to explore the scene through a combination of head movements and slight physical movement within their real-world space.

5.7 Post-Questionnaire

After the testing sessions were completed, participants were asked to answer the same set of questions as in the pre-test questionnaire. This repetition of questions served a critical role in assessing the changes in participants' knowledge or perception following their interaction with the AR, VR, or MR content.

The primary purpose of the post-questionnaire was to measure the effectiveness of the AR, VR, and MR experiences in enhancing the participants' understanding of marine conservation topics. By comparing the responses from the pre- and post-questionnaires, it was possible to identify any changes in knowledge or perceptions that occurred as a result of the immersive educational experience. This comparison allowed for a detailed analysis of how each type of immersive technology impacted learning outcomes. For example, a significant increase in correct answers in the post-questionnaire would indicate that the immersive experience successfully conveyed the scientific information. Additionally, changes in participants' responses provided insights into how well each technology facilitated engagement and retention of information.

Overall, the post-questionnaire was a crucial tool in evaluating the educational value of the AR, VR, and MR experiences, offering a direct measure of the impact these technologies had on participants' understanding and awareness of marine conservation issues.

5.8 Evaluation

The evaluation section was designed to assess the participants' experiences and learning outcomes after interacting with the AR, VR, or MR applications. The evaluation consisted of a series of questions that the participants answered on a scale from 1 (low) to 7 (high), focusing on various aspects of their experience. The purpose of this evaluation was to gauge the participants' levels of engagement, perceived value, and educational impact of the experience. By asking participants to rate their agreement with these statements, we aimed to measure not only the effectiveness of the immersive technologies in conveying marine science content but also the emotional and cognitive connections that participants formed during the experience. For example, questions like "I learned a lot with this experience" and "I am comfortable teaching others about what I have learned" were designed to assess the educational impact and knowledge retention. Meanwhile, questions like "I feel connected to whales" aimed to evaluate the emotional engagement and connection fostered by the immersive experience.

This evaluation provided valuable insights into how participants perceived the AR, VR, and MR experiences, and helped identify which medium was most effective in achieving the research objectives of enhancing marine literacy and fostering a connection with marine life. The results from these evaluations will be further analyzed in the results and discussion sections to understand how different factors, such as the medium used and the participants' backgrounds, influenced their overall experience and learning outcomes. The questions were as follows:

A. I found this experience interesting. B. I found this experience important. C. I found this experience useful. D. I found this experience difficult. E. I learned a lot with this experience. F. I am comfortable teaching others about what I have learned. G. I would repeat this experience. H. I would recommend this experience. I. I feel connected to whales.

5.9 Data Collection

The data collection process for this study was meticulously designed to ensure accuracy and reliability, given the significance of the research objectives. The primary method of data collection involved both digital and physical questionnaires, as well as observations made during the testing sessions.

Pre- and post-test questionnaires were used to assess participants' marine literacy before and after the testing, provided both digitally within the app and on printed physical copies. The physical copies were essential to mitigate potential user errors that might occur when interacting with VR/MR controls, ensuring responses were accurately recorded.

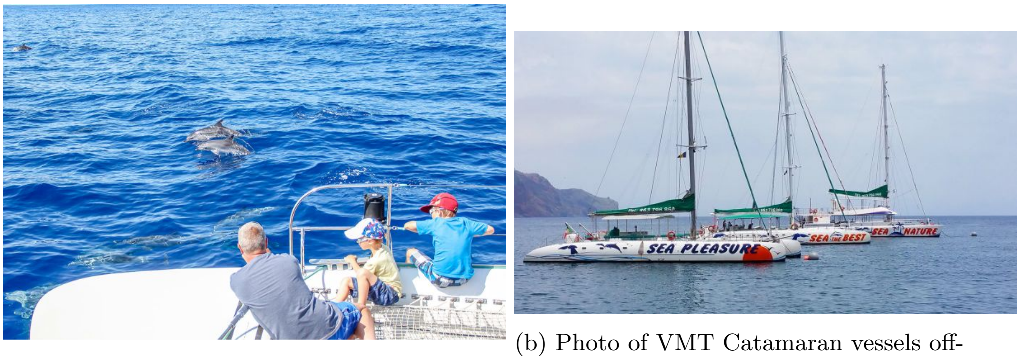
After the experience, participants completed an evaluation questionnaire, available in physical format, which captured their immediate reflections on the experience, their learning outcomes, and emotional responses. At the end of the testing session, participants were asked to manually write down their nationality, gender, and age on the physical questionnaire. This allowed for a straightforward collection of demographic data, crucial for the later analysis of different user groups' responses. Additional contextual data were also recorded, including weather conditions e.g., temperature, cloud cover and the emotional state of participants e.g., motivated, satisfied, non-motivated, attentive, low attentive. These details were particularly important for understanding the external factors that might influence participants' experiences and responses. Detailed observations were made during each session, noting any relevant participant behaviors or external factors that might impact the study. For example, comments on whether a participant was in a rush, appeared grumpy due to high temperatures, or was particularly happy because of recent whale sightings were recorded. These observations provided additional context for interpreting the results and understanding the participants' engagement levels.

After the testing sessions, all collected data were carefully transcribed into a structured Microsoft Excel file. The Excel workbook was organized into several tabs: one for AR data, one for MR data, one for VR data, and a final tab labeled "Results" for comparative analysis. Each tab included columns for the answers to the pre- and post-questionnaires, as well as the evaluation scores, demographic details, and contextual data. This structured organization was critical for ensuring that the data were easily accessible for analysis and that any patterns or trends could be readily identified.

The use of physical questionnaires helped reduce the risk of errors associated with digital input, particularly in a VR/MR setting where participants might struggle with navigation or selection. Consistent observation and note-taking ensured that all relevant factors were documented, adding another layer of reliability to the data collection process. This systematic approach to data collection was designed to capture a comprehensive picture of participants' experiences and learning outcomes, allowing for a thorough analysis of the effectiveness of AR, VR, and MR in marine science communication.

5.10 Ethical Considerations

During the execution of this research, several ethical considerations were meticulously addressed to ensure the integrity and respect of all parties involved. The study was conducted with the full cooperation and support of VMT Madeira, a marine tourism company based in Funchal, Madeira. This collaboration was facilitated by prior communication between my thesis supervisor, Marko Radeta, and Assistant Thesis Supervisor, Filipe Alves, who secured VMT Madeira's consent to use their space and interact with their clients for the study. Given the nature of the study, formal consent forms were deemed unnecessary. This decision was based on the fact that no personally identifiable information, such as names or ID numbers, was collected from participants. The only demographic data recorded were age, gender, and nationality, ensuring that all responses remained completely anonymous. The anonymity of participants was a priority, and the study was designed to protect their privacy at all stages. To facilitate the data collection process and enhance participant trust, a specially designed graphic t-shirt was worn, clearly identifying the researcher as part of MARE, a respected marine research institute, and indicating a partnership with VMT Madeira. This visual representation of the partnership helped reassure participants that the study was legitimate and that their involvement was part of a serious and meaningful research project.(see Figures 43 and 46a). The clients of VMT Madeira were informed in advance about the study by the boat personnel, who mentioned that there would be an opportunity to participate in a questionnaire and a digital experience upon returning to shore. This proactive communication helped set expectations and encouraged voluntary participation, ensuring that only those who were genuinely interested in the research took part.



(a) VMT clients observes dolphins, photo by VMT Madeira [70].

(b) Photo of VMT Catamaran vessels offshore, photo by VMT Madeira [70].

Fig. 46: VMT Catamarans and dolphin observation.

One of the key ethical considerations was to ensure that the research did not disrupt VMT Madeira's business operations or negatively impact their clients' experiences. By obtaining explicit permission from the company and working closely with their staff, the study was conducted in a manner that was respectful and considerate of both the business and its customers (see Figure 46b). This collaboration not only facilitated smoother data collection but also reinforced the ethical standards of the research.

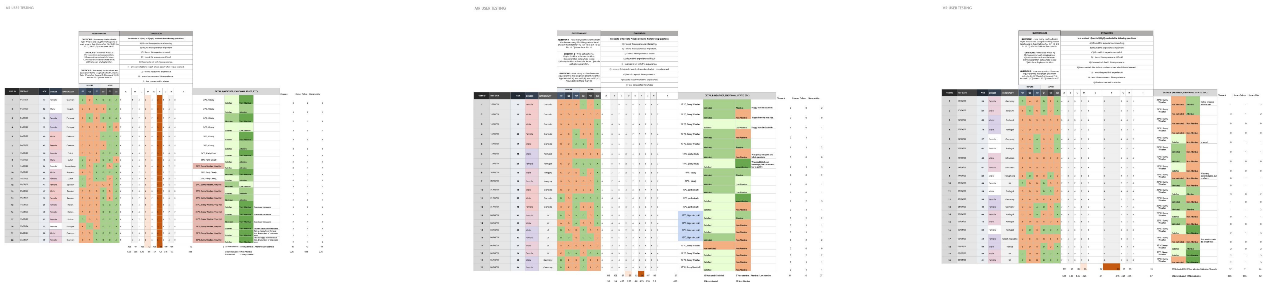
In conclusion, the ethical framework of this study was carefully crafted to protect participant anonymity, respect the operational environment of VMT Madeira, and ensure that all interactions were conducted with transparency and integrity (see Figure 47). This approach not only safeguarded the interests of all involved but also contributed to the overall success of the research .

Fig. 47: Recent photo of the VMT instructor teaching students about wmarine life conservation efforts, photo by VMT Madeira [70].

6 Results and Discussion

6.1 Results Overview

In this section, the key findings of the study will be presented, focusing on the outcomes of the experiments conducted with AR, VR, and MR technologies. The results will be structured to allow for a clear comparison between the different immersive experiences and their impact on participants' understanding and engagement with marine science. The results will be interpreted through various lenses, including demographic influences, pre- and post-questionnaire comparisons, and participant evaluations, and then analyzed to draw meaningful conclusions about the effectiveness of each technology in enhancing marine literacy and engagement (See Figures 48a, 48b and 48c). The analysis will also explore the potential external factors that may have influenced the outcomes, providing a comprehensive understanding of the results.



(a) Table with the AR Tests data.

(b) Table with the MR Tests data.

(c) Table with the VR Tests data.

Fig. 48: Data results of the study.

The findings will be contextualized within the broader scope of marine conservation communication, offering insights into how immersive technologies can be leveraged to foster greater public awareness and involvement. This section aims to provide a clear and detailed interpretation of the data, leading to informed discussions and conclusions in subsequent sections.

6.2 Pre-Questionnaire Results

The pre-questionnaire results revealed slight variations in baseline knowledge across the three groups: AR, VR, and MR. Before engaging with the interactive experiences, participants showed a general understanding of whale conservation and marine life, with identifiable knowledge gaps. In the AR group, 13 out of 60 answers were correct in the pre-questionnaire. In the VR group, 11 out of 60 answers were correct. In the MR group, 16 out of 60 answers were correct. These baseline results provide a benchmark for measuring the post-interaction knowledge gains, evaluating the effectiveness of each technology in enhancing participants' knowledge.

6.3 Post-Questionnaire Results

6.3.1 Changes in Knowledge and Understanding

Participants in the AR group demonstrated the most significant improvement in marine literacy. In the pre-questionnaire, they answered correctly in 13 out of 60 questions. After the experience, this increased to 49 out of 60 correct answers, reflecting a substantial gain of 36 correct responses. This suggests that the AR experience was highly effective in enhancing participants' grasp of the marine content.

The VR group also showed improvements, though not as pronounced as the AR group. In the pre-questionnaire, they answered 11 out of 60 questions correctly, which increased to 24 out of 60 correct answers after the VR experience. This gain of 13 correct responses indicates that while VR was effective, it may not have been as engaging or informative as AR in this context.

The MR group started with the highest pre-questionnaire score, with 16 out of 60 correct answers, which increased to 27 out of 60 correct answers post-experience. This gain of 11 correct responses suggests that while MR provided a valuable learning experience, it was less effective in driving significant knowledge gains compared to AR and VR. However, it is important to note that the MR group did not experience any increase in misunderstandings.

6.3.2 Comparative Analysis of Learning Outcomes

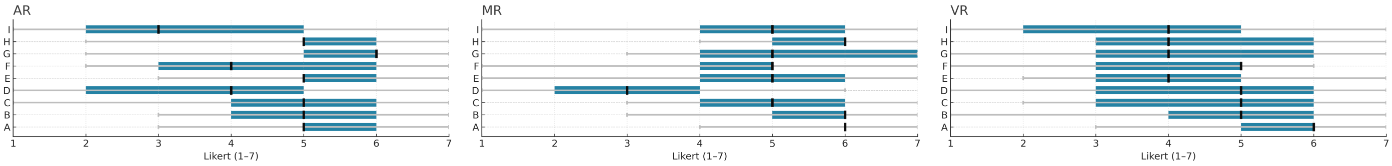
AR emerged as the most effective medium for enhancing marine literacy among participants. The significant increase in correct answers post-experience and the sharp decrease in misunderstandings highlight the immersive and informative nature of the AR experience. The interactive elements and the ability to explore 3D models in a real-world context likely contributed to this high engagement and understanding.

While VR was effective, the learning outcomes were moderate compared to AR. The increase in literacy was positive, but the experience did not significantly reduce misunderstandings, indicating that while VR can be engaging, it may require more refinement or additional educational scaffolding to match AR's effectiveness.

MR offered a balanced approach, with moderate improvements in literacy and a stable rate of understanding. The lack of increased misunderstandings is a positive outcome, suggesting that MR provides a safe learning environment with a good retention rate. However, the overall knowledge gain was less compared to AR, possibly due to the complexity or the dual focus on real and virtual elements, which might have divided the participants' attention.

In summary the AR experience was the most effective in enhancing participants' knowledge and understanding of marine life and whale conservation, followed by VR and MR. Each technology has its strengths, with AR excelling in engagement and knowledge transfer, VR providing a solid but less impactful experience, and MR offering a balanced but less transformative educational experience.

6.4 Participant Evaluation Responses



(a) AR Evaluation interquartile range and median chart.

(b) MR Evaluation interquartile range and median chart.

(c) VR Evaluation interquartile range and median chart

Fig. 49: Evaluation results of the study in interquartile range and median charts.

In this section, the detailed responses provided by participants to each evaluation question are examined. Responses are reported using the interquartile range (IQR) and the median (See Figures 49a, 49b and 49c). The median represents the middle value of the dataset, indicating the point at which half the responses fall above and half fall below. The IQR shows the range within which the middle 50% of responses lie, providing insight into the distribution and variability of participant evaluations. These responses were observed and discussed in relation to the study's research questions. The discussion also highlights the distinct strengths and limitations of AR, VR, and MR.

Question A: I found this experience interesting. – MR: Median = 6, IQR = 6–6 AR: Median = 5, IQR = 6–5 VR: Median = 6, IQR = 6–5

Participants across all mediums found the experiences interesting, with MR and VR being rated slightly higher. The interest in MR may be related to its novelty and the way it blends virtual and real-world elements, creating an engaging experience. AR also generated considerable interest, although responses were somewhat more varied.

Question B: I found this experience important. – MR: Median = 6, IQR = 6–5 AR: Median = 5, IQR = 6–4 VR: Median = 5, IQR = 6–4

Importance was rated somewhat higher in MR, possibly because participants could see clearer applications in real-world contexts, such as conservation or education. AR followed fairly closely, suggesting that its accessibility and potential for integration into daily life made it relevant for many participants, though not all. VR was also seen as important, though the responses were slightly lower and more mixed, perhaps because the fully virtual environment felt less immediately connected to real-life situations.

Question C: I found this experience useful. – MR: Median = 5, IQR = 6–4 AR: Median = 5, IQR = 6–4 VR: Median = 5, IQR = 6–3

Usefulness was recognized across all three technologies, with AR and MR generally perceived a little more positively due to their ability to integrate educational content with real-world settings. VR was also regarded as useful, though for some participants the complete immersion seemed less directly applicable, leading to slightly more varied views about its everyday relevance.

Question D: I found this experience difficult. – MR: Median = 3, IQR = 4–2 AR: Median = 4, IQR = 5–2 VR: Median = 5, IQR = 6–3
MR was rated as the easiest to use, likely due to its intuitive blending of digital and physical elements, which may have made navigation more straightforward. AR was slightly more challenging, particularly because of the need to align digital content with triggers in the real world. VR was considered the most difficult overall, with several participants possibly finding the total immersion disorienting or harder to manage compared to the other formats.

Question E: I learned a lot with this experience. – MR: Median = 5, IQR = 6–4 AR: Median = 5, IQR = 6–5 VR: Median = 4, IQR = 5–3
Learning appeared strongest in AR and MR, suggesting that both formats helped participants to connect digital information with real-world contexts in ways that supported knowledge retention. VR also contributed to learning, but its impact seemed somewhat lower, perhaps because participants were more focused on the immersive environment itself than on the educational content.

Question F: I am comfortable teaching others about what I have learned. – MR: Median = 5, IQR = 5–4 AR: Median = 4, IQR = 6–3 VR: Median = 5, IQR = 5–3
Comfort in teaching others was reported most clearly in MR, where participants seemed relatively confident about sharing what they had learned. VR showed a similar level of confidence, though responses were somewhat more dispersed. AR received slightly lower ratings, indicating that not all participants felt equally comfortable explaining what they had taken from the experience.

Question G: I would repeat this experience. – MR: Median = 5, IQR = 7–4 AR: Median = 6, IQR = 6–5 VR: Median = 4, IQR = 6–3
Participants were most inclined to repeat the AR experience, likely due to its accessibility and the relative ease of use compared to the other technologies. MR was also seen as appealing, with many participants expressing interest in repeating it, though responses were more varied. VR was less frequently mentioned as something participants would repeat, possibly because the immersive format required more effort and equipment, making it less convenient for repeated use.

Question H: I would recommend this experience. – MR: Median = 6, IQR = 6–5 AR: Median = 5, IQR = 6–5 VR: Median = 4, IQR = 6–3
Recommendation rates were highest in MR, suggesting that many participants considered it a valuable and engaging experience to share with others. AR also received positive recommendations, though to a slightly lesser degree. VR, while still recommended by some, scored the lowest, with responses indicating that it may have been less universally appealing.

Question I: I feel connected to whales. – MR: Median = 5, IQR = 6–4 AR: Median = 3, IQR = 5–2 VR: Median = 4, IQR = 5–2
Emotional connection was strongest in MR, where the blend of real and virtual elements may have supported a more immediate sense of presence. VR fostered a moderate level of connection, while AR was rated lower, suggesting that its format was less effective in producing emotional engagement compared to the other two.

6.4.1 Comparative Analysis of Evaluation Responses

AR and MR led in the questions related to learning (Question E) and teaching confidence (Question F). This may reflect AR's and MR's tendency to deliver content in a way that participants find understandable and transferable, likely due to its real-world applicability.
MR took a very slight lead overall above AR in the questions related to engagement and emotion (Questions A, B, C, G, H, and I). VR obtained lower scores in these items, which may indicate that while immersive, the experience was at times more overwhelming or less immediately relatable for some participants.

From the results tables (See Figures 48a, 48b and 48c), it can be observed that AR was slightly more consistent than MR in the questions related to engagement and emotion (Questions A, B, C, G, H, and I). VR showed a higher variability in responses, which may suggest a more polarized reaction, possibly due to its demanding nature or the unfamiliarity of the technology.

Each medium demonstrated distinct strengths and weaknesses. MR stood out in generating engagement, perceived importance, and emotional connection. This suggests that MR is highly effective for experiences where immersive yet contextualized learning and emotional engagement are paramount. However, its weakness lies in accessibility and complexity, which might limit its use in more general or everyday contexts.

AR excelled in fostering confidence in knowledge and perceived usefulness, making it an excellent tool for educational applications where practical, real-world relevance is essential. Its main weakness was in generating emotional connection and ease of use, where it showed less immersive potential compared to MR and was seen as slightly more challenging than expected. VR, while immersive, had more mixed reactions, which may indicate that it's best suited for audiences with prior experience or strong interest in fully immersive environments, as its complexity and total immersion could be less accessible to general audiences. its weakness was its lower learning outcomes and higher perceived difficulty. The fully virtual nature might have been overwhelming or less relatable, leading to more varied and less consistent participant reactions.

This analysis underscores the importance of choosing the right medium for the intended educational or experiential outcome, with each offering unique benefits depending on the context and audience.

6.5 Impact of External Factors

6.5.1 Weather Conditions and Temperature

The impact of onshore external factors such as weather conditions, temperature, and participants' emotional and attentional states significantly influenced the results of the AR, VR, and MR tests. Below, a detailed analysis is provided below, supported by evidence from the screenshots and data provided (See Figures 50, 51a, 51b and 51c).

In the MR sessions, the average temperature was 20°C, a generally comfortable range for participants. Weather conditions such as partly cloudy skies or light rain had a moderate impact on participants' attention and emotional state. For instance, participants remained attentive even in slightly challenging conditions like light rain or cooler temperatures, with 19 out of 20 participants reporting high motivation and satisfaction. However, under cloudy weather, virtual elements in MR were occasionally less clear, leading to some fluctuations in attentiveness. Despite these factors, MR demonstrated resilience across varying weather conditions.

AR was highly impacted by weather, particularly sunlight. The AR triggers, which rely on visual markers to activate content, often failed under direct sunlight, requiring participants to find shaded areas or adjust the angle of the device. The average temperature during AR testing was 26°C, with some days reaching as high as 31°C. Participants' discomfort with the heat is reflected in the emotional state data, where attention was generally high but showed variation, especially on hotter days. Notably, AR still managed to keep all 20 participants motivated or satisfied, with 18 being attentive or very attentive. The need for adjustments due to environmental conditions, such as sunlight, impacted the user experience, but the technology was generally well-received.

VR was particularly sensitive to the onshore testing conditions. With an average temperature of 20°C, similar to MR, VR should have been comfortable; however, the complete immersion required by VR made participants feel unsafe or disconnected from their surroundings. This discomfort was reflected in the higher rate of refusals to participate in VR testing and in the emotional state data, where 6 out of 20 participants reported being non-motivated, and 12 were non-attentive. The perception of enclosure and inability to monitor surroundings led to lower motivation and attentiveness scores, which aligns with the non-motivated and non-attentive responses observed in the data.

6.5.2 Emotional and Attentional State

In the MR testing, the emotional and attentional states were generally positive, with a significant number of participants (19 out of 20) reporting being motivated or satisfied. Attention was a mixed bag, with 9 participants attentive or very attentive, while 11 were non-attentive. This suggests that while MR is effective in maintaining a positive emotional state, the complexity of integrating real-world and virtual elements might create distractions, leading to variations in attention.

AR participants showed strong emotional and attentional states despite the environmental challenges. All 20 participants were motivated or satisfied, and 18 were attentive or very attentive, with only minor instances of low attentiveness. This suggests that AR, while sensitive to environmental conditions like sunlight, generally succeeds in engaging participants both emotionally and cognitively. The challenges faced, such as with AR triggers in bright sunlight, were mitigated by the participants' ability to adapt to the conditions.

The emotional and attentional state data for VR participants indicated the most significant challenges. With 6 participants reporting being non-motivated and 12 being non-attentive, it is clear that the immersive nature of VR, combined with the outdoor setting, was problematic. Participants likely felt isolated and disconnected from their surroundings, leading to lower engagement. This is supported by the feedback and refusal rates during VR testing.

6.5.3 Participant Feedback and Observations

Participants generally responded positively to MR, appreciating the balance between virtual and real-world elements. Feedback suggests that while MR was resilient under varied weather conditions, improvements in adapting to extreme light conditions would enhance the clarity and visibility of virtual elements. The emotional state data supports this, with most participants remaining motivated and attentive despite the occasional challenge posed by weather.

The AR experience was more challenging due to weather conditions, particularly bright sunlight. The feedback and data indicate that AR triggers were often ineffective in direct sunlight, leading to frustration and reduced attentiveness among participants. Despite these challenges, AR maintained high levels of motivation and attentiveness, reflecting its strong engagement potential even under suboptimal conditions.

Feedback from VR participants highlighted the discomfort with the enclosed nature of the experience, particularly in an open, outdoor setting. The emotional state data aligns with this, showing a significant number of participants reporting lower motivation and attentiveness. The discomfort caused by the headset, combined with the inability to see their surroundings, led to a generally lower willingness to engage with the VR experience.

6.5.4 Participant Rates and Adaptability to Environment

The data revealed a noticeable pattern of higher denial rates for VR testing compared to MR and AR, largely due to discomfort and safety concerns associated with VR's immersive nature in outdoor environments. Participants were more likely to refuse VR because of the isolation it imposed, a trend that remained consistent across various weather conditions. This suggests that the fully immersive experience of VR posed unique challenges not present in MR and AR.

MR showed the best adaptability to various environmental conditions, with participants generally remaining motivated and attentive despite minor weather-related challenges. AR and VR struggled with specific challenges like sunlight and enclosure, respectively. The variation in emotional state and attention data across the three mediums highlights the need for further refinement and adaptation of AR, VR, and MR technologies for onshore applications.

6.5.5 Motivation, Attention and Challenges

In AR testing, all 20 participants reported being either motivated or satisfied, highlighting AR's effectiveness in maintaining high motivation levels across the board. This consistent result reflects the medium's accessibility and engagement potential.

AR had the highest levels of attentiveness, with 18 participants being attentive or very attentive.

Most of the challenges were related to AR triggers failing under bright sunlight rather than screen visibility, which required adjustments to maintain engagement.

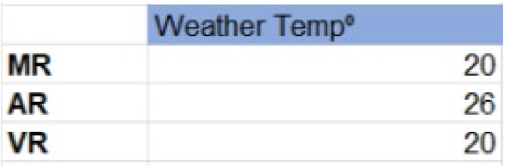
In VR testing, 13 participants were motivated or satisfied, while 6 participants were non-motivated.

VR had lower levels of attentiveness compared to AR, with only 8 participants being attentive or very attentive, and 12 were marked as non-attentive.

The enclosed nature of VR led to discomfort and lower engagement, particularly in outdoor settings.

In MR testing, 19 participants were motivated or satisfied, with only 1 participant as non-motivated. MR saw a mixed level of attentiveness, with 9 participants being attentive or very attentive, and 11 being non-attentive.

The integration of real and virtual elements in MR created a mixed experience that sometimes led to distractions, affecting attentiveness. In summary, AR demonstrated the highest motivation and attentiveness, suggesting it is the most adaptable and engaging medium for onshore, real-world settings, especially when the environmental challenges like sunlight were mitigated or when not detecting AR Triggers. VR faced the most significant challenges due to its immersive and enclosed nature, leading to lower engagement and higher refusal rates. MR showed strong potential but struggled with maintaining consistent attention, possibly due to the complexity of integrating real and virtual elements seamlessly and because direct sunlight sometimes made virtual elements less clear, which is a challenge that could be mitigated by refining the display technology. These findings underscore the importance of optimizing each technology for specific environmental conditions to enhance educational and engagement outcomes.



	Weather Temp°
MR	20
AR	26
VR	20

Fig. 50: Table that shows the weather temperature average across all tests.

(a) This graphs shows the various comparisons among external factors such as attention, motivation level and weather conditions for augmented reality.

(b) This graphs shows the various comparisons among external factors such as attention, motivation level and weather conditions mixed reality.

(c) This graphs shows the various comparisons among external factors such as attention, motivation level and weather conditions virtual reality.

Fig. 51: Various graphs comparing attention, motivation and weather conditions through all AR, VR and MR technologies.

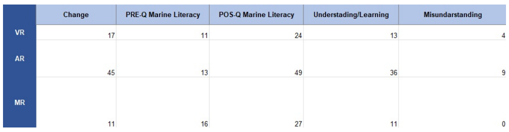
6.6 Comparative Analysis of AR, VR, and MR

6.6.1 (RQ1) Marine Literacy & Learning

AR was the most effective in transmitting information and learning, with correct answers increasing from 13 out of 60 in the pre-questionnaire to 49 out of 60 in the post-questionnaire (See Figures 52a and 52b). This was supported by the responses to questions related to knowledge and teaching confidence, where participants indicated feeling more knowledgeable after using AR. The need to frequently adjust to environmental conditions might have caused minor disruptions in learning, but these did not significantly impact overall outcomes.

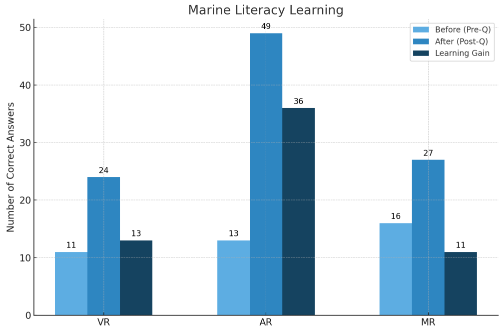
VR showed a moderate improvement in marine literacy, rising from 11 out of 60 correct answers in the pre-questionnaire to 24 out of 60 after the experience (See Figures 52a and 52b). Participants' confidence in their own knowledge was lower than in AR, but still indicated that VR can be effective for those who can comfortably engage with the technology. The challenges in attentiveness and motivation likely impacted learning outcomes, making VR less effective compared to AR in this context.

MR improved from 16 out of 60 correct answers in the pre-questionnaire to 27 out of 60 in the post-questionnaire (See Figures 52a and 52b). The blend of real and virtual worlds likely contributed to participants' ability to learn while being engaged. However, the novelty of MR might have distracted participants from fully focusing on the educational content, which could explain why it did not outperform AR in learning outcomes.



	Change	PRE-Q Marine Literacy	POS-Q Marine Literacy	Understading/Learning	Misundarstanding
VR	17	11	24	13	4
AR	45	13	49	36	9
MR	11	16	27	11	0

(a) PRE-Q VS POS-Q Table which compares marine literacy before and after tests.



(b) This graph illustrates the changes in marine literacy learning across three XR technologies: VR, AR, and MR. It shows pre-questionnaire (PRE-Q), post-questionnaire (POS-Q), and the overall learning increase (Learning).

Fig. 52: Marine Literacy represented in a table and graph

6.6.2 (RQ2) Engagement & Emotional Connection

AR participants reported positive reactions across several questions. For Question A "I found this experience interesting", AR responses had a median of 5 (IQR = 6–5). In Question B "I found this experience important", AR again showed a median of 5 (IQR = 6–4), while Question C "I found this experience useful" confirmed its practical value with a median of 5 (IQR = 6–4). Repetition and recommendation were also strong, with Question G "I would repeat this experience" scoring median 6 (IQR = 6–5) and Question H "I would recommend this experience" scoring median 5 (IQR = 6–5). The Question I "I feel connected to whales" was more moderate at median 3 (IQR = 5–2). Taken together, these results suggest that AR successfully balanced engagement with practicality. Its ability to keep participants engaged while allowing them to remain aware of their surroundings likely contributed to this outcome. Nevertheless, outdoor conditions, particularly bright sunlight interfering with AR triggers, occasionally disrupted the experience and may have slightly reduced the overall sense of enthusiasm.

VR participants also reported positive but more variable experiences. In Question A, VR responses had a median of 6 (IQR = 6–5), while Question B and Question C were lower, at medians of 5 (IQR = 6–4 and 6–3, respectively). For repetition and recommendation, Question G scored median 4 (IQR = 6–3) and Question H median 4 (IQR = 6–3). Emotional connection to whales in Question I was also moderate, median 4 (IQR = 5–2). Although lower scores reflect the challenges of full immersion in outdoor environments—including discomfort, attentional demands, and disconnection from the surroundings—VR still demonstrated strength in delivering a fully immersive experience that some participants found intriguing. This suggests VR may be particularly engaging in outdoor use for those already familiar with the technology, but less accessible for wider audiences.

MR responses suggested a tendency toward higher engagement and emotional resonance. In Question A, MR responses reached a median of 6 (IQR = 6–6), and Question B similarly scored median 6 (IQR = 6–5). Question C also had a positive outcome with a median of 5 (IQR = 6–4). For repetition and recommendation, MR was strong, with Question G at median 5 (IQR = 7–4) and Question H at median 6 (IQR = 6–5). Emotional connection to whales in Question I was also higher in MR, with a median of 5 (IQR = 6–4). These findings suggest that MR effectively fostered both engagement and emotional connection, supported by its blend of real and virtual elements that created a novel and compelling experience. At the same time, the novelty may have shifted participant focus more toward the medium itself than the content.

From the results table, it can be observed that AR was slightly more consistent than MR in the questions related to engagement and emotion (Questions A, B, C, G, H, and I) (See Figures 49a, 49b and 49c). The technology's familiarity and the ability to stay connected with the real world likely contributed to this consistency, even though occasional issues with triggers in bright sunlight caused minor disruptions.

VR showed a somewhat higher variability in responses, which may suggest a little more polarized reaction, with some participants highly enthusiastic while others disengaged. This variation may be largely due to the discomfort and disconnection associated with being fully immersed in an outdoor setting, where some participants felt less comfortable or safe.

MR demonstrated being generally consistent. While many participants found MR exciting and engaging, its novelty and added complexity may have made it less equally accessible for all, requiring more adaptation from users.

The results for whale connection, obtained from Question I, revealed differences across the three technologies.

AR participants reported a more limited connection to whales, with a median of 3 (IQR = 5–2). This suggests that while AR was effective in delivering information, the emotional connection to the content was weaker, possibly influenced by environmental factors such as sunlight disrupting triggers. VR participants reported a moderate connection, with a median of 4 (IQR = 5–2). The immersive environment may have supported emotional involvement for some, but issues with comfort and attentiveness in outdoor settings limited its impact. MR responses suggested a somewhat stronger connection to whales, with a median of 5 (IQR = 6–4). The blend of real and virtual elements appears to have enhanced the sense of presence and immediacy, allowing participants to feel more emotionally engaged with the whales. While this connection was higher, learning outcomes were not as strong as in AR, suggesting that some participants may have been more focused on the novelty of the experience itself rather than the educational content.

6.6.3 (RQ3) Ease of Use

The results for perceived difficulty (See Figures 49a, 49b and 49c), obtained from Question D, show clear differences across the three technologies. AR was seen as moderately difficult, with a median of 4 (IQR = 5–2), mainly due to issues with AR triggers in bright sunlight. This suggests that while AR is accessible, there are usability challenges that need to be addressed to improve the overall experience. The environmental sensitivity of AR triggers presents a barrier to ease of use, especially in sunny conditions.

VR was perceived as the most difficult to use, with a median of 5 (IQR = 6–3). The difficulties were largely related to the physical and emotional discomfort of using a VR headset outdoors, which detracted from the overall experience. The need to remain fully immersed and isolated from the surrounding environment made VR more challenging to use comfortably in this context.

MR was considered the least difficult, with a median of 3 (IQR = 4–2). Combined with its higher engagement scores, this suggests that participants found the integration of real and virtual elements relatively intuitive and engaging. The main challenge was maintaining a balance between real-world and virtual components, which some participants found disorienting, though this did not significantly detract from its overall ease of use.

6.6.4 Summary of Strengths & Weaknesses

AR appeared to be the most consistent in supporting learning and attentiveness, with clear gains in knowledge and generally stable engagement. Its main limitation was sensitivity to environmental conditions, particularly bright sunlight interfering with AR triggers rather than screen visibility.

VR provided a fully immersive experience but was associated with lower engagement and greater usability challenges. Discomfort and disconnection from the real environment seemed to limit both learning outcomes and emotional engagement, making it less well suited for onshore outdoor settings in its current form.

MR showed the strongest emotional connection to the content and positive engagement, supported by its blend of real and virtual elements. Learning outcomes, however, were less pronounced, possibly because the novelty of the technology drew attention away from the educational content. MR's performance was generally good but showed more variability in attentiveness and consistency across participants.

Overall, these findings suggest that AR may be the more suitable medium for onshore educational purposes, particularly for transmitting information and maintaining engagement. MR shows potential for fostering emotional connection and engaging interactions, while VR may need further refinement to be more practical in outdoor contexts.

6.7 Discussion

6.7.1 Results in Relation to the Study's Objectives

The primary objectives of this study were to assess the effectiveness of AR, VR, and MR in delivering educational content about whale conservation and marine literacy in an onshore environment. This assessment was grounded in participants' learning outcomes, their emotional and cognitive engagement, and the impact of external factors, particularly those related to the onshore setting. The findings suggest that AR, VR, and MR each presented distinct strengths and weaknesses, with varying levels of effectiveness depending on the context and the metrics evaluated.

In terms of marine literacy (Question E: learning), AR appeared to be the most effective medium. Correct responses increased from 13 out of 60 in the pre-questionnaire to 49 out of 60 in the post-questionnaire. This supports the study's objective of identifying the medium best suited for transmitting information. AR's ability to superimpose digital information onto the real world may have facilitated a clearer understanding of the content, although environmental conditions occasionally interfered with triggers.

MR also showed improvements in marine literacy, though less pronounced than AR, rising from 16 out of 60 correct answers pre-questionnaire to 27 out of 60 post-questionnaire. The blend of real and virtual elements may have helped participants relate better to the content, but the novelty of MR could have introduced some distraction from purely educational aspects.

VR demonstrated a smaller improvement in marine literacy, from 11 out of 60 correct answers pre-questionnaire to 24 out of 60 post-questionnaire. While the immersive nature of VR may have engaged some participants, it may also have diverted focus away from the educational content, as reflected in more modest outcomes in Questions E and F (learning and teaching confidence).

Regarding engagement and enthusiasm (Questions A, B, C, G, and H), MR tended to elicit somewhat higher levels of positive responses compared to AR and VR. For instance, Question A (interest) had a median of 6 (IQR = 6–6) in MR, compared to 5 (IQR = 6–5) in AR and 6 (IQR = 6–5) in VR. Repetition (Question G) and recommendation (Question H) also scored highly in MR, with medians of 5 (IQR = 7–4) and 6 (IQR = 6–5) respectively. These results suggest that MR's novelty and the blending of real and virtual elements created a more compelling experience for many participants.

AR followed closely, with Question B (importance) showing a median of 5 (IQR = 6–4). Question C (usefulness) also had a median of 5 (IQR = 6–4). Questions G and H (repeat and recommend) scored 6 (IQR = 6–5) and 5 (IQR = 6–5) respectively. These responses indicate that AR maintained a relatively high level of engagement, although environmental interruptions such as bright sunlight interfering with AR triggers may have dampened the experience somewhat.

VR showed comparatively lower levels of engagement, with Questions B and C (importance and usefulness) at medians of 5 (IQR = 6–4) and 5 (IQR = 6–3). Repetition and recommendation (Questions G and H) were lower, with medians of 4 (IQR = 6–3) and 4 (IQR = 6–3). These results suggest that while VR provided a novel and immersive environment, discomfort with the headset and disconnection from the surrounding setting may have limited its broader appeal.

With respect to emotional connection to whales (Question I), MR again suggested comparatively stronger outcomes, with a median of 5 (IQR = 6–4). This may reflect how the integration of real and virtual elements made the experience feel more authentic and immediate. AR showed a lower result, with a median of 3 (IQR = 5–2), while VR reached a median of 4 (IQR = 5–2). For AR, the emphasis on information delivery may have overshadowed emotional engagement, while for VR, the isolation of the fully immersive environment may have acted as a barrier to connection in the outdoor context.

Ease of use (Question D) also showed differences between the technologies. MR appeared to be the least difficult to use, with a median of 3 (IQR = 4–2), suggesting that participants generally found the integration of real and virtual elements intuitive. AR was somewhat more difficult, with a median of 4 (IQR = 5–2), as technical challenges such as sunlight interference with triggers occasionally disrupted usability. VR was reported as the most difficult, with a median of 5 (IQR = 6–3), reflecting both physical discomfort and the challenges of full immersion in an outdoor setting.

6.7.2 Discussion on Alignment with Existing Research and Potential Impacts

The findings of this study provide a more nuanced view of how AR, VR, and MR technologies may be integrated into whale-watching, sustainable tourism, and conservation efforts. This section considers how these findings align with, challenge, or expand upon the existing body of research, specifically focusing on whale-watching as a phenomenon, responsible and sustainable tourism, the potential of XR technologies in conservation, and the psychological impacts of virtual encounters with wildlife. Additionally, it addresses the technological constraints observed in the study and their possible implications for future XR development.

The relative effectiveness of AR and MR in supporting marine literacy and emotional connection to whales appears to align with previous research on whale-watching as a phenomenon, particularly in regions like Madeira Island where whale-watching is a significant tourist attraction. Prior studies have emphasized the importance of whale-watching being both educational and engaging to promote sustainable practices. The ability of AR and MR to provide real-time information and immersive experiences without disturbing the natural environment may be seen as a partial response to the challenges identified in responsible whale-watching practices.

The integration of XR technologies into whale-watching tours offers a potentially innovative approach to sustainable tourism. By allowing tourists to engage with marine life in a non-invasive manner, XR could help reduce the environmental impact of whale-watching. This may support the broader goals of sustainable tourism by balancing economic benefits with the preservation of natural habitats. Moreover, the educational component of XR experiences appeared to foster a deeper understanding and appreciation of marine ecosystems, which might contribute to more responsible tourist behavior.

At the same time, the study also suggested the need for technological improvements to maximize the potential of XR in sustainable tourism. For example, AR's sensitivity to bright sunlight and MR's challenges with image clarity indicate that while these technologies show promise, they require further refinement to be fully effective in diverse outdoor conditions. This observation is consistent with existing concerns in the literature regarding the deployment of XR in real-world environments.

The relatively strong emotional engagement observed with MR, together with the learning gains across AR and MR, suggested that XR technologies could be valuable tools for conservation education. The ability of MR to create more compelling narratives around marine life, as reflected in the whale connection results, may help foster empathy and a deeper understanding of conservation. This tendency is broadly consistent with research highlighting the role of immersive technologies in enhancing conservation messaging by making abstract concepts more tangible and emotionally resonant.

The application of XR in promoting responsible whale-watching practices may also be beneficial. By using AR and MR to simulate close encounters with whales, tourists could experience the awe of these animals without physical proximity, thereby reducing the likelihood of harmful interactions. This appears to support existing guidelines for responsible whale-watching that emphasize minimizing human impact on whale behavior and habitats.

Nevertheless, the study's findings also pointed to limitations that need to be addressed. For instance, the lower effectiveness of VR in maintaining emotional engagement and attentiveness suggested that, while immersive, it may not be as suitable for onshore educational purposes where maintaining a connection to the real world is important. This insight may challenge some of the more optimistic perspectives in the literature about the universal applicability of VR for conservation education.

The successful use of AR and MR in this study appears to support the growing body of research advocating for the integration of XR into tourism, particularly in marine environments. These technologies can enhance traditional experiences by providing interactive, educational content that is both informative and engaging. This aligns with the concept of "edutainment," where tourism experiences are designed to combine entertainment with education, offering a more holistic experience to visitors.

The findings also suggested that AR and MR may have a role in virtual or augmented marine explorations, making such experiences more accessible to a broader audience. This could be especially relevant in contexts where direct interaction with marine environments is not feasible, such as for schools or remote learning programs. The study's results contribute to ongoing research on XR for virtual field trips and tourism, highlighting the potential of these technologies to broaden access to marine education.

However, practical challenges remain, such as the need for reliable AR triggers in varying light conditions and improved image quality in MR. These issues reinforce the importance of continued technological innovation to ensure XR can be effectively deployed outdoors. This observation supports existing research noting the technical constraints of XR in real-world settings, suggesting that overcoming these barriers is critical for broader adoption.

The whale connection reported by MR participants appeared consistent with research on the psychological benefits of interacting with virtual animals. By combining real-world and digital elements, MR may foster deeper emotional engagement

with marine life, which is valuable for conservation education. This finding reflects literature on the role of empathy in encouraging pro-environmental behaviors, suggesting that XR could contribute meaningfully to environmental education.
The ability of XR to evoke emotional responses could also have broader implications for wildlife conservation. By simulating encounters with endangered species, XR may help raise awareness and generate support for conservation initiatives. This supports existing research emphasizing the role of emotional engagement in mobilizing conservation efforts, particularly where direct encounters are impractical.
At the same time, while the study demonstrated the potential of XR to enhance empathy for virtual animals, it also raised questions about long-term impacts on behavior change. Further research is needed to determine whether these emotional connections translate into sustained pro-environmental behaviors. This reflects the wider discourse in the literature about the importance of evaluating the long-term effectiveness of XR interventions in conservation education.
The study's observations on XR limitations in outdoor contexts also contribute to ongoing discussions about the constraints of applying these technologies in real-world conditions. Issues with AR triggers in bright sunlight, MR's image clarity, and VR's user discomfort highlight the need for continued innovation. This aligns with broader concerns about XR usability in diverse environments and underscores the need for more robust, user-friendly solutions.
Future development efforts may need to focus on addressing these limitations to strengthen the effectiveness of XR in outdoor settings. For AR, this could involve developing more reliable triggers and screens that perform better in bright light. For MR, improving image clarity and contrast may make digital elements more visible in varying conditions. For VR, designing lighter, more comfortable headsets could reduce user discomfort and improve usability.
Taken together, these findings suggest that XR technologies may play a meaningful role in tourism and education if these limitations are addressed. By overcoming technical barriers, developers could create more versatile XR solutions suitable for outdoor and real-world applications. This may accelerate adoption in tourism and educational contexts, positioning XR as a useful complement to traditional experiences.
This discussion highlights the potential contributions of XR to whale-watching, sustainable tourism, and conservation. The alignment with existing research suggests that XR may enhance learning, emotional engagement, and empathy for marine life, while also pointing to areas requiring technological improvement. By addressing these challenges, XR technologies could become more effective tools for education, tourism, and conservation, contributing to more sustainable and environmentally conscious practices.

6.8 Study limitations

6.8.1 Sample Size, Demographics & User Familiarity

While this study offers useful insights into the comparative effectiveness of AR, VR, and MR technologies in the context of whale-watching and marine education, several contextual factors should be considered when interpreting the findings and proposing future research directions.
The sample size in this study was adequate for the exploratory nature of the research, but like many field-based studies, its scope may limit the extent to which the findings can be generalized to all audiences. A larger or more diverse sample could have provided additional nuance, potentially revealing more detailed patterns or differences between the mediums. Thus, while the size itself was not a major weakness, the study may still benefit from replication with broader participant groups in future work.
The demographic composition of the participants, including factors such as age, gender, cultural background, and prior exposure to technology, may also have influenced the results. For example, younger participants who are more accustomed to digital technologies may have found the XR experiences more engaging compared to older participants who might be less familiar with them. Such differences could have introduced variability in the responses, suggesting that some findings may reflect the demographic characteristics of the sample rather than being universally applicable. Future studies could aim for an even more diverse participant pool to strengthen representativeness.
Another factor relates to the varying levels of participant familiarity and prior experience with XR technologies. Some participants may have used AR, VR, or MR previously, while others were likely encountering these technologies for the first time. This disparity in familiarity may have shaped their comfort levels, ease of use, and overall evaluation of the experiences. Participants with prior exposure might have reported more favorable experiences due to their familiarity with navigation and interaction in XR, whereas those without such experience may have found the technology less intuitive, poten-

tially lowering enthusiasm or engagement. This suggests that part of the variability in responses could be attributed to the learning curve associated with XR technologies rather than solely to the mediums themselves.

6.8.2 Accessibility, Quality of Technology & Content Optimization

The study was conducted using relatively accessible and affordable XR technology, which, while beneficial for real-world applicability, may not have offered the highest fidelity or the most advanced features available in the market. The AR and MR experiences were particularly constrained by the quality of the devices used, such as limitations in screen resolution, processing power, and the accuracy of AR triggers in varying lighting conditions.

The use of more affordable and less advanced technology likely impacted the overall user experience, potentially leading to lower enthusiasm, acceptance, and learning outcomes than might have been achieved with higher-end equipment. For example, the issues with AR triggers in bright sunlight and the less clear MR images could have detracted from the overall effectiveness of these mediums. This limitation suggests that the results might have been different if the study had used more sophisticated technology, possibly providing a more favorable evaluation of XR's potential.

While the interaction design was consistent across all three mediums, the content was specifically tailored to suit the unique capabilities and limitations of AR, VR, and MR. However, the content was not fully optimized to exploit the full potential of each medium. For instance, more advanced or customized content for each platform could have provided a richer experience and possibly yielded different outcomes.

This limitation implies that the study might not have captured the full potential of each medium. AR, VR, and MR technologies each have distinct strengths that could be better leveraged with fully optimized content. Therefore, the results might reflect the limitations of the content design rather than the inherent capabilities of the technologies themselves. Future studies could focus on developing more sophisticated content that fully utilizes the unique features of each XR medium to achieve more accurate comparisons.

6.8.3 Environmental Conditions, Distractions & Participant Fatigue

The study was conducted in onshore outdoor settings, which introduced various environmental factors such as weather, temperature, and lighting conditions. These factors, while relevant to the study's context, may have introduced challenges that would not typically be present in a controlled indoor environment. For instance, bright sunlight appeared to affect the visibility of AR content and the performance of AR triggers, while colder or hotter temperatures may have influenced participant comfort and engagement, particularly when using VR headsets.

The variability in environmental conditions may have contributed to differences in experiences across participants. For example, those who tested the technology in more favorable conditions, such as moderate temperatures or overcast skies, may have had a more positive experience compared to those who encountered more extreme weather. This environmental variability adds a degree of complexity to the findings, as it is difficult to fully separate the effects of the technology itself from the influence of external conditions.

The onshore setting also meant that participants were subject to various environmental distractions, such as background noise, the movement of other people, and natural elements like wind or water sounds. These distractions may have influenced participants' ability to remain fully focused on the XR experiences.

Such distractions could have reduced attention and engagement during the XR sessions, particularly for technologies like VR, which require deeper immersion. This may have affected the overall effectiveness of the experiences and suggests that results might differ in more controlled environments. Future research could explore the impact of these distractions in varied settings and consider strategies such as soundproofing or other measures to minimize external noise.

The length of the whale-watching sessions, combined with the intensity of the XR experiences, may also have contributed to participant fatigue, especially since both activities occurred consecutively within a single session. Fatigue could have reduced participant engagement and the effectiveness of the educational content.

Participant fatigue may have lowered motivation and attentiveness as the study progressed, particularly in longer sessions or with more demanding XR experiences like VR. This, in turn, may have influenced the results, making it harder to distinguish between the effects of the XR technology and the participants' tiredness. Future studies could consider shorter sessions or introducing breaks between different experiences to help mitigate fatigue.

6.8.4 Limited Scope of Content

The study focused on onshore, outdoor settings, which are specific to the context of whale-watching and marine education. While appropriate for this context, the findings may not be directly transferable to other environments where XR technologies could be applied, such as classrooms, museums, or other indoor venues. The results should therefore be understood in relation to the specific environmental conditions and context of this study. The effectiveness of AR, VR, and MR may vary in other settings due to differences in environmental controls, participant expectations, or the nature of the content being presented. Future research could benefit from testing these technologies in a wider range of contexts to gain a clearer understanding of their versatility and adaptability. The content used in the XR experiences was designed to fit the context of whale-watching and marine education. This focus, while relevant to the study, may limit how far the findings can be applied to other educational or experiential contexts. The specific subject matter could have shaped how participants responded to the XR technologies, meaning that outcomes might differ if the content were centered on another topic. This consideration suggests that the findings are most applicable to marine education and similar contexts, while future research may explore how these technologies perform with other types of content to assess their broader applicability.

6.8.5 Limitations in Data Collection Methods & Long-Term Impact

The study relied on self-reported data from questionnaires and evaluations, which may be subject to biases such as social desirability bias, where participants provide answers they believe are expected rather than their true feelings. Additionally, the limited use of objective performance metrics may have restricted the ability to fully capture the effectiveness of each medium. The reliance on self-reported data could have introduced some inaccuracies, as participants might not have recalled their experiences precisely or may have adjusted their responses based on perceived expectations. The absence of objective performance measures, such as behavioral tracking or physiological indicators of engagement, limited the ability to triangulate the self-reported data. Future research could incorporate such objective measures to provide a more comprehensive assessment of the effectiveness of AR, VR, and MR.

The questionnaires in this study were deliberately concise, focusing on targeted questions linked directly to the research objectives. While more extensive or standardized scales such as the System Usability Scale (SUS) for usability or the Intrinsic Motivation Inventory (IMI) for engagement and motivation are well established, they were not employed here in full to avoid participant fatigue and dropout in the onshore, field-based setting. This design choice prioritized maintaining ecological validity and encouraging participation. Nonetheless, this approach may have limited the breadth of the data collected, and future work could benefit from supplementing concise, context-specific items with longer, validated instruments such as SUS or IMI to provide greater comparability and depth. The study also concentrated on immediate responses and short-term learning outcomes. It did not assess long-term retention of information or the lasting impact of the XR experiences on participants. Without follow-up measures, it is difficult to determine whether the enthusiasm and knowledge reported during the sessions were retained over time. This consideration suggests that the findings are more reflective of immediate reactions rather than sustained educational benefits.

7 Conclusion and Future Works

7.1 Key Comparisons between XR Technology

This study explored the application of XR technologies—AR, VR, and MR—for enhancing onshore whale-watching experiences. Through the evaluation of user engagement, learning outcomes, emotional connections, and environmental factors, the findings suggest possible roles and limitations of XR in outdoor educational contexts, offering insights into how these technologies may be applied in practice.

7.1.1 Augmented Reality Strengths & Weaknesses

AR appeared to be the most effective in supporting learning outcomes. Correct responses in the marine literacy questionnaire increased from 13 out of 60 before the experience to 49 out of 60 after. This improvement may be attributed to AR's ability to overlay digital information in real-world contexts, which seemed to make learning more accessible and engaging. In terms of user experience, AR showed positive levels of attentiveness and enthusiasm, with median scores of 5 (IQR = 6–5) for interest (Question A), 5 (IQR = 6–4) for importance (Question B), and 5 (IQR = 6–4) for usefulness (Question C). The relative familiarity of handheld AR devices, combined with their straightforward integration into outdoor environments, appeared to support user comfort and engagement. At the same time, AR's weaknesses became evident in its reliance on physical triggers. Bright sunlight frequently interfered with trigger recognition, occasionally disrupting the continuity of the experience. These issues suggest that while AR shows promise for educational use, its effectiveness in outdoor contexts may depend on further refinement of the technology. Reducing dependence on markers and improving environmental recognition could make AR more reliable and adaptable in variable field conditions.

7.1.2 Virtual Reality Strengths & Weaknesses

VR's main strength appeared to lie in its immersive quality, providing participants with a fully simulated marine environment. This capacity for deep immersion may be particularly effective in controlled indoor contexts, where isolation from the real world could help sustain focus and engagement. VR therefore seems well suited for recreating whale-watching experiences in classrooms or at home, where external distractions are minimized. In the outdoor setting of this study, however, immersion also introduced challenges. Correct answers in the literacy questionnaire increased from 11 out of 60 pre-experience to 24 out of 60 post-experience, which was a smaller gain compared to AR and MR. Engagement was also more variable: Questions B and C (importance and usefulness) had median scores of 5 (IQR = 6–4 and 6–3, respectively), while repetition and recommendation (Questions G and H) were lower, at medians of 4 (IQR = 6–3 and 6–3). In addition, difficulty was rated highest for VR, with a median of 5 (IQR = 6–3). Several participants appeared less motivated and attentive in the outdoor context, where headset discomfort and disconnection from the surroundings seemed to reduce overall engagement. These findings suggest that while VR can create compelling immersive experiences, its suitability for outdoor whale-watching contexts may be more limited without further adaptation.

7.1.3 Mixed Reality Strengths & Weaknesses

MR appeared to offer a more balanced approach by blending real and virtual elements. This combination seemed to support emotional connection, particularly in relation to whales (Question I: median = 5, IQR = 6–4), and also generated relatively strong enthusiasm across several engagement measures. For example, Question A (interest) reached a median of 6 (IQR = 6–6), and Question H (recommendation) also scored a median of 6 (IQR = 6–5). In terms of usability, MR was rated as the least difficult of the three, with a median of 3 (IQR = 4–2), suggesting that participants generally found it intuitive to navigate. Correct answers in the literacy questionnaire increased from 16 out of 60 pre-experience to 27 out of 60 post-experience, indicating some learning gains, though not as pronounced as with AR. At the same time, MR's novelty may have acted as a distraction, with participants occasionally focusing more on the technology itself than on the educational content. The integration of real and virtual elements, while engaging, also introduced some challenges in maintaining visual clarity and consistency in outdoor conditions. These considerations suggest that MR has potential for combining immersion with situational awareness, but may require refinement to strengthen its educational impact in onshore environments.

7.2 Key Insights

7.2.1 (RQ1) Bridging the Gap in Public Awareness and Marine Literacy

The results suggested that AR was comparatively effective in supporting marine literacy. Correct answers in the literacy questionnaire increased from 13 out of 60 before the experience to 49 out of 60 after. This improvement may help address the concern that traditional whale-watching practices often provide limited educational content. XR technologies, by making marine education more accessible and engaging, appear to have the potential to contribute to raising awareness of the threats facing marine life and to promoting conservation efforts.

7.2.2 (RQ2) Fostering Engagement, Emotional Connection and Accessibility to Marine Life

XR technologies, particularly AR, appeared to support engagement in ways that addressed some of the limitations of traditional onshore whale-watching. AR's ability to overlay digital content onto real-world settings was reflected in positive responses on questions related to attentiveness and interest (e.g., Question A: median = 5, IQR = 6–5), suggesting that participants found the experience accessible and engaging. While these results indicate promise, the extent to which such engagement may translate into longer-term behavior change remains uncertain and would require further study. Establishing an emotional connection with whales is often difficult in onshore settings where direct encounters are absent. MR, by blending real and virtual elements, tended to foster comparatively stronger emotional responses. For example, Question I ("I feel connected to whales") reached a median of 5 (IQR = 6–4) in MR, higher than in AR (median = 3, IQR = 5–2) or VR (median = 4, IQR = 5–2). This suggests that MR may help bridge the gap between physical distance and emotional engagement, potentially encouraging a deeper appreciation for marine life and, in turn, supporting conservation motivations.

7.2.3 (RQ3) Overcoming the External Constraints of XR Technologies

The study suggested several constraints associated with the use of XR technologies in outdoor, onshore settings. Environmental factors such as weather, bright sunlight, and variable lighting may have influenced usability, particularly for AR where triggers did not always respond reliably. Hardware-related issues were also reported: VR tended to be perceived as the most difficult to use (Question D: median = 5, IQR = 6–3), partly due to headset discomfort and the demands of full immersion outdoors, while MR was generally rated as the least difficult (median = 3, IQR = 4–2). AR fell in between (median = 4, IQR = 5–2), reflecting that while generally manageable, usability was sometimes disrupted by environmental interference. These findings imply that participant comfort and environmental conditions may play an important role in shaping the effectiveness of XR in real-world contexts. Future developments—such as reducing AR's reliance on physical triggers or improving MR display clarity—could help address these challenges and support more consistent experiences in outdoor environments.

7.3 Comparative Analysis of XR Technologies in Onshore Settings

The research compared AR, VR, and MR to assess their effectiveness in educational outcomes, user engagement, and emotional connection. AR appeared to be the more accessible option for onshore educational purposes, particularly in supporting marine literacy. MR showed some potential in fostering emotional connections, while VR, although immersive, seemed to face challenges in outdoor settings due to its more isolating nature.

7.4 Foundation for Future Work

Given the findings, future research could focus on the following areas to enhance the application of XR technologies in outdoor and educational settings.

7.4.1 AR, MR and VR Optimization in Dynamic Environments

AR systems may benefit from reducing reliance on physical triggers, for instance through the use of machine learning approaches for environmental recognition that function more reliably under varied lighting conditions. Such improvements could enhance the consistency and user experience of AR, particularly in outdoor contexts. AR systems might also be improved by advances in graphical realism and the responsiveness of interactive elements, making the experience more immersive without necessarily compromising ease of use. Future MR systems could benefit from lighter and less intrusive equipment, including headsets and more intuitive interfaces that do not depend on handheld devices, thereby making the technology more accessible in outdoor settings. MR may also need to focus on improving visual clarity and contrast, especially in bright conditions. Advances in display technology could help address current limitations, making virtual elements more consistently visible regardless of environmental factors. VR might be best positioned for use in indoor or controlled environments, where its immersive capabilities can be more fully leveraged. Future work could focus on enhancing the realism of VR experiences while reducing discomfort associated with prolonged use. Combining VR with other XR approaches may also offer hybrid experiences that balance immersion with real-world awareness, potentially making VR more relevant in semi-outdoor settings such as covered observation decks or educational centers. Future studies may also consider the feasibility of MR in more dynamic environments, such as boats. MR's ability to blend real and virtual information could be advantageous in these situations, offering immersion while maintaining situational awareness. By contrast, the physical safety of using VR in such contexts remains uncertain and would require careful examination.

7.4.2 Empathy, Conservation Efforts and Accessible Tourism

Additional research is needed to understand how XR experiences, particularly MR, can foster empathy and a stronger connection to virtual representations of animals. This could involve longitudinal studies to measure the long-term impact of XR on attitudes towards conservation and wildlife protection. Future research could include follow-up assessments to evaluate the durability of learning and engagement over time. Traditional whale-watching practices often lead to ecological disturbances, including behavioral changes in whales, stress due to noise pollution, and the risk of physical harm from vessel collisions. The findings of this study could have significant implications for responsible whale-watching and sustainable tourism. By providing alternative experiences when whales are not present, XR technologies could reduce the ecological impact of tourism on marine environments. Future research should explore the role of XR in promoting conservation awareness and responsible interaction with wildlife. The XR technologies also offer a solution to the geographical and economic barriers associated with traditional whale-watching tours. The use of affordable XR systems like Google Cardboard and Aryzon allows a broader audience to participate in immersive marine experiences. While these technologies may not match the quality of high-end systems, they are significantly more cost-effective, making marine education accessible to people regardless of location or financial capability.

7.4.3 Technical and Environmental Constraints

Future work should address the technical constraints identified in this study, such as improving the outdoor visibility of AR and MR displays, reducing the weight and discomfort of XR headsets, and enhancing battery life for extended use. These improvements will be critical in making XR a practical and enjoyable tool for outdoor education and tourism.
This thesis has presented a comprehensive study of the effectiveness of Augmented Reality, Virtual Reality, and Mixed Reality in enhancing marine literacy and promoting whale conservation in onshore settings. Through detailed experimentation and analysis, it has been demonstrated that while each technology offers unique advantages, AR stands out as the most accessible and effective medium for transmitting information and engaging users in educational content. MR, with its ability to blend real and virtual elements, has shown great potential in fostering emotional connections to marine life, while VR, though highly immersive, faces challenges in outdoor settings due to its isolating nature.

7.4.4 Overview for Future Work

The small sample size, the accessibility of the technology used, environmental conditions, participant familiarity with XR, and the interaction design all potentially influenced the outcomes. Future research should aim to address these limitations by using larger, more diverse samples, higher-end XR technology, and more optimized content design to further explore the potential of AR, VR, and MR in educational and tourism contexts. In conclusion, while this research has made significant strides in understanding the role of XR technologies in marine conservation, it also highlights the ongoing need for innovation and refinement. The proposed advancements in AR and MR, coupled with the careful consideration of environmental factors, will be crucial in driving the next generation of immersive educational experiences. This thesis thus provides a solid foundation for future research, encouraging continued exploration and development in this promising field. The findings of this research lay the groundwork for future explorations in the intersection of XR technologies and environmental conservation. By identifying the strengths and limitations of AR, VR, and MR in onshore whale-watching experiences, this study serves as a crucial reference point for developing more immersive, user-friendly, and effective educational tools. Future work can build on this foundation by exploring offshore applications, improving the technological aspects such as AR trigger mechanisms and MR clarity, and expanding the research to a broader demographic to enhance the generalizability of the results. Moreover, the insights gained from this study have implications beyond whale-watching, offering valuable lessons for the broader fields of sustainable tourism, marine conservation, and interactive education. By integrating these technologies more effectively into real-world settings, we can create powerful tools for education and conservation that not only inform but also inspire and engage the public in meaningful ways.

A Appendix

A.1 Inspiration

As a child, my imagination was boundless, often blurring the lines between the real and the fantastical. I would envision mythical creatures—like the majestic dragons from stories and animated films—soaring through the skies of my everyday world. The allure of riding a giant, winged beast home or exploring hidden realms filled with fantastical beings was a frequent daydream. This ability to overlay our mundane reality with extraordinary elements is a natural part of childhood play and creativity. As children, we engage in this kind of augmented reality through play, using toys, books, or films as tools to transport ourselves into otherworldly adventures. Whether it's imagining ourselves as heroes in a story or envisioning the inanimate as alive, these experiences are early forms of immersive interaction with the world around us. It's in these moments that we not only engage with our imaginations but also develop a deep-seated desire to bring those imagined worlds to life. Today, with the advent of XR technologies these childhood dreams are no longer confined to the imagination. XR has the potential to bring imagined worlds into our everyday lives, allowing us to interact with digital creatures and environments as if they were part of our physical surroundings. This technology doesn't just replicate the experiences we've had in traditional digital gaming; it transcends them by integrating virtual elements directly into our reality, creating a seamless blend of the fantastical and the real. It's not just about being in a different world but about transforming our existing world into something more—an augmented, enriched version of reality where the fantastical becomes part of the everyday. As we continue to develop and refine this technology, its potential will be explored in ways that were once only possible in our minds. My inspiration for applying XR to enhance whale-watching experiences is deeply rooted in this desire to bridge the gap between imagination and reality. Just as I once envisioned dragons in the sky, XR allows us to overlay digital elements—like breaching whales—onto our physical environment. This approach not only makes these encounters more immersive and accessible but also fosters a deeper connection to the natural world. By simulating close encounters with whales through XR, we can promote a more sustainable form of interaction that reduces the ecological impact on these magnificent creatures. Furthermore, XR technologies offer an opportunity to make whale-watching experiences more inclusive, overcoming the geographical and economic barriers that often limit participation. By bringing these experiences to a broader audience, XR can play a crucial role in raising awareness about marine conservation and inspiring a collective effort to protect our oceans. As technology continues to evolve, XR stands as a powerful tool in our ongoing quest to augment reality, transforming how we connect with the environment. It fulfills a childhood dream—turning imagination into reality—while also serving a greater purpose: fostering a sustainable and empathetic relationship with the natural world.

A.2 AR Test Results

AR USER TESTING

QUESTIONNAIRE
QUESTION 1 - How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime? A) 1 in 10; B) 3 in 10; C) 5 in 10; D) More than 5 in 10.
QUESTION 2 - Who eats What? A) Phytoplankton eats zooplankton; B)Zooplankton eats whale feces; C)Phytoplankton eats whale feces; D)Whale eats phytoplankton.
QUESTION 3 - How many scuba divers are equivalent to the length of a North Atlantic Right Whale? A) Around 7; B) Around 12; C) Around 20; D) More than 20.

EVALUATION
In a scale of 1(low) to 7(high) evaluate the following questions:
A) I found this experience interesting.
B) I found this experience important.
C) I found this experience usefull.
D) I found this experience difficult
E) I learned a lot with this experience.
F) I am confortable to teach others about what I have learned.
G) I would repeat this experience.
H) I would recommend this experience.
I) I feel connected to whales

					BEFORE			AFTER												DETAILS (WEATHER, EMOTIONAL STATE, ETC)						
USER ID	TEST DATE	AGE	GENDER	NATIONALITY	Q1	Q2	Q3	Q1	Q2	Q3	A	B	C	D	E	F	G	H	I					Channe +	Literacy Before	Literacy After
1	04/07/23	47	Female	German	D	D	A	D	C	A	4	5	5	3	4	3	5	4	2	24°C, Cloudy	Satisfied	Very Attentive		3	2	3
2	04/07/23	82	Male	English	C	B	C	B	C	A	5	4	6	6	5	3	5	6	4	24°C, Cloudy	Satisfied	Attentive		3	0	2
3	04/07/23	18	Female	Portugal	C	C	C	D	C	A	6	6	7	3	7	2	7	7	6	24°C, Cloudy	Motivated	Very Attentive		2	1	3
4	04/07/23	17	Female	Portugal	C	B	C	B	C	D	5	6	5	5	4	3	4	4	4	24°C, Cloudy	Satisfied	Low Attentive		3	0	1
5	06/07/23	40	Male	German	C	D	D	D	C	A	5	4	5	4	6	6	6	6	4	20°C, Cloudy	Satisfied	Very Attentive		3	0	3
6	06/07/23	45	Female	German	C	B	C	B	C	A	4	5	5	6	4	6	6	5	5	20°C, Cloudy	Satisfied	Attentive		3	0	2
7	11/07/23	20	Female	Dutch	C	D	B	D	C	A	7	4	4	1	7	3	7	4	3	24°C, Partly Cloud	Satisfied	Very Attentive		3	0	3
8	11/07/23	18	Male	Dutch	D	D	B	D	C	B	5	6	6	4	5	4	6	5	3	24°C, Partly Cloudy	Satisfied	Attentive		2	1	2
9	14/07/23	26	Female	Luxemburg	D	D	A	D	D	A	6	6	6	2	6	4	4	2	2	29°C, Sunny Weather, Very Hot	Satisfied	Attentive		0	1	2
10	19/07/23	46	Male	Slovakia	B	D	A	D	C	A	6	4	7	1	7	2	7	7	2	23°C, Partly Cloudy	Motivated	Very Attentive		2	1	3
11	19/07/23	51	Female	Dutch	D	D	A	D	D	A	5	3	4	4	6	3	6	5	4	23°C, Partly Cloudy,	Satisfied	Attentive		0	2	2
12	09/08/23	47	Female	Spanish	D	D	C	C	B	A	7	7	6	5	7	6	6	6	5	27°C, Sunny Weather, Very Hot	Motivated	Low Attentive		3	1	1
13	09/08/23	47	Male	Spanish	A	D	D	D	D	A	4	5	4	4	3	2	3	3	3	27°C, Sunny Weather, Very Hot	Satisfied	Attentive		2	0	2
14	09/08/23	13	Female	Spanish	A	D	C	D	D	A	7	7	7	6	7	5	4	5	3	27°C, Sunny Weather, Very Hot	Motivated	Attentive		2	0	2
15	11/08/23	25	Female	Italian	C	D	B	D	C	A	5	5	5	5	5	4	6	5	1	31 °C, Sunny Weather, Very Hot	Satisfied	Very Attentive	Saw many cetaceans	3	0	3
16	11/08/23	40	Female	Italian	A	D	B	D	C	A	3	5	5	1	4	5	7	7	7	31 °C, Sunny Weather, Very Hot	Satisfied	Very Attentive	Saw many cetaceans	3	0	3
17	11/08/23	51	Female	Italian	D	D	D	D	C	A	6	6	7	7	5	7	6	7	3	31 °C, Sunny Weather, Very Hot	Motivated	Very Attentive	Saw many cetaceans	2	1	3
18	23/08/24	21	Female	Portugal	A	C	B	D	C	A	6	6	1	1	6	3	6	7	4	29 °C,Sunny Weather, Very Hot	Satisfied	Very Attentive	Grumpy because of high temp	2	1	3
19	23/08/24	28	Male	German	C	D	A	D	C	A	4	3	4	2	5	6	2	5	2	29 °C,Sunny Weather, Very Hot	Satisfied	Very Attentive	Not so happy from the boat ride, low number of cetaceans seen.	2	1	3
20	23/08/24	30	Female	German	C	A	A	D	C	A	5	4	4	2	5	5	6	6	2	29 °C,Sunny Weather, Very Hot	Satisfied	Very Attentive	Not so happy from the boat ride, low number of cetaceans seen.	2	1	3
											105	101	103	72	108	84	109	106	73	0	20 Motivated / S:	18 Very attentive / Attentive / Low attentive		45	13	49
											5,25	5,05	5,15	3,6	5,4	4,2	5,45	5,3	3,65		8 Non motivated 5 Motivated	0 Non Attentive 11 Very Attentive		2,25	0,65	2,45

Fig. 53: AR user tests (See Figure 48a.

A.3 VR Test Results

VR USER TESTING

QUESTIONNAIRE

QUESTION 1 - How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime? A) 1 in 10; B) 3 in 10; C) 5 in 10; D) More than 5 in 10.

QUESTION 2 - Who eats What? A) Phytoplankton eats zooplankton; B)Zooplankton eats whale feces; C)Phytoplankton eats whale feces; D)Whale eats phytoplankton.

QUESTION 3 - How many scuba divers are equivalent to the length of a North Atlantic Right Whale? A) Around 7; B) Around 12; C) Around 20; D) More than 20.

EVALUATION

In a scale of 1(low) to 7(high) evaluate the following questions:

A) I found this experience interesting.

B) I found this experience important.

C) I found this experience usefull.

D) I found this experience difficult

E) I learned a lot with this experience.

F) I am confortable to teach others about what I have learned.

G) I would repeat this experience.

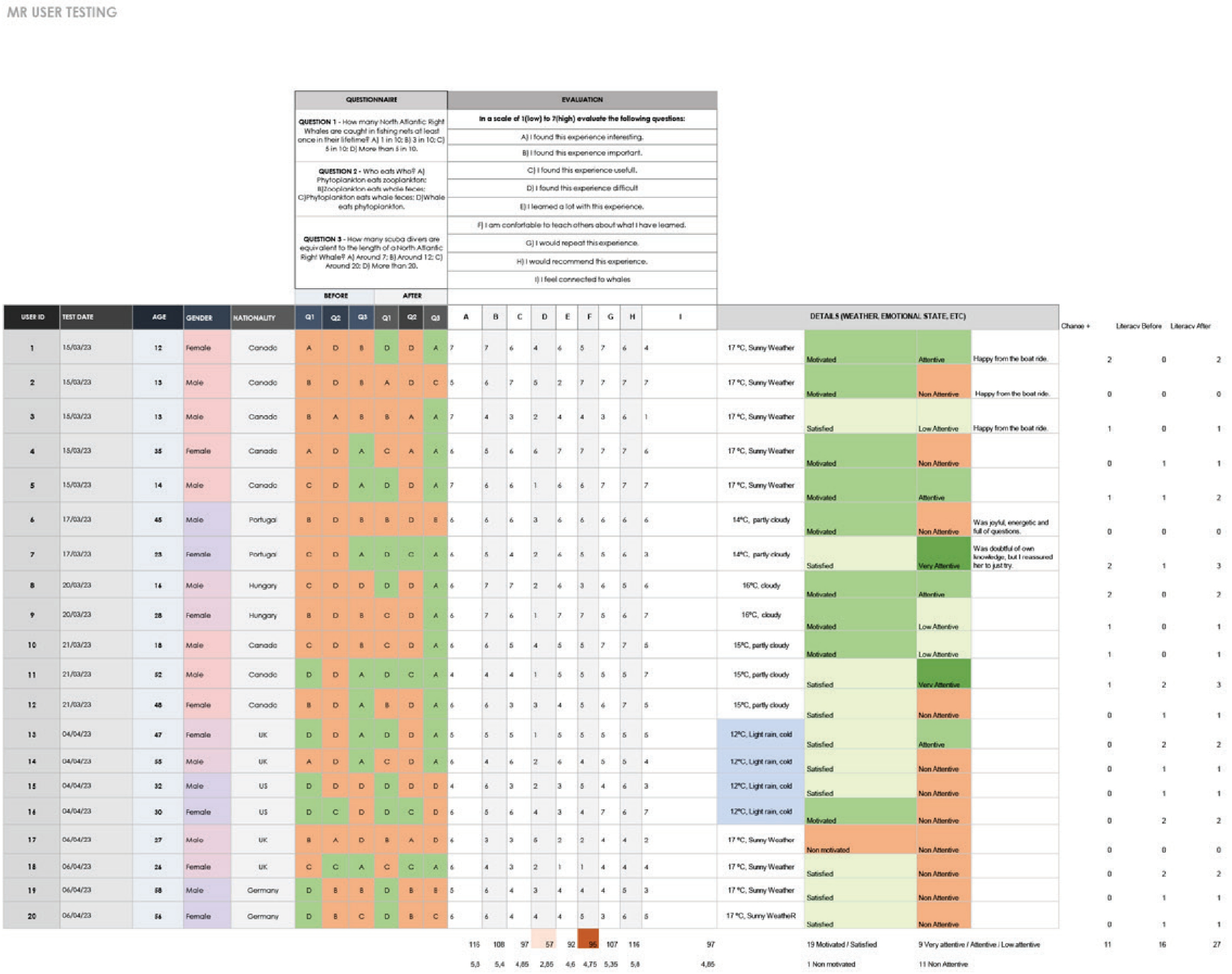
H) I would recommend this experience.

I) I feel connected to whales

					BEFORE			AFTER												DETAILS (WEATHER, EMOTIONAL STATE, ETC)						
USER ID	TEST DATE	AGE	GENDER	NATIONALITY	Q1	Q2	Q3	Q1	Q2	Q3	A	B	C	D	E	F	G	H	I					Change +	Literacy Before	Literacy After
1	10/04/23	28	Female	Germany	D	A	C	D	B	A	4	6	3	1	3	5	2	3	1	21 °C, Sunny Weather	Non motivated	Attentive	Not so engaged with the app	1	1	2
2	10/04/23	25	Male	Belgium	B	C	C	D	D	A	4	6	3	1	3	5	2	3	1	21 °C, Sunny Weather	Non motivated	Attentive		3	1	2
3	12/04/23	53	Male	Portugal	B	D	B	B	D	B	3	3	3	6	4	3	4	4	1	21 °C, Sunny Weather	Non motivated	Non Attentive		0	0	0
4	12/04/23	14	Male	Portugal	C	D	B	C	D	B	4	4	2	7	2	2	3	3	1	21 °C, Sunny Weather	Non motivated	Non Attentive		0	0	0
5	12/04/23	27	Female	Germany	B	A	A	B	A	A	6	4	4	5	3	3	4	4	2	21 °C, Sunny Weather	Satisfied	Non Attentive	In a rush	0	1	1
6	12/04/23	42	Female	Portugal	C	D	A	C	D	A	6	6	6	6	6	6	6	6	6	21 °C, Sunny Weather	Motivated	Non Attentive		0	1	1
7	14/04/23	42	Male	Lithuania	B	D	B	C	D	C	6	6	6	5	4	5	5	6	6	16 °C, Sunny Weather	Motivated	Non Attentive		0	0	0
8	14/04/23	41	Female	Lithuania	B	D	B	C	D	C	6	6	6	5	4	5	5	6	6	16 °C, Sunny Weather	Satisfied	Non Attentive		0	0	0
9	14/04/23	28	Male	Hong Kong	B	C	D	B	C	D	4	2	3	5	3	2	4	4	4	16 °C, Sunny Weather	Non motivated	Non Attentive	Was very aknowledgable, but in a hurry	0	1	1
10	28/04/23	54	Female	UK	D	D	D	D	D	D	7	7	7	2	7	3	7	7	5	22 °C, Sunny Weather	Motivated	Non Attentive		0	1	1
11	28/04/23	24	Male	Portugal	C	D	B	D	C	C	5	4	4	5	4	4	4	4	4	22 °C, Sunny Weather	Satisfied	Attentive		3	0	2
12	28/04/23	35	Female	Germany	B	A	B	C	A	B	7	5	5	4	4	5	7	7	5	22 °C, Sunny Weather	Motivated	Non Attentive		1	0	0
13	28/04/23	40	Female	Germany	C	A	A	D	A	A	7	7	6	5	5	6	7	7	5	22 °C, Sunny Weather	Motivated	Attentive		1	1	2
14	28/04/23	44	Female	Portugal	C	D	A	C	D	A	6	3	3	7	2	2	7	5	3	22 °C, Sunny Weather	Satisfied	Non Attentive		0	1	1
15	28/04/23	12	Male	Portugal	B	D	B	B	D	B	6	6	6	6	6	6	6	6	6	22 °C, Sunny Weather	Motivated	Non Attentive		0	0	0
16	02/05/23	34	Female	Portugal	C	C	B	D	C	A	5	5	5	4	4	5	3	3	3	22 °C, Sunny Weather	Satisfied	Very Attentive		2	1	3
17	03/05/23	60	Female	Czech Republic	C	B	B	C	B	B	5	5	3	6	3	1	3	3	1	18 °C, Sunny Weather	Non motivated	Non Attentive	She was in a rush, did it really fast	0	0	0
18	03/05/23	44	Male	France	B	D	B	D	D	A	6	6	6	3	6	6	4	4	4	18 °C;Sunny Weather	Satisfied	Attentive		2	0	2
19	03/05/23	60	Male	UK	D	D	D	D	C	A	7	5	5	1	5	5	1	7	7	18°C, Sunny Weather	Satisfied	Very Attentive		2	1	3
20	03/05/23	51	Female	UK	D	D	D	D	C	A	7	1	3	1	4	4	1	3	3	18 °C, Sunny Weather	Non motivated	Very Attentive		2	1	3
											111	97	89	85	82	83	85	95	74		13 Motivated / S	8 Very attentive / Attentive / Low att		17	11	24
											5,55	4,85	4,45	4,25	4,1	4,15	4,25	4,75	3,7		6 Non motivated	12 Non Attentive		0,85	0,55	1,2

Fig. 54: VR user tests (See Figure 48c)

A.4 MR Test Results



MR USER TESTING

QUESTIONNAIRE	EVALUATION
QUESTION 1 - How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime? A) 1 in 10; B) 3 in 10; C) 5 in 10; D) More than 5 in 10.	**In a scale of 1(low) to 7(high) evaluate the following questions:** A) I found this experience interesting. B) I found this experience important.
QUESTION 2 - Who eats Who? A) Phytoplankton eats zooplankton; B)Zooplankton eats whale feces; C)Phytoplankton eats whale feces; D)Whale eats phytoplankton.	C) I found this experience usefull. D) I found this experience difficult E) I learned a lot with this experience.
QUESTION 3 - How many scuba divers are equivalent to the length of a North Atlantic Right Whale? A) Around 7; B) Around 12; C) Around 20; D) More than 20.	F) I am confortable to teach others about what I have learned. G) I would repeat this experience. H) I would recommend this experience. I) I feel connected to whales

					BEFORE			AFTER												DETAILS (WEATHER, EMOTIONAL STATE, ETC)						
USER ID	TEST DATE	AGE	GENDER	NATIONALITY	Q1	Q2	Q3	Q1	Q2	Q3	A	B	C	D	E	F	G	H	I					Change +	Literacy Before	Literacy After
1	15/03/23	12	Female	Canada	A	D	B	D	D	A	7	7	6	4	6	5	7	6	4	17 °C, Sunny Weather	Motivated	Attentive	Happy from the boat ride.	2	0	2
2	15/03/23	13	Male	Canada	B	D	B	A	D	C	5	6	7	5	2	7	7	7	7	17 °C, Sunny Weather	Motivated	Non Attentive	Happy from the boat ride.	0	0	0
3	15/03/23	13	Male	Canada	B	A	B	B	A	A	7	4	3	2	4	4	3	6	1	17 °C, Sunny Weather	Satisfied	Low Attentive	Happy from the boat ride.	1	0	1
4	15/03/23	35	Female	Canada	A	D	A	C	A	A	6	5	6	6	7	7	7	7	6	17 °C, Sunny Weather	Motivated	Non Attentive		0	1	1
5	15/03/23	14	Male	Canada	C	D	A	D	D	A	7	6	6	1	6	6	7	7	7	17 °C, Sunny Weather	Motivated	Attentive		1	1	2
6	17/03/23	45	Male	Portugal	B	D	B	B	D	B	6	6	6	3	6	6	6	6	6	14°C, partly cloudy	Motivated	Non Attentive	Was joyful, energetic and full of questions.	0	0	0
7	17/03/23	23	Female	Portugal	C	D	A	D	C	A	6	5	4	2	6	5	5	6	3	14°C, partly cloudy	Satisfied	Very Attentive	Was doubtful of own knowledge, but I reassured her to just try.	2	1	3
8	20/03/23	16	Male	Hungary	C	D	D	D	D	A	6	7	7	2	6	3	6	5	6	16°C, cloudy	Motivated	Attentive		2	0	2
9	20/03/23	28	Female	Hungary	B	D	B	C	D	A	6	7	6	1	7	7	5	6	7	16°C, cloudy	Motivated	Low Attentive		1	0	1
10	21/03/23	18	Male	Canada	C	D	B	C	D	A	6	6	5	4	5	5	7	7	5	15°C, partly cloudy	Motivated	Low Attentive		1	0	1
11	21/03/23	52	Male	Canada	D	D	A	D	C	A	4	4	4	1	5	5	5	5	7	15°C, partly cloudy	Satisfied	Very Attentive		1	2	3
12	21/03/23	48	Female	Canada	B	D	A	B	D	A	6	6	3	3	4	5	6	7	5	15°C, partly cloudy	Satisfied	Non Attentive		0	1	1
13	04/04/23	47	Female	UK	D	D	A	D	D	A	5	5	5	1	5	5	5	5	5	12°C, Light rain, cold	Satisfied	Attentive		0	2	2
14	04/04/23	55	Male	UK	A	D	A	C	D	A	6	4	6	2	6	4	5	5	4	12°C, Light rain, cold	Satisfied	Non Attentive		0	1	1
15	04/04/23	32	Male	US	D	D	D	D	D	D	4	6	3	2	3	5	4	6	3	12°C, Light rain, cold	Satisfied	Non Attentive		0	1	1
16	04/04/23	30	Female	US	D	C	D	D	C	D	6	5	6	4	3	4	7	6	7	12°C, Light rain, cold	Motivated	Non Attentive		0	2	2
17	06/04/23	27	Male	UK	B	A	D	B	A	D	6	3	3	6	2	2	4	4	2	17 °C, Sunny Weather	Non motivated	Non Attentive		0	0	0
18	06/04/23	24	Female	UK	C	C	A	C	C	A	6	4	3	2	1	1	4	4	4	17 °C, Sunny Weather	Satisfied	Non Attentive		0	2	2
19	06/04/23	58	Male	Germany	D	B	B	D	B	B	5	6	4	3	4	4	4	5	3	17 °C, Sunny Weather	Satisfied	Non Attentive		0	1	1
20	06/04/23	56	Female	Germany	D	B	C	D	B	C	6	6	4	4	4	5	3	6	5	17 °C, Sunny WeatheR	Satisfied	Non Attentive		0	1	1
											116	108	97	57	92	95	107	116	97		19 Motivated / Satisfied	9 Very attentive / Attentive / Low attentive		11	16	27
											5,8	5,4	4,85	2,85	4,6	4,75	5,35	5,8	4,85		1 Non motivated	11 Non Attentive				

Fig. 55: MR user tests (See Figure 55).

B Appendix

B.1 Storyboard & User Journey

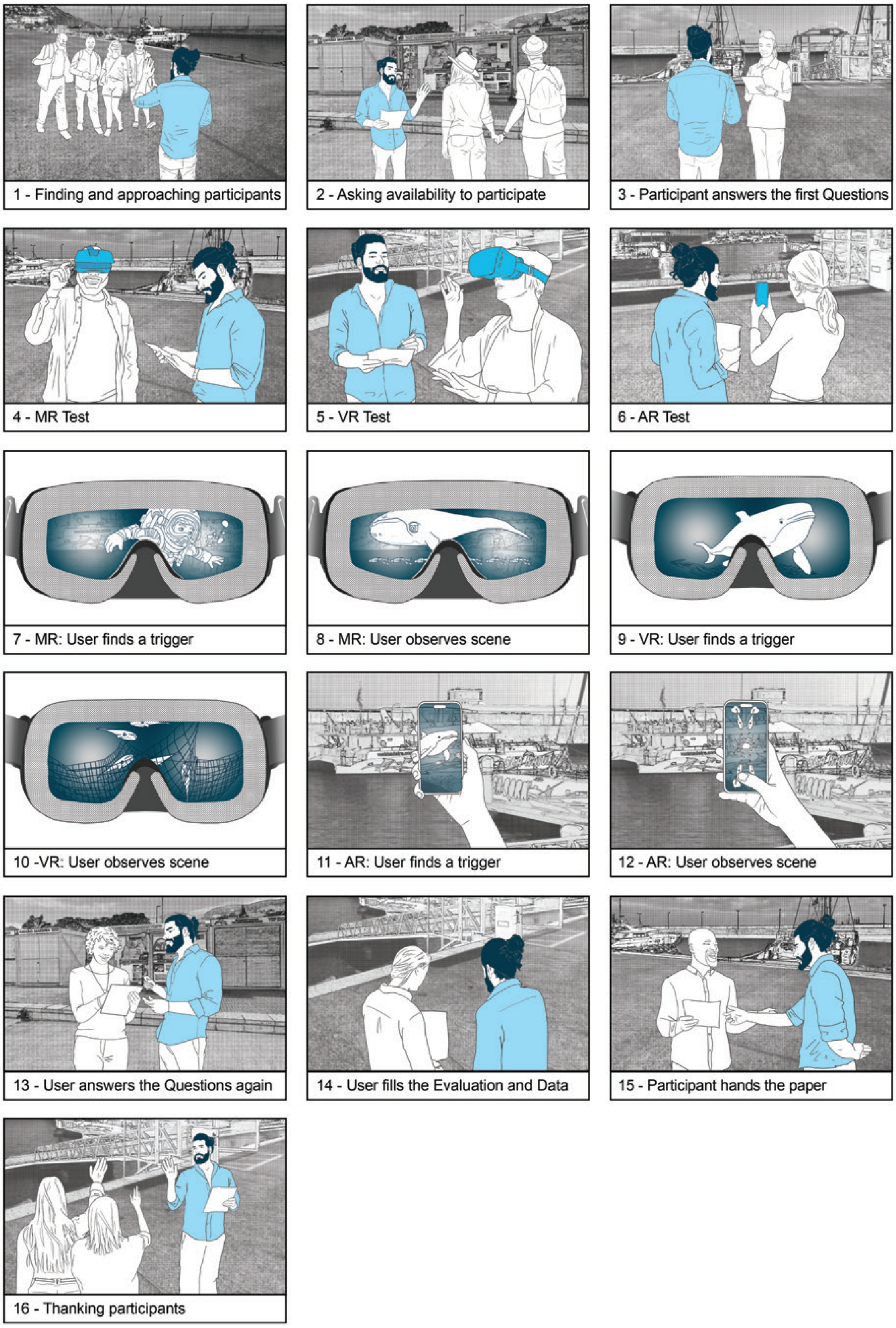


Fig. 56: See Figures 42) This storyboard illustrates the process of testing XR technologies with participants. It begins with recruiting and explaining the study, followed by the individual AR, VR, and MR testing sessions. Participants provide feedback on their experiences. The process concludes with data collection and participant evaluation.

C Appendix

C.1 App Low-Fidelity Wireframe

Who eats whom?

How many scuba divers are equivalent to the length of a North Atlantic Right Whale?

How many North Atlantic Right Whale are caught by fish net at least once in their lifetime?

INSTRUCTIONS

1 - Take the quiz first.

2 - Scan each whale image.

3 - When you finished the experience, take again the quiz to see if you learned something new.

ABOUT

ARDome is a part of the INTERAQUATICA project, whose goal is to design and produce Interactive Experiences based on Geodesic Domes. Inspired in this case by the North Atlantic Right Whale. The objective is to raise awareness in marine conservation concerns currently affecting the ecosystems, which are a consequence of anthropological activities.

We are all responsible for the conservation of the planet and it is our duty to prevent the iminent ecological colapse. Are you doing your part?

Fig. 57: Low-Fidelity Wireframe of the app inter- face, illustrating the main navigation flow and layout. The interface includes sections for playing the experience, viewing educational content ('Did You Know?'), app information ('About'), and usage instructions (See Figure 39a).

C.2 App High-Fidelity Wireframe

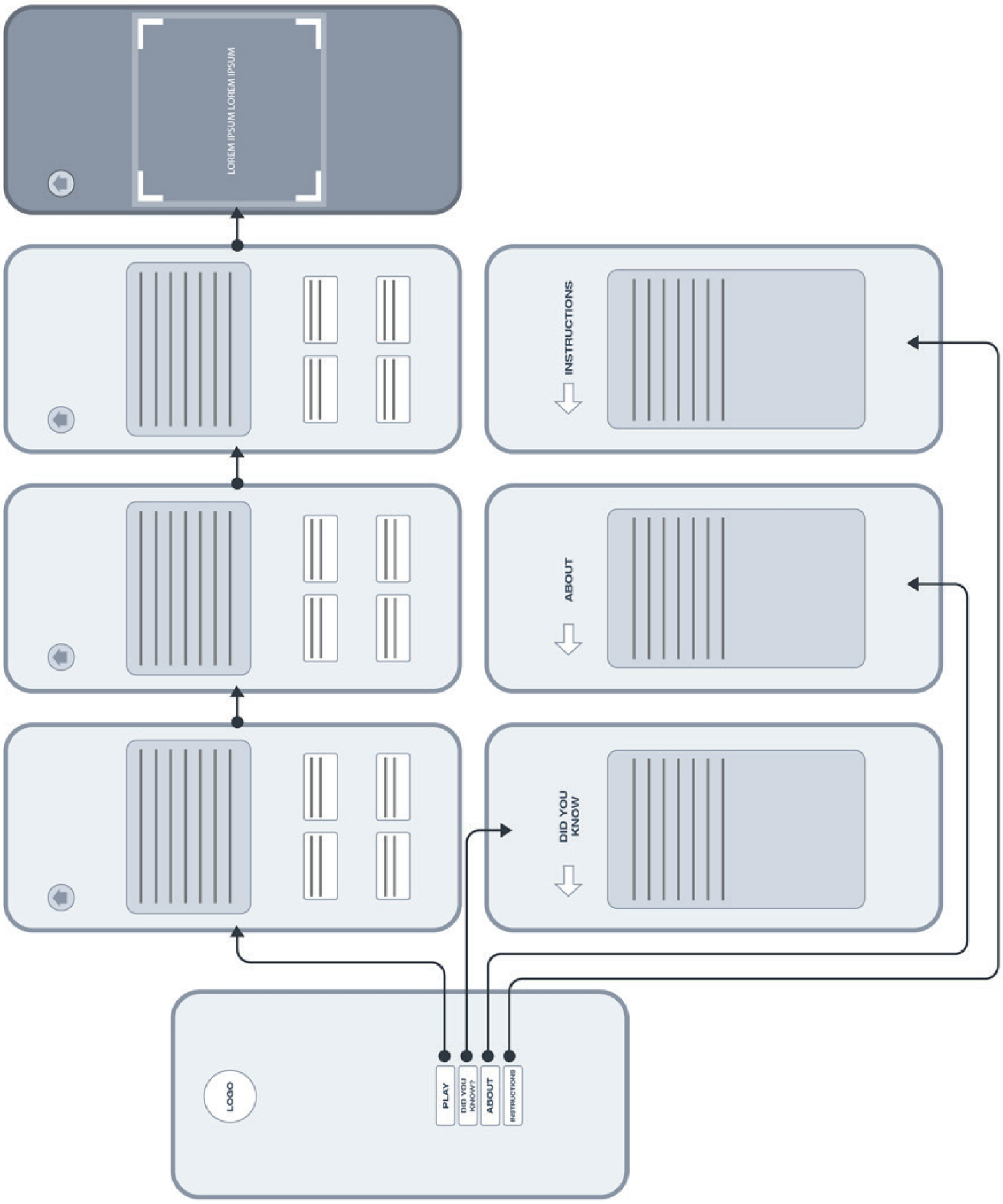


Fig. 58: High-Fidelity Wireframe of the ARDome App: An overview of the ARDome application interface, showcasing the user journey from engaging with quiz questions related to whale conservation, to scanning augmented reality images and viewing educational content(See Figure 39b).

D Appendix

D.1 Participant Demographics

The study involved 60 participants, whose demographics were meticulously recorded and analyzed to identify potential patterns or biases in the results. Participants were categorized by age, gender, and nationality:

D.1.1 Age

In the MR tests, the younger participants (12 and 13 years old) from Canada showed a significant improvement in learning outcomes. They were able to transition from incorrect to correct answers in all three questions (Q1, Q2, Q3), reflecting a strong understanding gained from the MR experience. Their evaluation scores were consistently high, indicating they found the experience engaging and educational. Notably, the younger participants generally scored high in their evaluations (e.g., scores of 7 for interest and learning). Older participants (e.g., 58, 56 years old)** also showed improvement, particularly in Q2, but less consistently across all questions. This age group reported mixed evaluation scores, suggesting that while they found the MR experience useful, it may have been slightly less intuitive for them compared to younger participants. The older participants had more varied results, with some scoring lower on engagement and learning (scores ranging from 4 to 6). This suggests that younger participants were more engaged and possibly found the MR technology easier to use. In VR tests, the younger group (12-14 years old) had mixed results; some retained incorrect answers (particularly in Q3), which suggests that while VR was engaging, it may have been challenging for them to fully grasp or retain the information presented. Their evaluation scores reflected this, with lower scores in areas like understanding and confidence in teaching others. Older participants (42-53 years old)** generally demonstrated more substantial learning, with consistent improvement in Q2 and Q3. This group rated the experience positively in the evaluation, particularly in terms of the usefulness and importance of the content, indicating a strong engagement and better comprehension through the VR medium. Interestingly, the younger participants showed less engagement (scoring lower on recommendations and connection to whales), while older participants were more varied, with some scoring high on engagement but low on the difficulty of use. This might indicate that older participants found the VR experience challenging but still engaging. In AR tests, among older participants (e.g., 82 years old), there was a noticeable improvement in understanding as they corrected their initial wrong answers in Q1 and Q2. However, younger participants (18-20 years old) showed more variability in their improvements, with some not correcting their mistakes, suggesting that AR might not have been as effective for certain individuals in reinforcing correct information. Despite this, evaluation scores were generally positive, especially regarding the interest and engagement generated by the AR experience. Older participants had more consistent scores, generally scoring higher in learning (5-7) but varied in engagement. Younger participants showed more variability, with some scoring very high on engagement and others less so.

D.1.2 Gender

In MR tests, females tended to show more consistent improvements, shifting from incorrect to correct answers across most questions, especially in Q2 and Q3. Their evaluation scores were generally high, indicating they found the MR experience interesting, useful, and engaging.

Males , while also improving, showed more variability, particularly in Q3, which might suggest that they found certain aspects of the MR experience less intuitive. Their evaluation scores reflected this, showing a slightly lower enthusiasm in repeating the experience or feeling connected to whales Females tended to rate the experience as slightly more important and useful (with scores typically around 6-7) compared to males, who had a broader range in their scores (from 4 to 7).

In VR tests, Females demonstrated more substantial learning, especially in Q1 and Q2, where they corrected most of their initial wrong answers. Their evaluation scores were high, indicating they found the VR experience both important and engaging. Males, on the other hand, had mixed results, with some retaining incorrect answers, which was reflected in lower scores for understanding and confidence in sharing what they learned.

Females often rated their connection to whales and the importance of the experience higher (scores of 6-7) compared to males, who generally rated their experiences lower (4-6). This suggests that females might have found the VR content more emotionally engaging or relevant.

In AR tests, Females again demonstrated stronger improvements, particularly in Q2 and Q3, and generally provided higher evaluation scores, reflecting a positive reception of the AR content
Males showed more varied improvements, with some not correcting initial wrong answers. Their evaluation scores were lower in areas like perceived usefulness and the likelihood of recommending the experience, indicating a less impactful learning experience. Females tended to score higher on the usefulness of the experience, while males were slightly more variable in their engagement and learning scores. This could suggest that females found AR more practical and applicable, while males had mixed reactions.

D.1.3 Nationality

In MR tests, German and Canadian participants showed consistent improvements across all questions, particularly in Q1 and Q2, reflecting strong learning outcomes. Their evaluation scores were also high, suggesting that these participants found the MR experience highly engaging and educational. They scored high in terms of engagement and connection to whales (scores of 6-7), which could be related to their national context and possibly more familiarity or interest in environmental issues Portuguese participants were more variable, with less consistent improvements, indicating potential cultural or language barriers. Their evaluation scores were slightly lower, particularly in the areas of understanding and usefulness. Indicating either less engagement or more challenges in using the technology.
In VR tests, participants displayed strong learning outcomes, with many transitioning from wrong to correct answers across most questions. Their evaluation scores were higher on engagement and learning outcomes, indicating that they found the VR experience to be effective in communicating the content. Portuguese participants, however, had more mixed results, with some not changing incorrect answers, which was reflected in lower evaluation scores, particularly in perceived difficulty and understanding, but with some scoring very high in certain aspects (like interest and importance).
In AR tests, Spanish and German participants showed significant improvements in Q1 and Q2, with most participants correcting their initial wrong answers. Their evaluation scores were high, with many scoring 6-7 on the evaluation questions, indicating a strong engagement with the AR content. Portuguese participants were more variable in their results, and this was reflected in their evaluation scores, which were lower in areas like perceived usefulness and overall engagement with the AR experience.

D.1.4 Family and Couples Dynamics

In both MR and AR groups, family members or couples often showed similar learning outcomes, indicating that shared experiences in these immersive environments might reinforce learning through discussion and mutual support. For instance, in the AR group, a group from Spain both improved their answers in Q2 and Q3, suggesting that the shared experience helped reinforce correct information. Their evaluation scores were also aligned, showing that they found the experience both interesting and useful. In MR, a similar pattern was observed among Canadian participants who were part of a family group, indicating that shared experiences might help reinforce learning through discussion or mutual support. This could imply that shared experiences in immersive technology can amplify certain responses, either positively or negatively, depending on the group's dynamics.

D.2 Influence of Demographics on Learning and Evaluation Outcomes

When analysing the results between different ages, younger participants (12-14 years) generally showed strong improvements in MR and AR, shifting from incorrect to correct answers more consistently. This suggests that these technologies were particularly effective learning tools for this age group, as reflected in their high evaluation scores which demonstrated more comfort with the technology across all three platforms (MR, VR, AR), resulting in higher engagement and learning scores. However, in VR, younger participants were less consistent in improving their answers, indicating potential challenges with the format, as reflected in their lower scores in understanding and usefulness. Older participants, while varied, often found the experiences more challenging, particularly in VR, where the scores indicated some difficulty in use.
About the differences between gender results, Females across all groups demonstrated more consistent learning outcomes and provided higher evaluation scores, as they generally rated the experiences as more emotionally engaging and relevant, generally rated the experiences as more emotionally engaging and relevant,particularly in MR and AR. This suggests that

these immersive technologies were particularly effective for female participants in terms of engagement and knowledge retention. Males showed more variability in their learning outcomes and generally provided lower evaluation scores, particularly in VR, suggesting that they may have found certain aspects of the experiences less engaging or harder to understand, often scoring lower on emotional connection but similar on other practical aspects like usefulness.

Taking into account the participants nationality, German participants consistently showed strong learning outcomes across all groups, reflected in their high evaluation scores, particularly in MR and AR. This suggests that their cultural or educational background may have supported effective learning in immersive environments and likely reflecting cultural or educational backgrounds that emphasize environmental awareness. Portuguese and Spanish participants were more variable, with some not correcting their initial answers, which was reflected in lower evaluation scores, particularly in understanding and usefulness, , possibly indicating differences in familiarity with the technology or content.

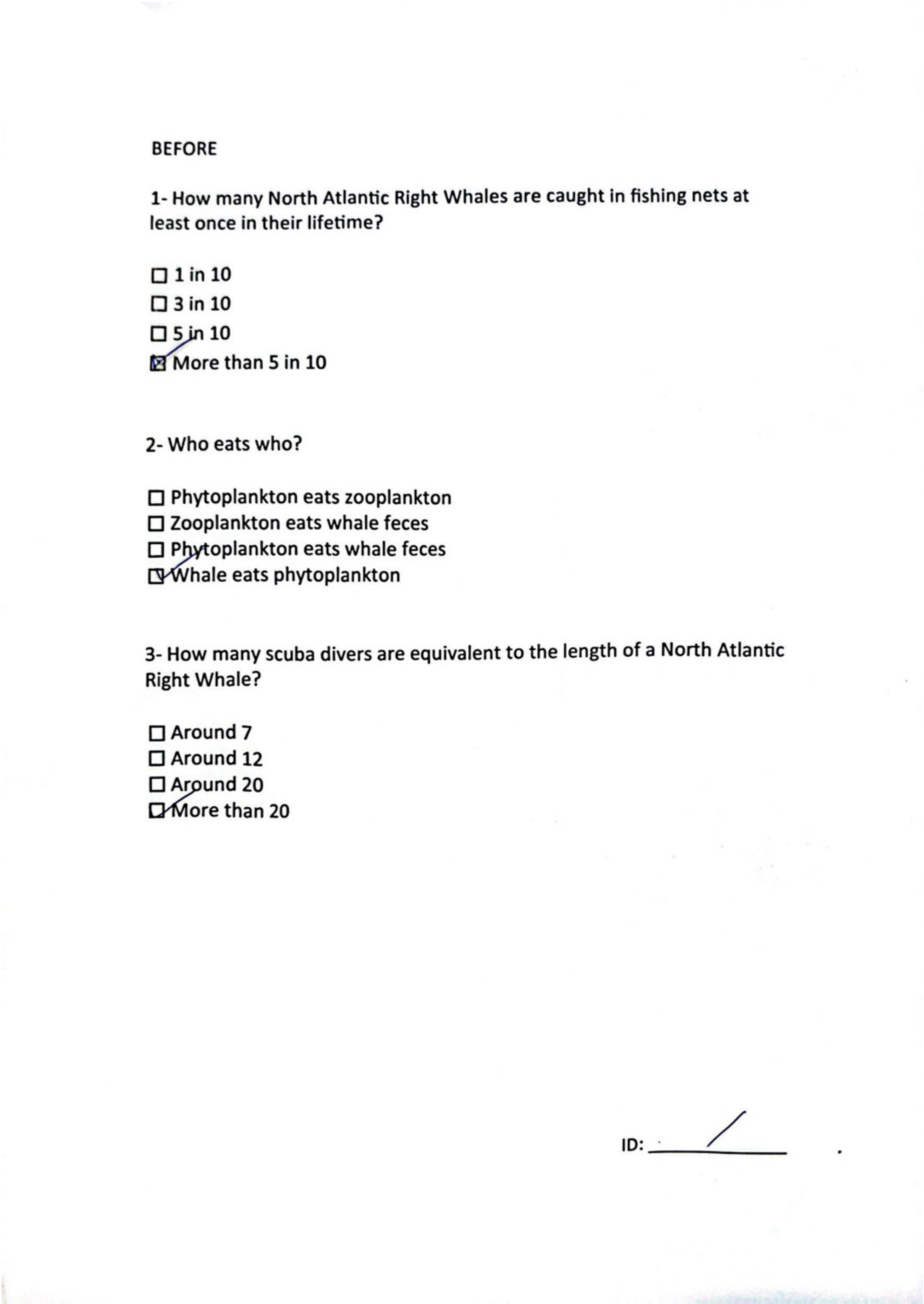
The data also suggests that family members or couples who participated together often had similar learning outcomes and evaluation scores. This indicates that shared experiences in immersive environments can enhance learning, likely through discussion and mutual support. This was particularly evident in the AR and MR groups, where family members showed aligned improvements and positive evaluation scores. The influence of shared experiences was evident, particularly in family groups, where similar scores suggested mutual reinforcement of perceptions. This dynamic can be important in understanding how group experiences in immersive environments might differ from individual ones, potentially affecting the overall results and interpretations.

This demographic analysis not only highlights the diversity of the participant pool but also provides a context for interpreting the results, understanding the different ways that demographics can influence engagement, learning, and interaction with immersive technologies.

E Appendix

E.1 Questionnaire

E.1.1 Questionnaire in English



BEFORE

1- How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime?

☐ 1 in 10
☐ 3 in 10
☐ 5 in 10
☒ More than 5 in 10

2- Who eats who?

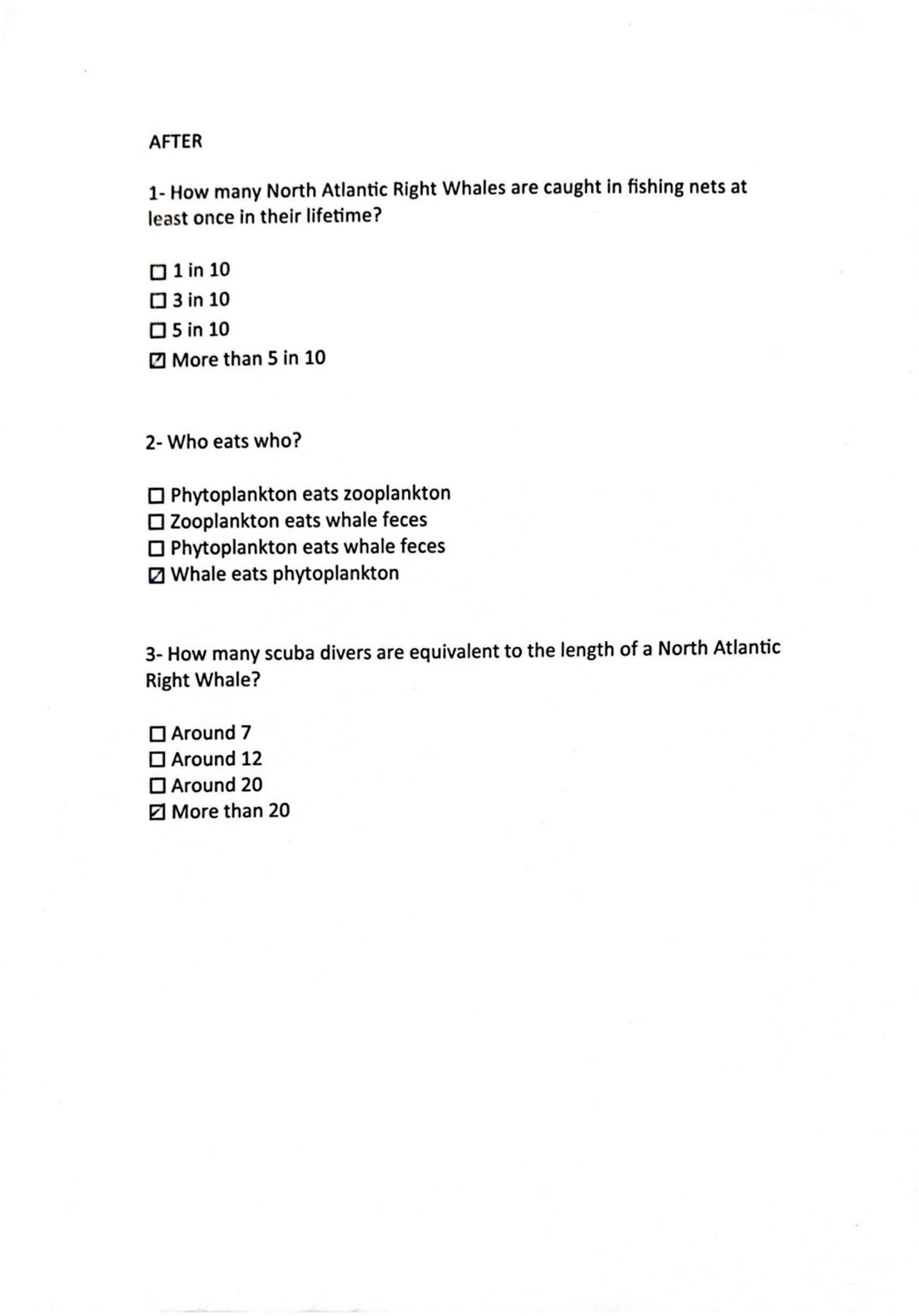
☐ Phytoplankton eats zooplankton
☐ Zooplankton eats whale feces
☐ Phytoplankton eats whale feces
☑ Whale eats phytoplankton

3- How many scuba divers are equivalent to the length of a North Atlantic Right Whale?

☐ Around 7
☐ Around 12
☐ Around 20
☑ More than 20

ID: /

Fig. 59: An example of the front page of the questionnaire in english, the Before questions are presented.



AFTER

1- How many North Atlantic Right Whales are caught in fishing nets at least once in their lifetime?

☐ 1 in 10
☐ 3 in 10
☐ 5 in 10
☑ More than 5 in 10

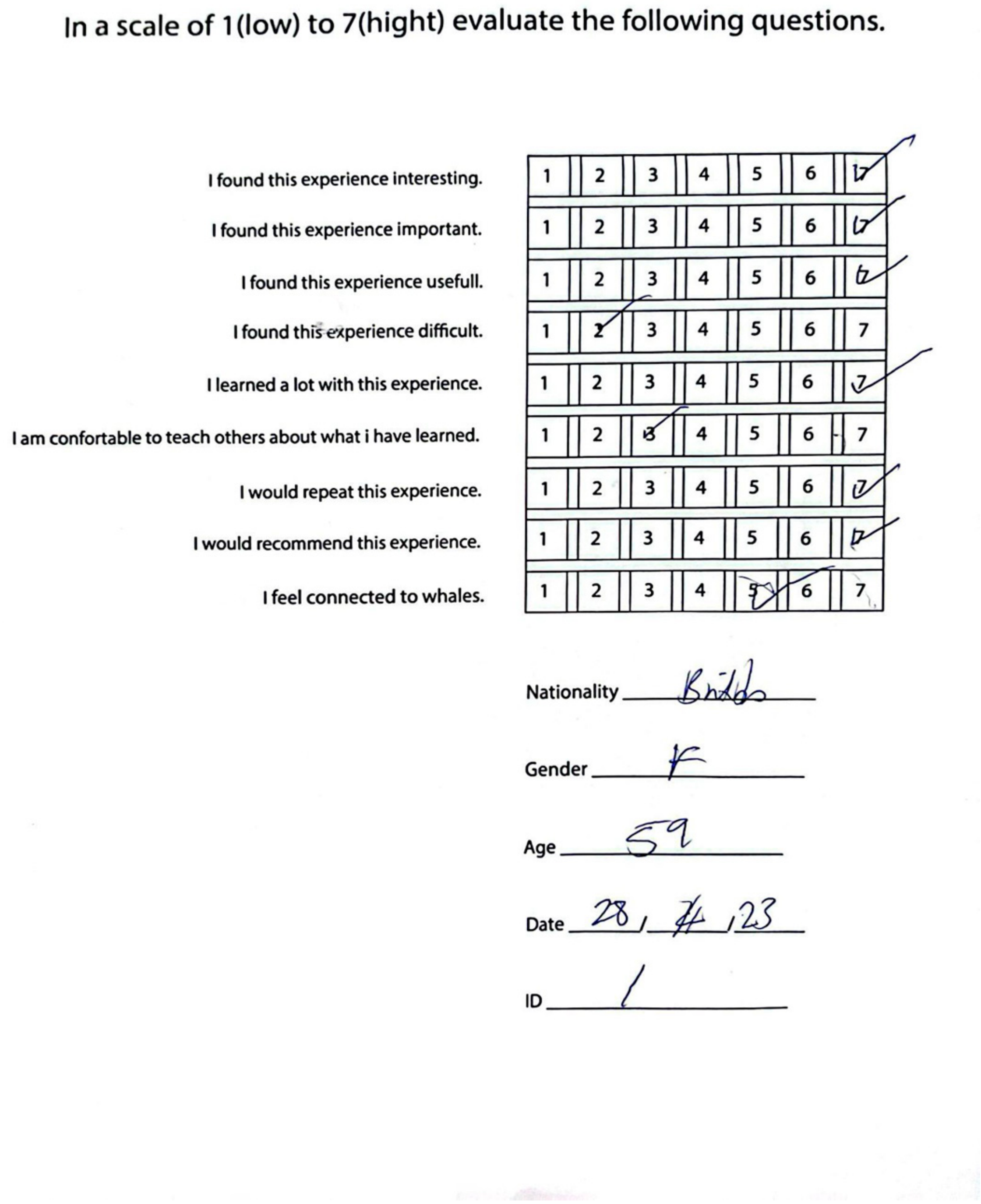
2- Who eats who?

☐ Phytoplankton eats zooplankton
☐ Zooplankton eats whale feces
☐ Phytoplankton eats whale feces
☑ Whale eats phytoplankton

3- How many scuba divers are equivalent to the length of a North Atlantic Right Whale?

☐ Around 7
☐ Around 12
☐ Around 20
☑ More than 20

Fig. 60: An example of the second page of the questionnaire in english, the After questions are presented.



In a scale of 1(low) to 7(hight) evaluate the following questions.

I found this experience interesting.	1	2	3	4	5	6	[✓ 7]
I found this experience important.	1	2	3	4	5	6	[✓ 7]
I found this experience usefull.	1	2	3	4	5	6	[✓ 7]
I found this experience difficult.	1	[✓ 2]	3	4	5	6	7
I learned a lot with this experience.	1	2	3	4	5	6	[✓ 7]
I am confortable to teach others about what i have learned.	1	2	[✓ 3]	4	5	6	7
I would repeat this experience.	1	2	3	4	5	6	[✓ 7]
I would recommend this experience.	1	2	3	4	5	6	[✓ 7]
I feel connected to whales.	1	2	3	4	[✓ 5]	6	7

Nationality British

Gender F

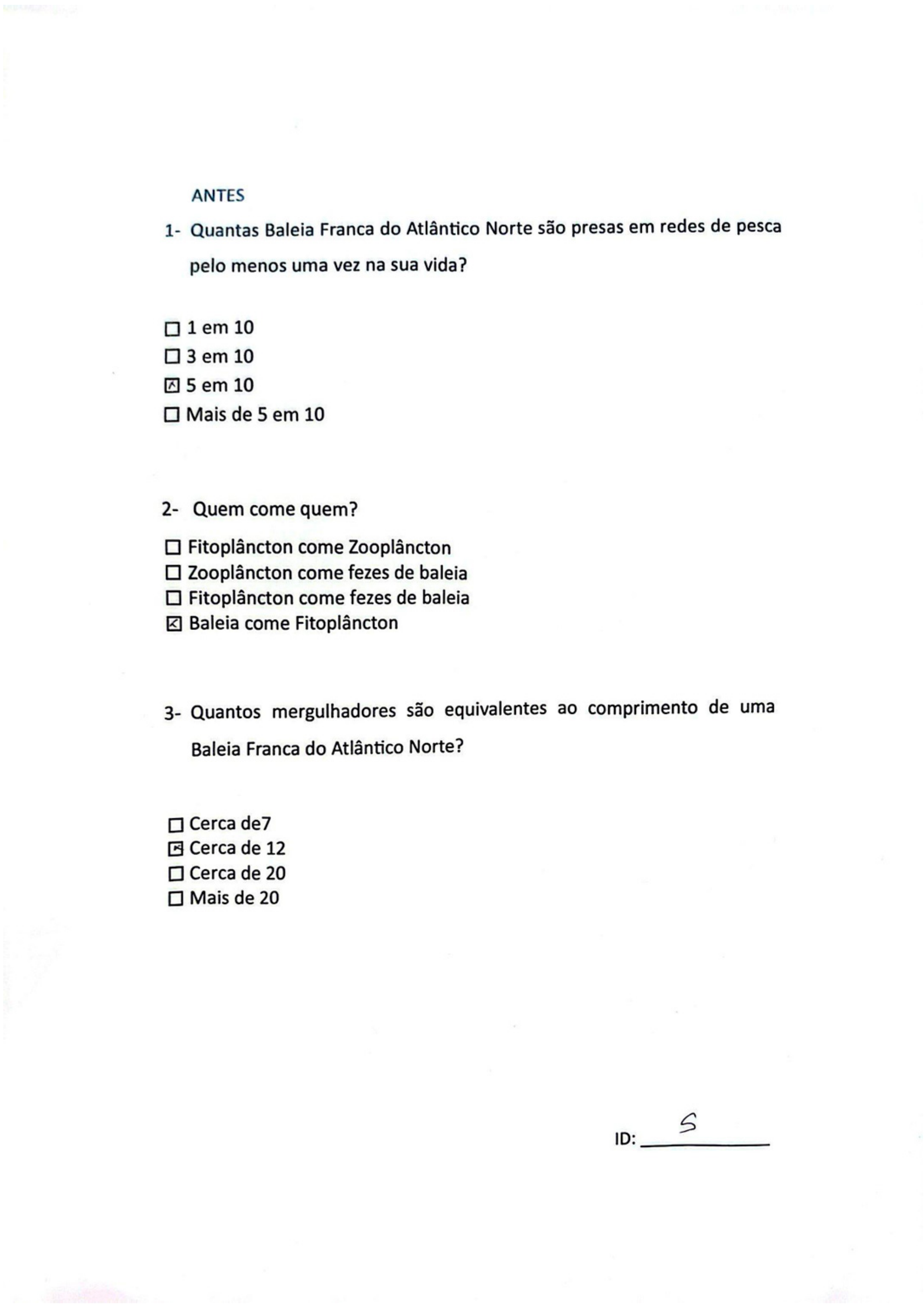
Age 59

Date 28/4/23

ID 1

Fig. 61: An example of the last page of the questionnaire in english, the Evaluation questions are presented.

E.1.2 Questionnaire in Portuguese



ANTES

1- Quantas Baleia Franca do Atlântico Norte são presas em redes de pesca pelo menos uma vez na sua vida?

☐ 1 em 10
☐ 3 em 10
☒ 5 em 10
☐ Mais de 5 em 10

2- Quem come quem?

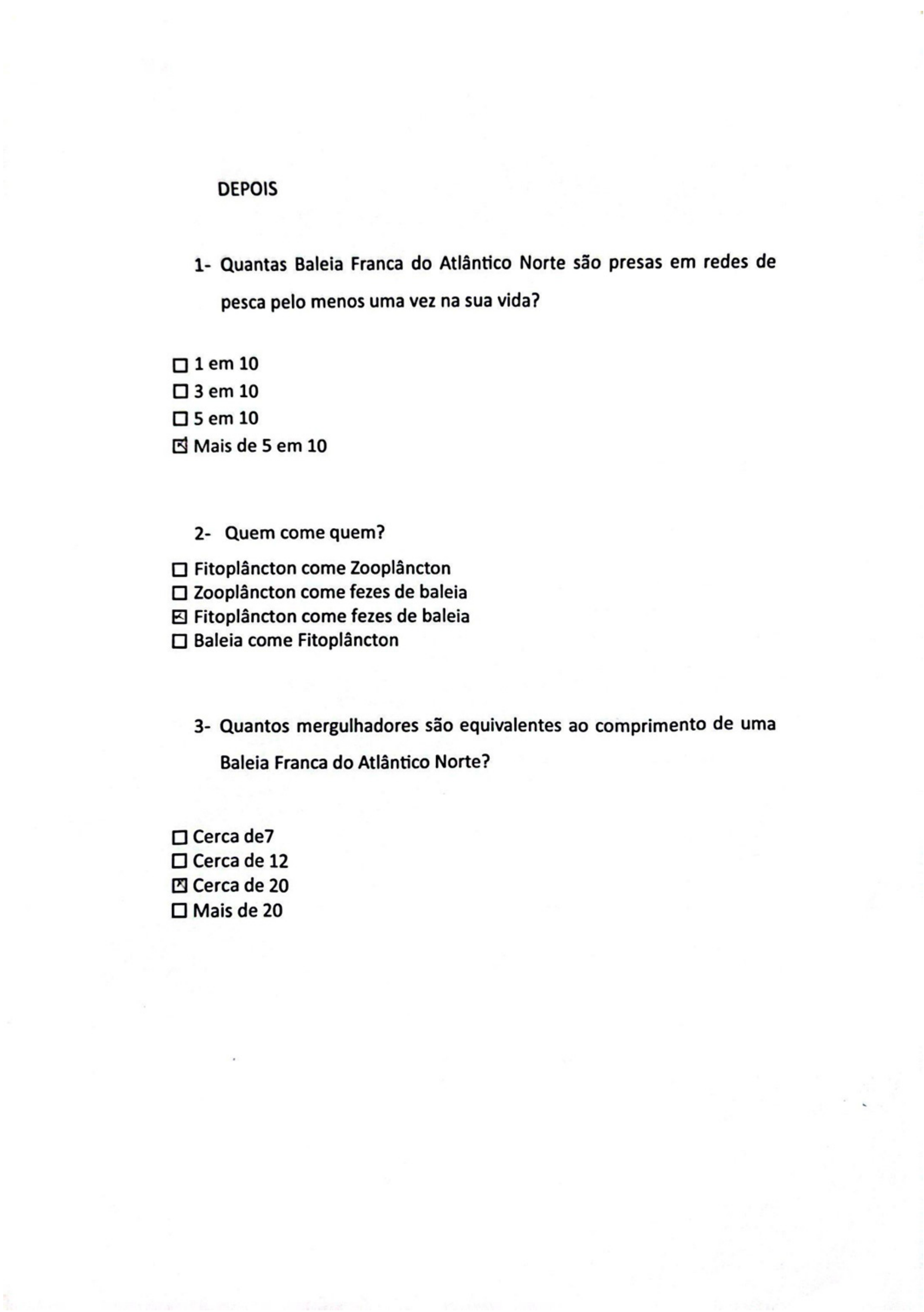
☐ Fitoplâncton come Zooplâncton
☐ Zooplâncton come fezes de baleia
☐ Fitoplâncton come fezes de baleia
☒ Baleia come Fitoplâncton

3- Quantos mergulhadores são equivalentes ao comprimento de uma Baleia Franca do Atlântico Norte?

☐ Cerca de7
☒ Cerca de 12
☐ Cerca de 20
☐ Mais de 20

ID: S

Fig. 62: An example of the front page of the questionnaire in portuguese, the Before questions are presented.



DEPOIS

1- **Quantas Baleia Franca do Atlântico Norte são presas em redes de pesca pelo menos uma vez na sua vida?**

☐ 1 em 10
☐ 3 em 10
☐ 5 em 10
☒ Mais de 5 em 10

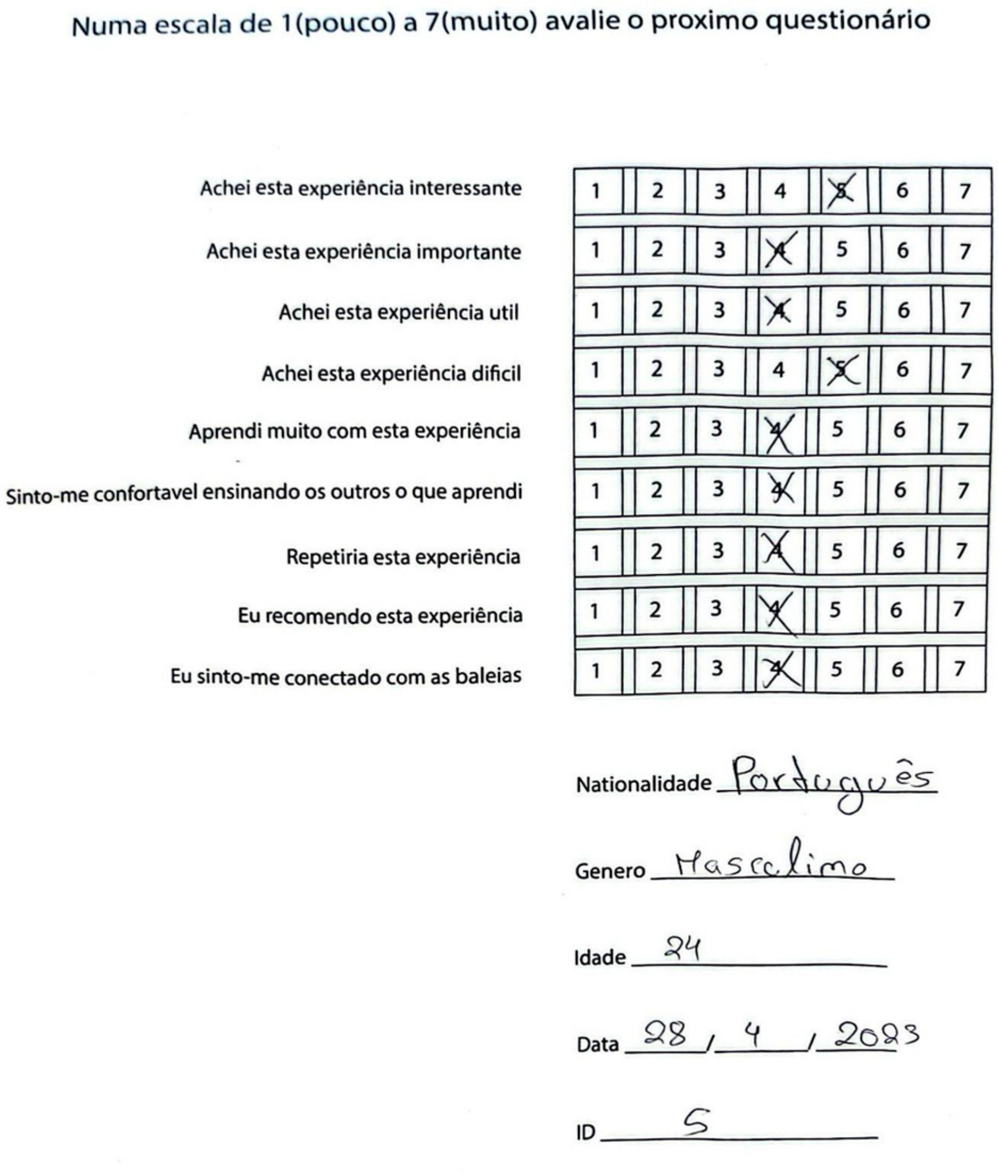
2- **Quem come quem?**

☐ Fitoplâncton come Zooplâncton
☐ Zooplâncton come fezes de baleia
☒ Fitoplâncton come fezes de baleia
☐ Baleia come Fitoplâncton

3- **Quantos mergulhadores são equivalentes ao comprimento de uma Baleia Franca do Atlântico Norte?**

☐ Cerca de7
☐ Cerca de 12
☒ Cerca de 20
☐ Mais de 20

Fig. 63: An example of the second page of the questionnaire in portuguese, the After questions are presented.



Numa escala de 1(pouco) a 7(muito) avalie o proximo questionário

Achei esta experiência interessante	1	2	3	4	[✓ 5]	6	7
Achei esta experiência importante	1	2	3	[✓ 4]	5	6	7
Achei esta experiência util	1	2	3	[✓ 4]	5	6	7
Achei esta experiência dificil	1	2	3	4	[✓ 5]	6	7
Aprendi muito com esta experiência	1	2	3	[✓ 4]	5	6	7
Sinto-me confortavel ensinando os outros o que aprendi	1	2	3	[✓ 4]	5	6	7
Repetiria esta experiência	1	2	3	[✓ 4]	5	6	7
Eu recomendo esta experiência	1	2	3	[✓ 4]	5	6	7
Eu sinto-me conectado com as baleias	1	2	3	[✓ 4]	5	6	7

Nationalidade Português

Genero Masculino

Idade 24

Data 28 / 4 / 2023

ID 5

Fig. 64: An example of the last page of the questionnaire in portuguese, the Evaluation questions are presented.

Bibliography

[1] Sun Joo Ahn, Joshua Bostick, Elise Ogle, Kristine L Nowak, Kara T McGillicuddy, and Jeremy N Bailenson. Experiencing nature: Embodying animals in immersive virtual environments increases inclusion of nature in self and involvement with nature. *Journal of Computer-Mediated Communication*, 21(6):399–419, 2016.

[2] María Belén Argüelles, Mariano Coscarella, Ana Fazio, and Marcelo Bertellotti. Impact of whale-watching on the short-term behavior of southern right whales (eubalaena australis) in patagonia, argentina. *Tourism Management Perspectives*, 18:118–124, 2016.

[3] WWL Au and M Green. Acoustic interaction of humpback whales and whale-watching boats. *Marine Environmental Research*, 49(5):469–481, 2000.

[4] Veronique S Ávila-Foucat, A Sánchez Vargas, A Frisch Jordan, and OM Ramírez Flores. The impact of vessel crowding on the probability of tourists returning to whale watching in banderas bay, mexico. *Ocean & coastal management*, 78:12–17, 2013.

[5] Abdelkader Bellarbi, Christophe Domingues, Samir Otmane, Samir Benbelkacem, and Alain Dinis. Augmented reality for underwater activities with the use of the dolphyn. In *2013 10th IEEE International Conference on Networking, Sensing and Control (ICNSC)*, pages 409–412. IEEE, 2013.

[6] Charles Benton, Robert Nitzel, and Tom Zysk. Merging ocean/maritime models and arctic operations using mission planning toolkits and augmented reality. In *OCEANS 2008*, pages 1–6. IEEE, 2008.

[7] Giovanna Bertella. Experiencing nature in animal-based tourism. *Journal of outdoor recreation and tourism*, 14:22–26, 2016.

[8] Johannes Blum, Christoph Rockstroh, and Anja S Göritz. Heart rate variability biofeedback based on slow-paced breathing with immersive virtual reality nature scenery. *Frontiers in Psychology*, 10:2172, 2019.

[9] Tara J Brigham. Reality check: basics of augmented, virtual, and mixed reality. *Medical reference services quarterly*, 36(2):171–178, 2017.

[10] Matthew HEM Browning, Katherine J Mimnaugh, Carena J van Riper, Heidemarie K Laurent, and Steven M LaValle. Can simulated nature support mental health? comparing short, single-doses of 360-degree nature videos in virtual reality with the outdoors. *Frontiers in psychology*, 10:2667, 2020.

[11] Fabio Bruno, Loris Barbieri, Marino Mangeruga, Marco Cozza, Antonio Lagudi, Jan Čejka, Fotis Liarokapis, and Dimitrios Skarlatos. Underwater augmented reality for improving the diving experience in submerged archaeological sites. *Ocean Engineering*, 190:106487, 2019.

[12] John Bucher. *Storytelling for virtual reality: methods and principles for crafting immersive narratives.* Taylor & Francis, 2017.

[13] Licia Calvi, Carlos P Santos, Joey Relouw, Bojan Endrovski, Chris Rothwell, Antonio Sarà, Serena Lucrezi, Marco Palma, and Ubaldo Pantaleo. A vr game to teach underwater sustainability while diving. In *2017 Sustainable Internet and ICT for Sustainability (SustainIT)*, pages 1–4. IEEE, 2017.

[14] Yu-Lien Chang and Chia-Ling Tien. Development of mobile augmented-reality and virtual-reality simulated training systems for marine ecology education. In *The 24th International Conference on 3D Web Technology*, pages 1–3, 2019.

[15] Ge Chen, Bo Li, Fenglin Tian, Pengbo Ji, and Wenqing Li. Design and implementation of a 3d ocean virtual reality and visualization engine. *Journal of Ocean University of China*, 11(4):481–487, 2012.

[16] Chientzu Candace Chou and Daniel A Hoisington. Promises and constraints of virtual reality integration: Perceptions from pre-service teachers and k-12 students. In *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)*, pages 361–363. IEEE, 2018.

[17] Andrés M Cisneros-Montemayor, Ussif Rashid Sumaila, Kristin Kaschner, and David Pauly. The global potential for whale watching. *Marine Policy*, 34(6):1273–1278, 2010.

[18] Sharon Coen, Ian Drumm, and Stefania Fantinelli. Promoting pro-environmental behaviour through augmented reality and persuasive informational power: a pilot study. *Human Affairs*, 29(3):339–351, 2019.

[19] Coldplay. Coldplay - upup (official video), 2016. Accessed: 2024-05-05.

[20] Raphael Costa. *Aquatic Virtual Reality: From Feasibility to Application.* PhD thesis, The University of Texas at San Antonio, 2020.

[21] Raphael Costa, Rongkai Guo, and John Quarles. Towards usable underwater virtual reality systems. In *2017 IEEE Virtual Reality (VR)*, pages 271–272. IEEE, 2017.

[22] Eleanor Cranmer, Timothy Jung, A Miller, et al. Implementing augmented reality to increase tourist attraction sustainability. 2016.

[23] Paul A Cunningham, Edward H Huijbens, and Stephen L Wearing. From whaling to whale watching: examining sustainability and cultural rhetoric. *Journal of Sustainable Tourism*, 20(1):143–161, 2012.

[24] Susanna Curtin. Wildlife tourism: The intangible, psychological benefits of human–wildlife encounters. *Current Issues in Tourism*, 12(5-6):451–474, 2009.

[25] Susanna Curtin and Gitte Kragh. Wildlife tourism: Reconnecting people with nature. *Human dimensions of wildlife*, 19(6):545–554, 2014.

[26] Ryan DeMares. Human peak experience triggered by encounters with cetaceans. *Anthrozoös*, 13(2):89–103, 2000.

[27] Roman Egger and Larissa Neuburger. Augmented, virtual, and mixed reality in tourism. *Handbook of e-Tourism*, pages 1–25, 2020.

[28] Níels Einarsson. From good to eat to good to watch: whale watching, adaptation and change in icelandic fishing communities. *Polar Research*, 28(1):129–138, 2009.

[29] engagevr. Magic leap magnopus whale demo, 2019. Accessed: 2024-05-05.

[30] eyeSphere. Augmented reality whale (arkit), 2018. Accessed: 2024-05-05.

[31] Geraldine Fauville, Jeremy N Bailenson, and Anna Carolina Muller Queiroz. Virtual reality as a promising tool to promote climate change awareness. *Technology and Health*, pages 91–108, 2020.

[32] Géraldine Fauville, Anna CM Queiroz, Linda Hambrick, Bryan A Brown, and Jeremy N Bailenson. Participatory research on using virtual reality to teach ocean acidification: a study in the marine education community. *Environmental education research*, pages 1–25, 2020.

[33] News Flare. Giant whale jumps out of nowhere - incredibly close whale encounters!, 2019. Accessed: 2024-05-05.

[34] Robert G Franklin Jr, Anthony J Nelson, Michelle Baker, Joseph E Beeney, Theresa K Vescio, Aurora Lenz-Watson, and Reginald B Adams Jr. Neural responses to perceiving suffering in humans and animals. *Social neuroscience*, 8(3):217–227, 2013.

[35] Martina R Fröschl. Computer-animated scientific visualizations in the immersive art installation noise aquarium. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 183–187. IEEE, 2020.

[36] Thomas Fuchs. The virtual other: empathy in the age of virtuality. *Journal of Consciousness Studies*, 21(5-6):152–173, 2014.

[37] Bandage G. Abzu actual vr, 2016. Accessed: 2024-05-05.

[38] VR game 1809. Vr-subnautica5(google cardboard,vr box,vr, 2019. Accessed: 2024-05-05.

[39] Brian Garrod and David A Fennell. An analysis of whalewatching codes of conduct. *Annals of Tourism Research*, 31(2):334–352, 2004.

[40] Lukas Gruber, Denis Kalkofen, and Dieter Schmalstieg. Color harmonization for augmented reality. In *2010 IEEE International Symposium on Mixed and Augmented Reality*, pages 227–228. IEEE, 2010.

[41] Dai-In Han, Timothy Jung, and Alex Gibson. Dublin ar: implementing augmented reality in tourism. In *Information and communication technologies in tourism 2014*, pages 511–523. Springer, 2013.

[42] Wei-Che Hsu, Ching-Mei Tseng, and Shih-Chung Kang. Using exaggerated feedback in a virtual reality environment to enhance behavior intention of water-conservation. *Journal of Educational Technology & Society*, 21(4):187–203, 2018.

[43] Olivier Hugues, Jean-Marc Cieutat, and Pascal Guitton. An experimental augmented reality platform for assisted maritime navigation. In *Proceedings of the 1st Augmented Human International Conference*, pages 1–6, 2010.

[44] Ibrews. Magic leap's newest experience "undersea" - some thoughts, 2019. Accessed: 2024-05-05.

[45] Indestry. Orca in a shopping mall: Ocean adventure augmented reality experience by inde at allee budapest, 2016. Accessed: 2024-05-05.

[46] Dhruv Jain, Misha Sra, Jingru Guo, Rodrigo Marques, Raymond Wu, Justin Chiu, and Chris Schmandt. Immersive terrestrial scuba diving using virtual reality. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 1563–1569, 2016.

[47] Joen and Amalie. Incredible whale watching experience madeira has it all!, 2020. Accessed: 2024-05-05.

[48] Arne Kalland. Management by totemization: whale symbolism and the anti-whaling campaign. *Arctic*, pages 124–133, 1993.

[49] Yuki Katsumata, Wataru Yamada, and Hiroyuki Manabe. Optical see-through head-mounted display with deep depth of field using pinhole polarizing plates. In *The Adjunct Publication of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 102–104, 2019.

[50] Behrang Keshavarz. Exploring behavioral methods to reduce visually induced motion sickness in virtual environments. In *International Conference on Virtual, Augmented and Mixed Reality*, pages 147–155. Springer, 2016.

[51] Myung Ja Kim, Choong-Ki Lee, and Timothy Jung. Exploring consumer behavior in virtual reality tourism using an extended stimulus-organism-response model. *Journal of Travel Research*, 59(1):69–89, 2020.

[52] Gudrun Klinker, Didier Stricker, and Dirk Reiners. Augmented reality: A balance act between high quality and real-time constraints. *Mixed Reality–Merging Real and Virtual Worlds, Ohmsha & Springer Verlag*, pages 325–346, 1999.

[53] R de Koeijer. Augmented reality for cultural heritage-comparing a cardboard device with a mobile handheld device in a museum setting. Master's thesis, 2018.

[54] Hollis Kool. The ethics of immersive journalism: A rhetorical analysis of news storytelling with virtual reality technology. *Intersect: The Stanford journal of science, technology, and society*, 9(3), 2016.

[55] Svetlana Krasovskaya. *Innovation study:" Economic contribution of the whale-watching industry for the Madeira Archipelago"*. PhD thesis, 2018.

[56] Andrey Krekhov, Sebastian Cmentowski, Katharina Emmerich, and Jens Krüger. Beyond human: Animals as an escape from stereotype avatars in virtual reality games. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, pages 439–451, 2019.

[57] Andrey Krekhov, Sebastian Cmentowski, and Jens Krüger. Vr animals: Surreal body ownership in virtual reality games. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, pages 503–511, 2018.

[58] Magic Leap. Magic leap virtual reality behold the future, 2021. Accessed: 2024-05-05.

[59] Youngo Lee and Jongmyong Choi. Tideland animal ar: Superimposing 3d animal models to user defined targets for augmented reality game. *International journal of multimedia and ubiquitous engineering*, 9(4):343–348, 2014.

[60] Balqis Lim. Exploring the ocean via augmented reality. *The New Straits Times*, 2019.

[61] Yishuo Liu, Yichuan Zhang, Shiliang Zuo, and Wai-Tat Fu. Boatar: a multi-user augmented-reality platform for boat. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, pages 1–2, 2018.

[62] Yuqi Liu. The application of virtual reality in empathy establishment: Foresee the future. In *2020 5th International Conference on Computational Intelligence and Applications (ICCIA)*, pages 188–193. IEEE, 2020.

[63] Mark A Livingston, Zhuming Ai, J Edward Swan, and Harvey S Smallman. Indoor vs. outdoor depth perception for mobile augmented reality. In *2009 IEEE Virtual Reality Conference*, pages 55–62. IEEE, 2009.

[64] lobosonda. Madeira's best whale watching experience!, 2022. Accessed: 2024-05-05.

[65] lobosonda. Whale watching in madeira, 2022. Accessed: 2024-05-05.

[66] Tiago Lopes and Francisco António dos Santos da Silva. Responsible nature tourism development models: The case study of whale watching in the azores. In *Managing, Marketing, and Maintaining Maritime and Coastal Tourism*, pages 113–131. IGI Global, 2020.

[67] Su-Ju Lu and Ying-Chieh Liu. Integrating augmented reality technology to enhance children's learning in marine education. *Environmental Education Research*, 21(4):525–541, 2015.

[68] Holo Lux. Underwater ar, 2017. Accessed: 2024-05-05.

[69] MaasaiSightings. Whale jumps out of nowhere during sight seeing tour., 2018. Accessed: 2024-05-05.

[70] VMT Madeira. A dream that was born like the sunrise: on the sea. Accessed: 2024-05-05.

[71] Kevin Markwell. *Animals and tourism: Understanding diverse relationships*, volume 67. Channel View Publications, 2015.

[72] Kiki McMillan, Kathie Flood, and Russ Glaeser. Virtual reality, augmented reality, mixed reality, and the marine conservation movement. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27:162–168, 2017.

[73] Nicolas Meurs. Whale in the sky, 2016. Accessed: 2024-05-05.

[74] Cees Midden, Teddy McCalley, Jaap Ham, and Ruud Zaalberg. Using persuasive technology to encourage sustainable behavior. *Sustainability WS Pervasive*, 113:83–86, 2008.

[75] Sean Morey and Jason Crider. Hyperanimals: Inverting nature through pokémon go. *ISLE: Interdisciplinary Studies in Literature and Environment*, 27(2):287–306, 2020.

[76] Sue Muloin. Wildlife tourism: The psychological benefits of whale watching. *Pacific Tourism Review*, 2(3-4):199–213, 1998.

[77] Putu Liza Kusuma Mustika, Alastair Birtles, Yvette Everingham, and Helene Marsh. The human dimensions of wildlife tourism in a developing country: watching spinner dolphins at lovina, bali, indonesia. *Journal of Sustainable Tourism*, 21(2):229–251, 2013.

[78] Alaeddin Nassani. Antarctica marine ar: an augmented reality experience of the ross sea marine protected area. 2019.

[79] Emilie Nicolas. Emilie nicolas - pstereo (official video), 2015. Accessed: 2024-05-05.

[80] Nahal Norouzi, Gerd Bruder, Jeremy Bailenson, and Greg Welch. Investigating augmented reality animals as companions. In *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, pages 400–403. IEEE, 2019.

[81] Benjamin Nuernberger, Eyal Ofek, Hrvoje Benko, and Andrew D Wilson. Snaptoreality: Aligning augmented reality to the real world. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 1233–1244, 2016.

[82] Leif Oppermann, Lisa Blum, Jun-Yeong Lee, and Jung-Hyub Seo. Areef multi-player underwater augmented reality experience. In *2013 IEEE international games innovation conference (IGIC)*, pages 199–202. IEEE, 2013.

[83] Mark Orams. Economic activity derived from whale-based tourism in vava'u, tonga. *Coastal management*, 41(6):481–500, 2013.

[84] Mark B Orams. Historical accounts of human-dolphin interaction and recent developments in wild dolphin based tourism in australasia. *Tourism Management*, 18(5):317–326, 1997.

[85] Karen Oslund. Protecting fat mammals or carnivorous humans? towards an environmental history of whales. *Historical Social Research/Historische Sozialforschung*, pages 63–81, 2004.

[86] C Palestini and A Basso. The photogrammetric survey methodologies applied to low cost 3d virtual exploration in multidisciplinary field. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, 42, 2017.

[87] Susan E Parks, Mark Johnson, Douglas Nowacek, and Peter L Tyack. Individual right whales call louder in increased environmental noise. *Biology letters*, 7(1):33–35, 2011.

[88] Kyle A Pettijohn, Chad Peltier, Jamie R Lukos, and Adams T Biggs. Comparison of virtual reality and augmented reality: safety and effectiveness. Technical report, Naval Medical Research Unit Dayton Wright-Patterson AFB United States, 2019.

[89] Adiyen Poke. Wailmer spotlight hour fast catching pokemon, 2023. Accessed: 2024-05-05.

[90] Adam Kosaka Prueitt, Kyle Cooper Bryant, Michael Raymond Racine, Patrick Lawrence Petersen, and Timothy Steven Bujnevicie. The urban whale: A serious game about the north atlantic right whale, and a template for future endangered species games. 2015.

[91] Antti Revonsuo. Consciousness, dreams and virtual realities. *Philosophical Psychology*, 8(1):35–58, 1995.

[92] Jose Luis Rubio-Tamayo, Manuel Gertrudix Barrio, and Francisco García García. Immersive environments and virtual reality: Systematic review and advances in communication, interaction and simulation. *Multimodal Technologies and Interaction*, 1(4):21, 2017.

[93] Matthew Edward Brannon Russell, Brittney Hoffman, Sarah Stromberg, and Charles R Carlson. Use of controlled diaphragmatic breathing for the management of motion sickness in a virtual reality environment. *Applied psychophysiology and biofeedback*, 39(3-4):269–277, 2014.

[94] JH Ryu. Reality & effect: A cultural history of visual effects. georgia state university, 2007.

[95] Maria V Sanchez-Vives and Mel Slater. From presence to consciousness through virtual reality. *Nature Reviews Neuroscience*, 6(4):332–339, 2005.

[96] Mark Sawicki and Juniko Moody. A brief history of computer graphics. In *Filming the Fantastic with Virtual Technology*, pages 21–58. Routledge, 2020.

[97] Holger Schnädelbach, Boriana Koleva, Martin Flintham, Mike Fraser, Shahram Izadi, Paul Chandler, Malcolm Foster, Steve Benford, Chris Greenhalgh, and Tom Rodden. The augurscope: a mixed reality interface for outdoors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 9–16, 2002.

[98] Alexandra Sierra Rativa, Marie Postma, and Menno Van Zaanen. The influence of game character appearance on empathy and immersion: Virtual non-robotic versus robotic animals. *Simulation & Gaming*, 51(5):685–711, 2020.

[99] Telmo Gonçalves Silva. Xr interfaces for enhancing user engagement and learning in onshore whale-watching, 2025. Accessed: 2025-08-26.

[100] Mel Slater and Maria V Sanchez-Vives. Enhancing our lives with immersive virtual reality. *Frontiers in Robotics and AI*, 3:74, 2016.

[101] Anne R Smink, Sanne Frowijn, Eva A van Reijmersdal, Guda van Noort, and Peter C Neijens. Try online before you buy: How does shopping with augmented reality affect brand responses and personal data disclosure. *Electronic Commerce Research and Applications*, 35:100854, 2019.

[102] Holly Smith, Amy Samuels, and Stuart Bradley. Reducing risky interactions between tourists and free-ranging dolphins (tursiops sp.) in an artificial feeding program at monkey mia, western australia. *Tourism management*, 29(5):994–1001, 2008.

[103] Andrew H Stevens and Thomas Butkiewicz. Reducing seasickness in onboard marine vr use through visual compensation of vessel motion. In *2019 IEEE conference on virtual reality and 3D user interfaces (VR)*, pages 1872–1873. IEEE, 2019.

[104] Wolfgang Stuerzlinger and Chadwick A Wingrave. The value of constraints for 3d user interfaces. In *Virtual Realities*, pages 203–223. Springer, 2011.

[105] J Edward Swan, Adam Jones, Eric Kolstad, Mark A Livingston, and Harvey S Smallman. Egocentric depth judgments in optical, see-through augmented reality. *IEEE transactions on visualization and computer graphics*, 13(3):429–442, 2007.

[106] Aaron Tkaczynski and Sharyn Rundle-Thiele. Identifying whale-watching tourist differences to maximize return on investment. *Journal of Vacation Marketing*, 25(3):390–402, 2019.

[107] Yueh-Feng Tsai and David Kaufman. Interacting with a computer-simulated pet: Factors influencing children's humane attitudes and empathy. *Journal of Educational Computing Research*, 51(2):145–161, 2014.

[108] Iis P Tussyadiah, Dan Wang, Timothy H Jung, and M Claudia tom Dieck. Virtual reality, presence, and attitude change: Empirical evidence from tourism. *Tourism Management*, 66:140–154, 2018.

[109] Antonio Vasiljević, Bruno Borović, and Zoran Vukić. Augmented reality in marine applications. *Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike*, 62(2):136–142, 2011.

[110] VisitMadeiraOfficial. Dolphins and whales watching - madeira islands, 2021. Accessed: 2024-05-05.

[111] AirPano VR. Underwater life, marsa alam, egypt. 360 video in 8k, 2023. Accessed: 2024-05-05.

[112] Azores Whale Watching. Whale watching azores islands, 2021. Accessed: 2024-05-05.

[113] wevrtransport. Underwater life, marsa alam, egypt. 360 video in 8k, 2022. Accessed: 2024-05-05.

[114] Rob Williams, Andrew W Trites, and David E Bain. Behavioural responses of killer whales (orcinus orca) to whale-watching boats: Opportunistic observations and experimental approaches. *Journal of Zoology*, 256(2):255–270, 2002.

[115] Mario Martínez Zarzuela, Francisco J Díaz Pernas, Leire Barroso Martínez, David González Ortega, and Miriam Antón Rodríguez. Mobile serious game using augmented reality for supporting children's learning about animals. *Procedia computer science*, 25:375–381, 2013.

[116] Xin-hua Zhao, Yao Sun, and ZZ Lu. Virtual simulation of submarine motion in virtual ocean environment. *Journal of System Simulation*, 18(SUPPL. 1):226–229, 2006.