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Original Article

A VR-Based Learning Environment for Teaching Coral Reef Ecology to Junior High School Students

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Abstract - *This study presents a Collaborative Virtual Reality Learning Environment (CVLE) on coral reef ecosystems, designed for junior high school students to learn through hands-on experience (Learning by doing). The proposed system uses Virtual Reality technology (VR) for the purpose of developing a supplementary learning tool, experienced through the Oculus Quest 2. This VR-based learning system uses Game-Based Learning (GBL) through a mission system, developed with the Unity game engine and Normcore SDK to support collaborative interaction via voice chat. The learning scenario begins with an exploration of organism characteristics, followed by completing three mission levels while observing the ecosystem dynamics. The system features agent-to-agent interactions among organisms, allowing users to observe biological changes and comprehend the roles and relationships of organisms. The results revealed that system usage had a statistically significant impact on participants' scores (p = 0.0137). Additionally, the VR application rendered at a frame rate of 45 to 70 fps, which is sufficient for system usage. Participants expressed high satisfaction regarding both system usability (4.06/5) and value for specific tasks (4.21/5), with scores ranging from 4 to 5, confirming the system's effectiveness for the target users. Participants agreed that this proposed system was beneficial in helping to enhance their understanding of the roles and relationships of organisms, and they enjoyed the learning experience.*

Keywords - *Virtual Reality, Collaborative learning, Coral reef ecosystem, Game-Based Learning, Educational technology.*

1. Introduction

Science subjects, especially those related to ecosystems, are complex and dynamic, requiring visualization to understand. Learning by doing is key to retention and the creation of lasting knowledge. Edgar Dale's Cone of experience has shown that hands-on experience enhances learning and retention more effectively than symbolic information [1]. This active learning allows learners to build understanding from real-world experience and concretely connect concepts.

However, ecosystem topics present unique challenges due to their abstract nature and complex relationships, which are difficult to grasp solely through classroom instruction. Furthermore, marine ecosystems have limitations regarding accessibility to the actual environment, as Markowitz et al. (2018) noted that these limitations in both visualization and distance can be overcome by using Virtual Reality (VR) technology to simulate the underwater world [2]. This helps learners engage in a safe and realistic simulation.

In the context of science education in Thailand, especially at the junior high school level, the teaching of such complex content still focuses on lectures and uses the two-dimensional media from textbooks [3]. While this method covers curriculum content, it may limit learners' opportunities to form clear mental models of ecosystem interactions and lack engagement with the subject directly. This leads to the need to develop innovative supplementary learning tools to bridge this gap and promote more effective learning.

While a substantial body of research has emerged concerning Virtual Reality (VR)-based science education, Haozhe Jiang et al. (2025) recent review indicates that extant studies predominantly concentrate on higher education and elementary school settings, or they encompass broad STEM subjects [4].

Although junior high school has been the subject of some VR research, there persists a need for immersive learning tools specifically designed for the unique curricula and intricate content pertinent to this age group, exemplified by coral reef ecology.

Furthermore, existing educational programs and extended reality applications focused on marine ecology are frequently developed for general awareness initiatives, rather than being formally incorporated into K-12 curricula [5].

Recent research significantly highlights a limitation in that most existing VR educational tools tend to isolate learners, focusing primarily on individual learning experiences [6]. Although full co-learning environments can help mitigate social isolation, they may simultaneously introduce cognitive overload for learners.

Therefore, there remains a demand for lightweight peer-support mechanisms, such as real-time consultation by voice chat, that foster collaboration without overwhelming individual learners.

To address these limitations and advance beyond previous isolated VR tools, this research developed a Virtual Reality (VR) learning system focusing on coral reef ecosystems. This system is intended as a supplementary learning tool for junior high school students. The proposed system does not focus solely on entertainment via game elements (Game-based learning) but provides learners with the opportunity for "Learning by Doing" in a virtual environment that safely simulates a marine ecosystem for exploration without having to travel to a physical location.

Learners can also exchange knowledge and discuss with teammates through voice chat, promoting collaborative learning and enhancing their understanding of complex content. In this study, "collaborative" is defined as lightweight peer-supported exploration facilitated through real-time voice chat, rather than full cooperative task completion.

2. Related Works

2.1. Immersive Technologies: Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)

Immersive technologies offer new ways for humans to interact with digital information and environments. The primary technologies in this group include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), each possessing distinct characteristics and applications, as detailed in the following Table1.

To develop a supplementary instructional medium on coral reef ecosystems for junior high school students, this study chose to utilize Virtual Reality (VR) technology. This choice was made because it aligns with the learning objectives of this research in several key ways.

First, VR enables the creation of highly immersive and realistic experiences. Coral reef ecosystems are environments that most students cannot directly access or experience in their daily lives. VR can truly reproduce the intricacies and liveliness of a coral reef, allowing students to feel as though they are diving themselves [7].

Second, VR enables Experiential Learning [2]. In this way, students can learn about the behavior of organisms on the reef and types of corals, and the intricate relationships between different ecosystem components, in this way, because it is experiential learning. This approach is student-centered and helps learners construct their own knowledge (Constructivism).

Table 1. Comparison of key features of VR, AR, and MR technologies

Feature	VR	AR	MR
Core Definition	Digital environment replaces the real world [7]	Digital information overlays the real world [8]	Digital objects merge and interact with the real world [9]
Perception of Real World	Blocked out	Maintained (digitally enhanced)	Maintained (digitally integrated)
Level of Immersion	Very High	Low - Medium	Medium - High
Primary Interaction	Virtual world	Digital info + Real world	Real world + Virtual world
Key Hardware	HMDs (e.g., Oculus Quest, HTC Vive)	Smartphones, Tablets, AR Glasses	MR Headsets (e.g., Microsoft HoloLens)
Educational Application Examples	Simulating complex/ inaccessible scenarios (e.g., surgery, deep-sea diving) [10]	Displaying contextual info on real objects (e.g., historical site data) [11]	3D modeling in real contexts, collaborative tasks with real & virtual objects [12]

Third, VR provides interactivity. Unlike traditional two-dimensional media (e.g., books or videos), learners can navigate their own way through object-containing virtual space. Students can examine small organisms that are normally invisible in real life and trace the food web pathways amongst them directly. This process helps students understand [10] and retain the material. Fourth, VR presents complex content. Ecosystems require environmental components to intermingle closely with living ones. VR can present these various relationships in a three-dimensional way that is easier to understand and more accessible visually than a written description or static images [7]. Through this means, this system helps students form clear mental models of what the roles and relationships are between organisms in a coral reef. Finally, VR offers a controlled learning environment where students are free to explore and experiment without worrying about their own safety or the possible impact on a real-life ecosystem [13].

2.2. VR in Edutainment and Education

The adoption of VR in education is a burgeoning sector with evidence of success. The VR in education market is expected to be worth $31.28 billion USD in 2025 and $81.13 billion USD by 2030, suggesting considerable investment and confidence in this technology [14]. This growth is largely driven by VR's ability to turn passive learning into an active, experiential one. This makes it a powerful tool for science and environmental education, capable of meeting the challenge of teaching complex, abstract, or inaccessible concepts by reproducing complex virtual worlds for learners to explore and interact with. This approach allows for a deeper understanding than traditional education does.

Several key studies show that Virtual Reality (VR) is effective in education [15]. For example, Markowitz [2] found that a Virtual Reality (VR) experience on ocean acidification tended to increase knowledge significantly, while provoking a heightened sense of personal connection and more positive attitudes about engagement with environmental changes. Similarly, a study in [16] comparing a biology lesson in VR with a traditional video evidenced that the VR group outperformed the traditional video group in learning, as well as their positive emotions and engagement.

The success of these studies suggests potential for future applications, especially when it comes to adjusting VR's potential to more specialized ecological and educational contexts. Therefore, the system presented in this study was designed to advance this goal. This research utilizes VR's established advantages to produce educational materials that align with Thailand's core curriculum and specifically target the country's coral reef ecosystems, addressing a specific gap in the creation of VR learning innovations that are relevant to the local context.

2.3. How VR Improves Science Learning

Traditional science education often faces two main problems: students cannot picture abstract concepts, and insufficient equipment, or the experiments are too dangerous. Virtual Reality (VR) can transform difficult things into clear visual experiences, for example, students can virtually walk on Mars, dive into the deep ocean or shrink themselves to look inside a cell. This direct experience helps students understand difficult concepts better than reading books [17, 18]. Virtual Reality (VR) also helps reduce the risks and costs of real-world laboratories. Students can mix dangerous chemicals and conduct experiments as many times as they want in the virtual world without danger and waste valuable materials. This technology creates equal opportunities for all students to access these experiments, regardless of the school's budget [13]. Additionally, realistic environments with game-like elements help to increase student engagement and motivation. Their achievements and understanding improve significantly when students actively participate and enjoy learning [16, 18].

2.4. Critical Reflection

The investigation of existing literature has shown several notable limitations. First, as Lin et al. (2024) pointed out, although VR can effectively contribute to increasing learner engagement and learning outcomes, most of the studies were conducted in higher education or elementary schools, where little literature is available for junior high school learners [15]. Second, most of the VR apps related to marine ecosystems are focused on ocean awareness or general ocean education campaigns rather than integration into formal K-12 curricula. Third, existing VR learning tools focus on individual experiences, which may lead to learners feeling isolated. Moreover, there are a few VR-based science learning tools specifically developed for the Thai educational context. These limitations highlight the need for future research to develop and evaluate VR tools that are curriculum-aligned and localized-a gap this study aims to address

2.5. Comparative Analysis

As described in Table 2, a comparative review of existing VR applications in marine and ecology education reveals several differences between previous studies and the current study. Markowitz et al. (2018) demonstrated that VR-based field trips significantly enhanced knowledge of ocean acidification among higher education students. Similarly, Keith et al. (2026) reported improved engagement and knowledge gains in undergraduate coral reef ecology courses [19]. Fauville et al. (2024) explored underwater VR for marine environmental education, focusing primarily on ocean literacy and public awareness. These studies target higher education students or the public and focus more on ocean awareness than on learning objectives aligned with formal curricula. In contrast, the current study focuses on junior high school students within Thailand's National Science Curriculum, specifically addressing coral reef ecosystem roles. The system uses game-based learning and inquiry-based missions requiring active interaction with the ecosystem, differing from the observation methods found in previous marine VR tools. Furthermore, a lightweight peer collaboration mechanism via voice chat addresses limitations related to social isolation in previous VR learning environments while avoiding the cognitive demands associated with full collaboration tasks.

Table 2. Comparative analysis of similar research

Comparative topics	Previous research	This study
Target group	Higher education/the public	Junior high school
Objective	Ocean awareness	Curriculum-aligned science learning (Thailand)
Interaction	Observation exploration	Game-based learning + missions
Collaboration	Individual	Peer support via voice chat

3. Proposed System

This research presents a Collaborative Virtual Reality Learning Environment (CVLE) for learning coral reef ecosystems as a supplementary learning tool. This system uses Virtual Reality (VR) to simulate the living environment through collaborative learning. The VR application usage scenario of the system is shown in Figure 1. The educational content in the application includes the roles and relationships of organisms living in coral reefs. The system is experienced through the Oculus Quest 2, which is a Head-Mounted Display (HMD) connected to a computer via the Oculus Link, with users to interact with the organisms in the system using touch controllers.

3.1. System Overview

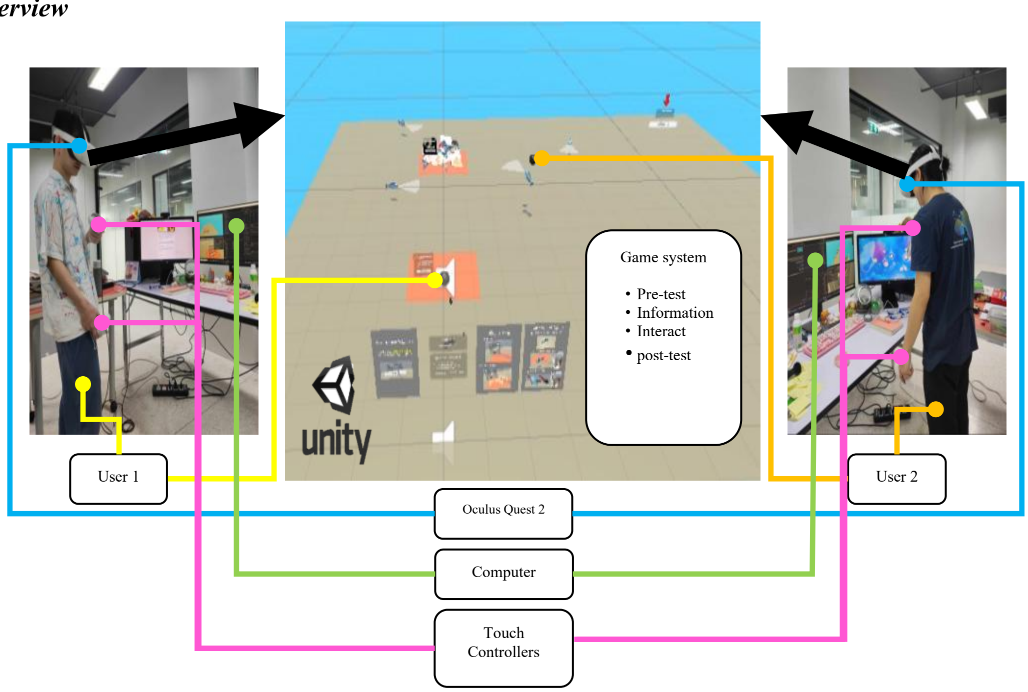

Fig. 1 System overview

The learning environment created in the system is a 3D virtual world that simulates a coral reef ecosystem.

This allows users to explore the area, communicate and consult with teammates, and complete various missions/tasks aligned with assigned learning activities.

The system's main functions include:

- Two types of interaction systems:
  The virtual environment within the system incorporates two distinct interaction patterns: users-to-agent and agent-to-agent interactions. This interactive simulation allows users to observe and understand the dynamics of life firsthand.

- Game-based learning system:
  This system uses the principles of Game-Based Learning (GBL) by structuring learning content into various tasks or missions within the system. This aims to increase motivation and engagement among learners to improve learning outcomes.

- Voice chat with friends:
  The system features a real-time voice chat function for consulting about problems with friends. However, missions/tasks must be completed individually; tasks cannot be delegated to friends.

- Automated Evaluation Module:
  This assessment is designed to measure learning outcomes. Individual pre-test and post-test assessments are conducted to measure knowledge gain. All assessments are performed by the user within the VR environment.

3.2. System Diagram

Figure 2 shows an overview of the system diagram. The process begins at the physical level. This process starts when the user performs a physical action with the VR device. The operating system sends this data to the application level for further processing. Within this level, the Normcore SDK is used to convert the user's state into a Message (msg). This message is transmitted via network protocol to the Normcore server located at the API level. The server is then responsible for broadcasting this update by distributing it to all other clients connected to the session.

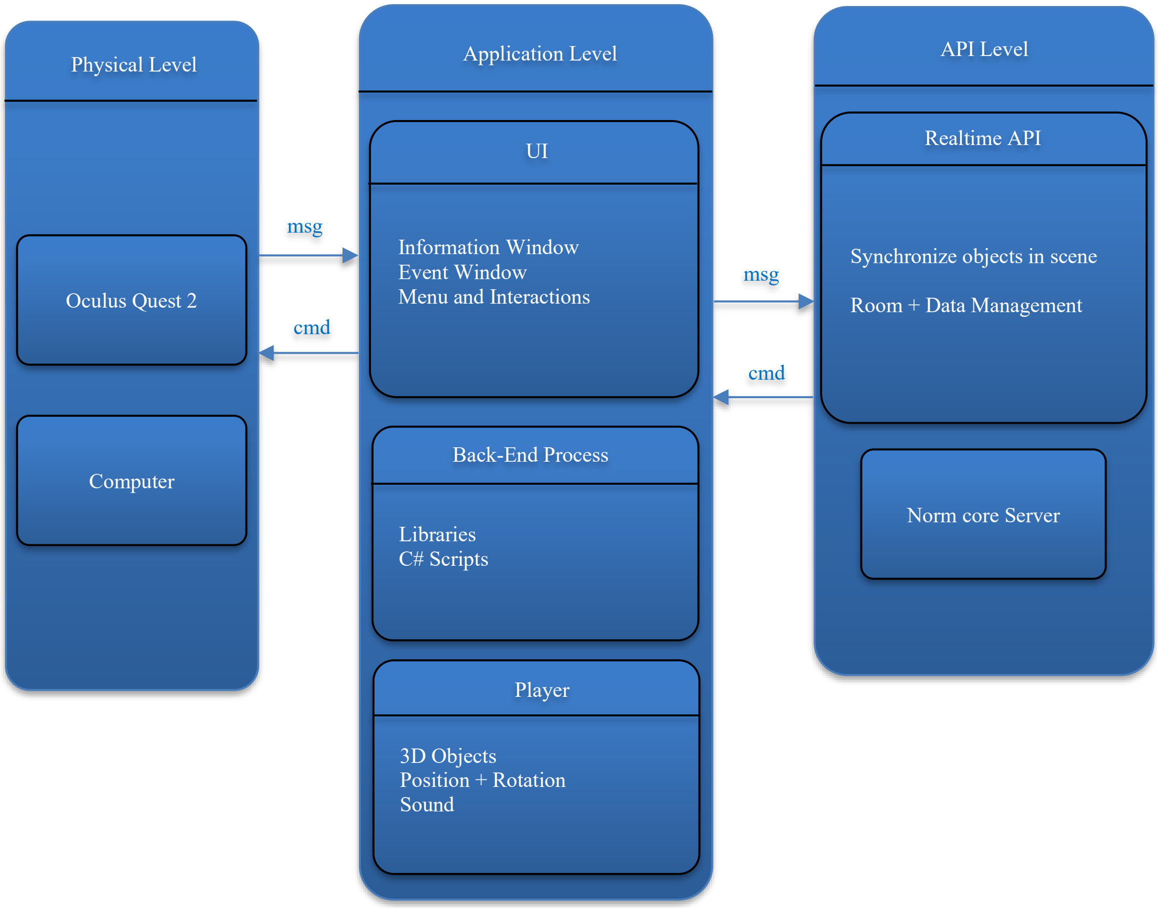

Fig. 2 System diagram

3.2.1. The Physical Level

The physical level consists of tangible hardware, which is the user's end device. This level comprises three main components: the Oculus Quest 2, a computer, and the Oculus Link cable, which serves as an intermediary for data transmission between the two devices. The computer functions as the primary processor for the application, while the Oculus Quest 2 displays real-time visuals to the user.

3.2.2. The API Level

The API level acts as an intermediary for data communication. Data from the hardware client is forwarded to the system. The researcher uses the Normcore library, which provides real-time API and server services to create voice chat functions on the Unity application. The Unity application connects in real-time to the Normcore server to manage data exchange.

3.2.3. The Application Level

The Application level is where the virtual reality software is generated using the Unity game engine. This level covers the creation of all software components, including the design of the virtual environment scenes, GUI development, scripting behaviors for the system's virtual organisms, and the implementation of voice chat. Finally, this level leads to the creation of an application for use on Oculus Quest 2.

3.3. Data Flow

The system's data flow diagram is shown in Figure 3. The process begins with an input signal from pressing a button on the touch controller, which sends commands from the Oculus Quest 2 to the software running on the computer. Then, the Oculus Quest 2 displays the images on the screen. Upon logging in, the user wears the Oculus Quest 2, and the system begins receiving input from the touch controller or voice chat.

Two users can communicate via voice chat, but cannot perform tasks for each other. When the system receives voice chat data or the user's position, the Normcore client in Unity connects to the Normcore server, which is managed via "Realtime Sessions". Normcore automatically manages this via cloud-based servers. For the assessment section, when the user presses the pre-test or post-test button, the system connects to Google forms and directs the user to the testing window.

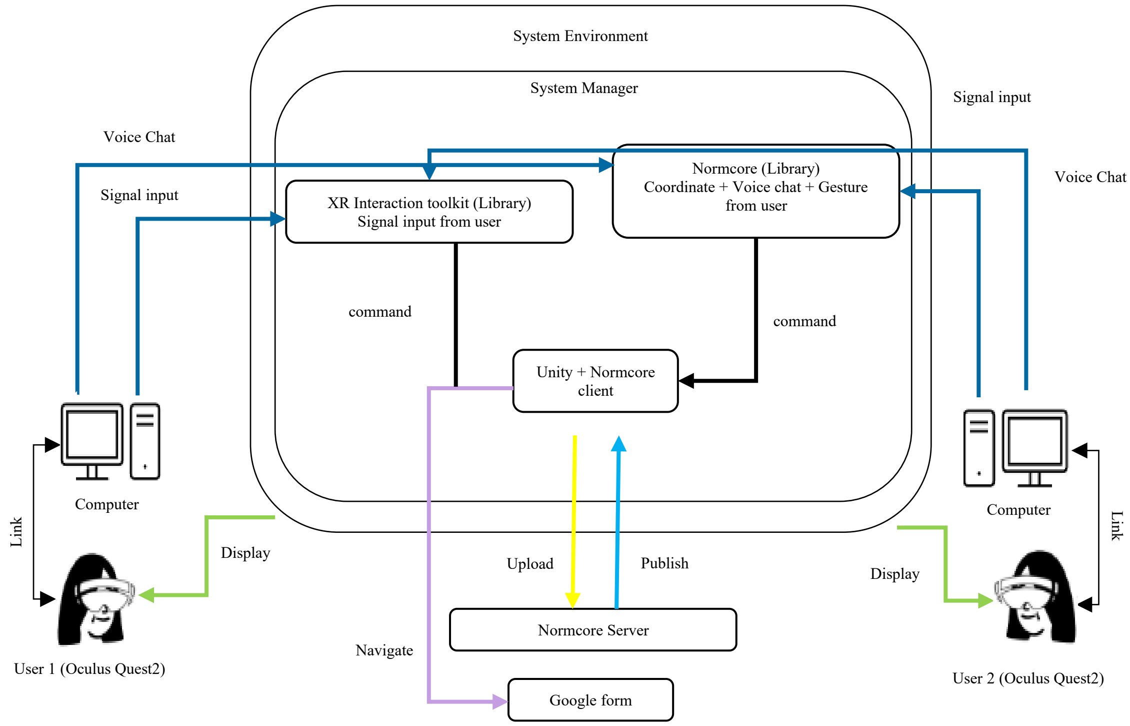

Fig. 3 Data flow diagram

3.4. Data Synchronization

The software is installed on each user's computer, which is connected to the Oculus Quest 2 via Oculus Link, as shown in Figure 4. Users can interact with others by using voice chat through the Normcore server. This system is designed for simultaneous use over the internet, requiring all users to be on the same LAN segment. The data transmitted through the Normcore server includes the user's voice chat and position. This function is implemented using Normcore's Realtime API, which is used to create voice chat and user avatars.

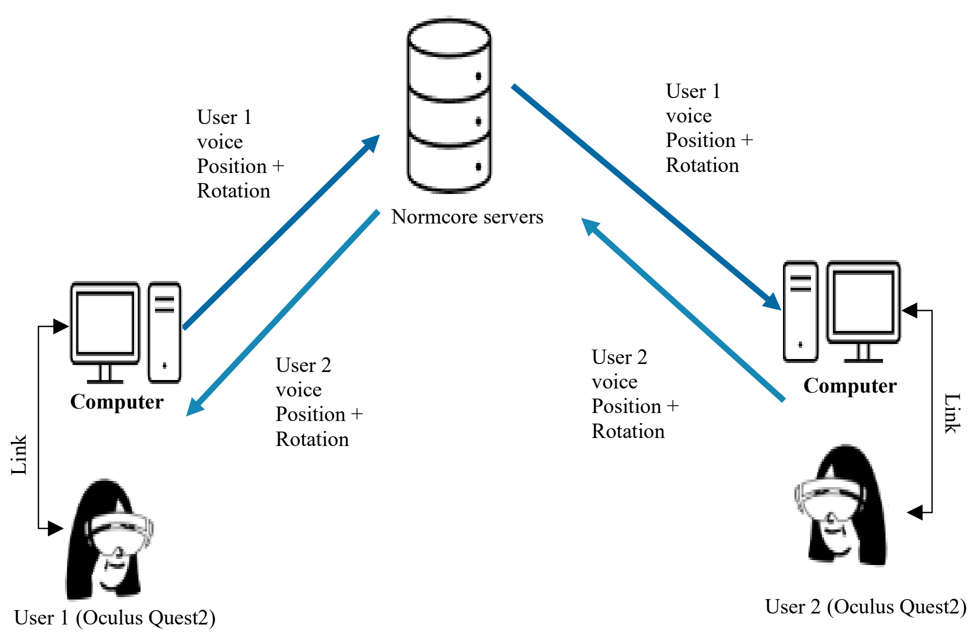

Fig. 4 Connecting collaborative systems between users

The user avatar in the system moves according to the user's body in the real world. For example, if the user moves their left arm, the avatar's left arm will follow, as shown in Figure 5.

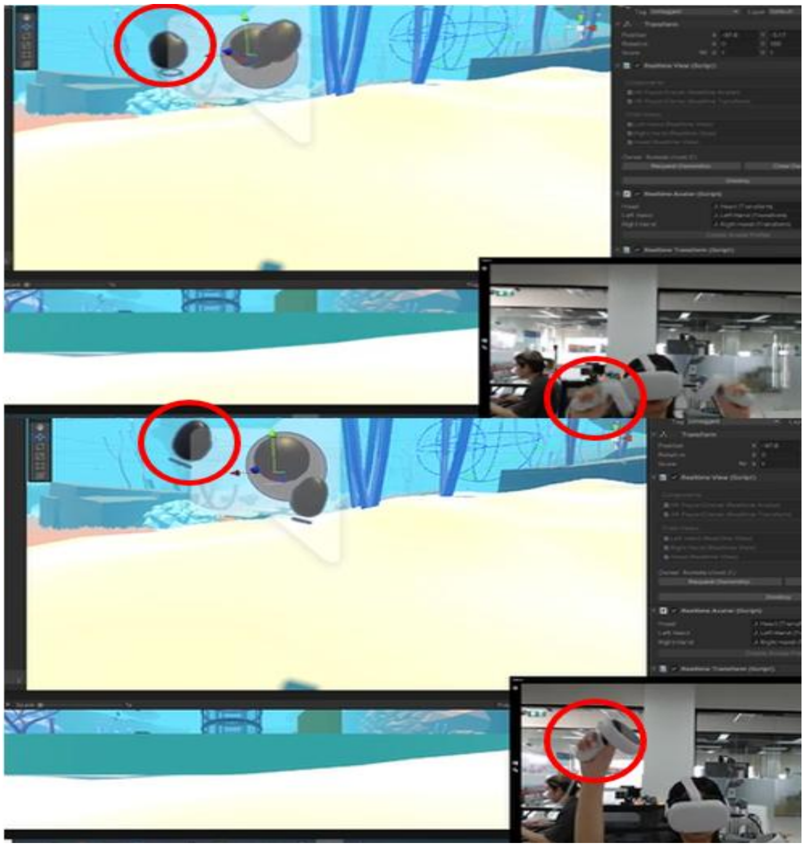

Fig. 1 User avatars in the system compared to reality

The avatar functions as a user's representative, consisting of the head, left and right arms and mouth as shown in Figure 6.

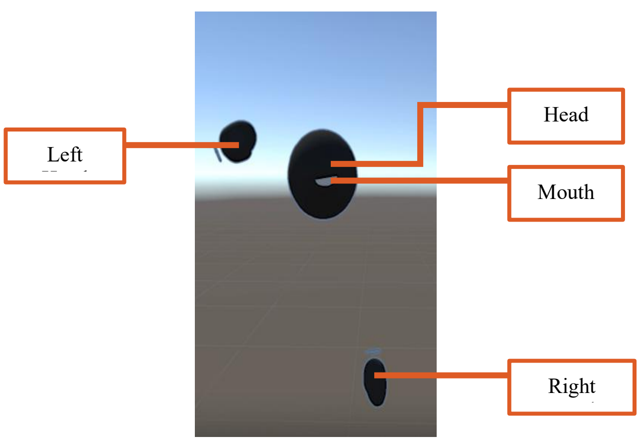

Fig. 6 A user avatar in the system

3.5. Hardware and Software Components

3.5.1. Oculus Quest 2

In this paper, the Oculus Quest 2 is used as the primary VR hardware (Figure 7), with 128 GB of storage and two touch controllers. Since it does not require external base stations, it is easy to set up. This device features a high-resolution display and a 120 Hz refresh rate, suitable for smooth and realistic visual display for the user. In addition, this model is designed to be about 20% lighter and 15% smaller than the original model [20], providing greater convenience for users during learning sessions. It is also convenient for development and system usage as it can connect to a computer via Oculus Link.

Fig. 2 Oculus Quest 2

3.5.2. Controller Tracking and Play Area

The Oculus Quest 2 features six Degrees of Freedom (6DoF) tracking, an all-in-one system that allows users to move naturally without using external sensors. Inside the Oculus Quest 2 is a guardian system that allows users to define virtual boundaries in the physical play area to avoid collisions with objects in the physical world. This feature is adaptable to various environments, such as classrooms or homes [20].

3.5.3. Unity XR Interaction Toolkit and Normcore

The system uses the Unity XR Interaction toolkit to develop interactive functions in VR applications for user-to-agent and agent-to-agent interaction. This toolkit provides a framework that enables 3D and UI interactions through Unity input events, making it easy to develop basic functions of the system in this research, such as basic object hover, utility for interacting with XR Origin, and basic canvas UI interaction with XR controllers [21].

For voice chat, this research uses Normcore, a real-time multiplayer networking SDK for Unity, because it is compatible with the XR interaction toolkit and has low latency. Normcore enables synchronous communication between users by managing the replication of positions, voice and object states over a cloud-hosted network, which simplifies the server setup and is easy to use for development.

3.6. Game Content Design

The researcher surveyed and gathered information to develop educational content on the topic of ecosystems for junior high school students. The content framework is primarily based on the science textbook published by The Institute for the Promotion of Teaching Science and Technology (IPST). The content design process is shown in Figure 8.

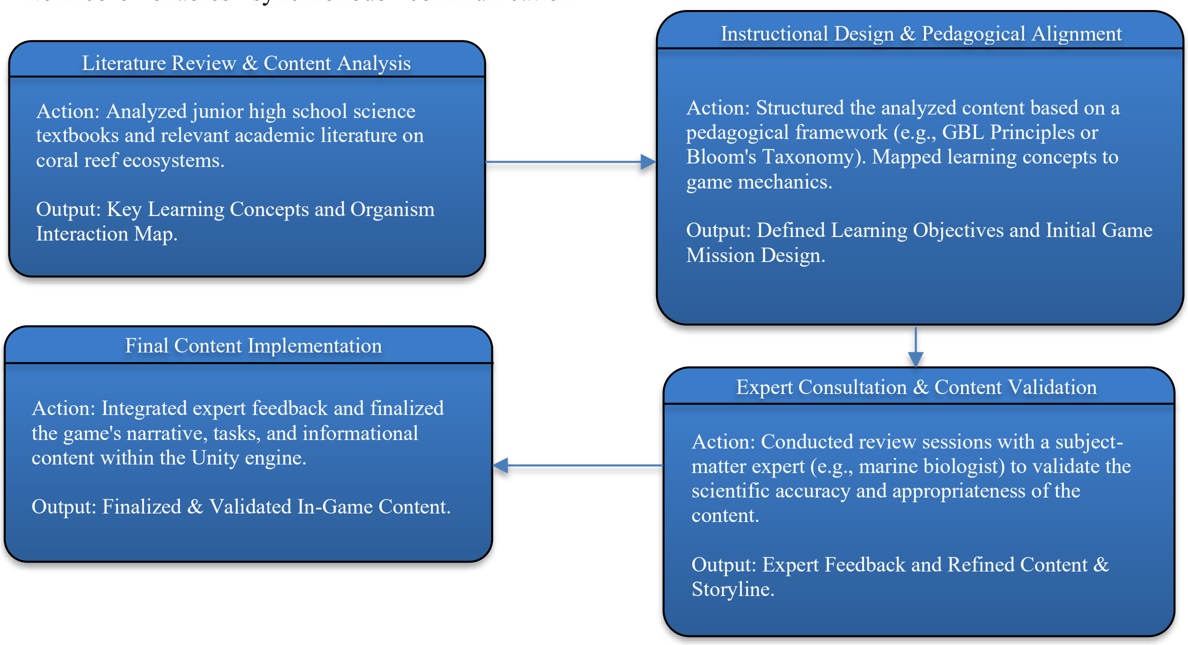

Fig. 3 Game content design

3.6.1. Curriculum Analysis and Content Scoping

The core curriculum content was analyzed and identified as related to the topic of "Ecology," basing the main content on the IPST science textbook, which is the national standard. Afterward, a comparative study was conducted to identify and select consistent topics across the textbooks. A comparison between the content in the IPST textbook and teacher's manual versus six other commercially available science textbooks revealed two topics that appeared consistently in every textbook: "Roles of Organisms in Ecosystem" and "Relationships between Organisms". Therefore, these two topics are the core content of the game.

3.6.2. Expert Consultation and Requirements Gathering

Following the identification of core topics in 3.6.1, the researcher presented the curriculum analysis of the proposed system to subject matter experts to verify content and gather system design requirements. The researcher consulted with two staff members in the IPST compulsory science department and faculty members of the target group.

The key points are summarized as follows:

- The proposed system aims to be a supplementary learning tool for junior high school students.
- The selected topics, "Roles of Organisms" and "Relationships between Organisms," were confirmed as appropriate and sufficient for the system's content.
- Experts suggested that the ecosystem should feature a variety of organisms and should be clearly defined whether the ecosystem is saltwater or freshwater.
- A key recommendation from experts (if possible) is that the system should allow learners to directly interact with the content rather than reading information within the system.
- The system should include methods for individual assessment.

3.6.3. Instructional Design and Content Structuring

The content and functions of the system were designed and organized according to Bloom's taxonomy objectives to help students transition from passive learning to active learning. The researcher utilized both the content structured by Bloom's taxonomy and the insights from expert consultations to create the system content.

3.7. Pedagogical Framework

In this study, the VR-based learning environment was designed based on Constructivism, emphasizing that learners construct their own knowledge through active interaction rather than passive learning [22, 23].

This system uses two Constructivist principles, consisting of Active and Social Constructivism. Active Constructivism is used through game-based learning, where learners construct their own knowledge through play and exploration via system tasks/missions [22, 24].

Social constructivism is supported by optional peer consultation via voice chat, helping learners receive assistance from their partners when facing challenging tasks, consistent with Vygotsky et al. (1978) concept of the Zone of Proximal Development [23].

These two Constructivist principles also align with Edgar Dale's Cone of Experience [1], which suggests that direct experiences yield the highest levels of learning retention.

Specific design elements in this study were applied based on the following pedagogical principles.

3.7.1. Inquiry-based Observation

Learners must observe the ecosystem that develops after their interaction with environmental elements, such as planting seaweed or releasing virtual sharks. Moreover, the system does not explicitly state which fish are herbivores or carnivores, so learners must infer the roles of organisms in the system by observing which fish eat the planted seaweed or hunt other fish.

These processes promote learners to think critically and construct their own understanding of ecological relationships through direct observation.

3.7.2. Experiential Consequences

The researcher designed a non-directive method to teach about the ecosystem. For example, learners must decide whether to dispose of the dead fish. If ignored, the virtual water will gradually deteriorate. This helps learners discover the important role of decomposers and environmental conservation through hands-on experience.

3.7.3. Cognitive Load Management

The system design manages all three components of Cognitive Load Theory [25]. Intrinsic load is decreased through leveling game-based missions from easy to complex tasks. Extraneous load is reduced through two prior training methods. Participants will first receive a demonstration of the Oculus Quest 2 equipment from the staff, then enter a tutorial room to familiarize themselves with the UI before taking the main mission. The collaborative function was designed as optional; learners must complete missions individually but may consult with their partners via voice chat when needed [6], reducing social isolation without adding cognitive demands. Germane load is promoted through inquiry-based observation that requires learners to observe and analyze the environment by themselves.

3.8. Learning Scenario Design

The VR learning scenario design aims to engage learners in interactive learning by simulating the roles of various organisms in an ecosystem. This helps learners understand the relationships between organisms and the consequences of actions taken by learners and organisms through interaction and voice chat with other learners.

3.8.1. User Roles

The user assumes the role of "Ecosystem Observer" in this system. They can interact with the environment in various ways, such as releasing a virtual shark or collecting fish carcasses to observe changes in the system. This role is designed to help learners understand the relationship between living organisms and their impacts within an ecosystem through exploration in a virtual environment.

3.8.2. Learning Objective and Expected Outcomes

Data from the game content design was used to create the expected learning outcomes for the system, as summarized in Table 3.

Table 3. Expected outcomes

<table>
<tr><th>Expected outcome</th><th>Activity</th><th>Bloom's Level</th><th>Assessment Method</th></tr>
<tr><td>Users can identify which organisms are producers, consumers, or decomposers.</td><td rowspan="2">Planting Producers: Users must plant producers, such as seaweed, in designated areas of the environment.

Observing Impact: Users can release a shark into the ecosystem and are prompted to observe the subsequent changes.</td><td>Recognize, Analyze, Define</td><td rowspan="2"></td></tr>
<tr><td>Users understand the different roles of organisms</td><td>Recognize, Analyze, Define</td></tr>
</table>

(producers, consumers, decomposers).	Encouraging Exploration: Checkpoints are placed in each area to motivate players to explore the virtual world. Consequence System: If a fish dies, the player has the option to either collect the carcass or leave it. Leaving the carcass results in water pollution. Once the water becomes polluted, it remains so even if the carcass is removed later. Progressive Complexity: The complexity of the ecosystem increases as the user advances to higher levels.		Pre-test and post-test
Users can differentiate between the various types of interspecies relationships.		Recognize, Define	

3.8.3. Collaborative Interaction

Learners can communicate with each other via voice chat to discuss missions/tasks and content. However, they cannot complete tasks for each other, emphasizing individual learning.

3.8.4. Auto-Assessment in VR

Learners are assigned missions in each level while using the VR environment, encourage them to explore the ecosystem through designated checkpoints. These checkpoints help learners thoroughly explore the area and organisms. Once learners have completed all the tasks at each level, they can press a button to take a post-test that links to a Google form for an assessment of their overall understanding gained from using the system.

3.9. Population and Sample Selection

3.9.1. Population and Requirement

This system was developed to use as a supplementary learning tool for junior high school students (Grades 7-9) on the topic of "Roles and Relationships of Organisms in Ecosystems". Participants were recruited via voluntary response sampling methods. They could apply individually or through their school, provided they could travel to the testing site.

3.9.2. Inclusion criteria and Ethics

To ensure safety and reduce extraneous variables, participants were screened based on the following criteria:

- No underlying diseases, visual impairments, or motion sickness. Nearsighted participants must use eyeglass frames not exceeding 142 mm in width to fit the VR headset safely.
- All participants have normal reading/writing abilities and are currently enrolled in junior high school.
- All participants provided voluntary assent, followed by formal written informed consent from their parents/guardians, and they were able to complete the entire session.

3.9.3. Participant Characteristics

A total of 35 participants met the criteria and completed the session, consisting of 20 females and 15 males. Their actual ages ranged from 11 to 16 years. Regarding prior experience with Virtual Reality (VR), 34 participants were first-time VR users, while one participant had previous experience with a different VR system.

3.10. Tools

This study employed a mixed-methods approach to evaluate the VR learning system. Quantitative data were collected through pre-test, post-test, and satisfaction questionnaires.

Qualitative data were collected through three methods: emotional checklist, open-ended responses and photographic documentation.

3.10.1. Pre-test and Post-Test

A one-group design (pre-test and post-test) was employed. This study did not aim to compare the VR system versus the traditional method, but rather to examine whether the system itself could produce a statistically significant improvement in participants' knowledge scores.

The objective of the pre-test was to assess the participants' basic knowledge of the content before using the system. The test was designed to cover the main learning content, consisting of the roles and relationships of organisms in marine ecosystems.

The assessment was multiple-choice, with each item having only one correct answer.

The post-test was administered after the participants had completed all missions and tasks in the system. It utilized the same set of questions as the pre-test, with the hypothesis that the participants would have a statistically significant increase in the post-test scores. This increased score is interpreted as evidence of improved understanding of the content gained from using the system.

All assessment items were developed in consultation with experts from IPST. These items align with junior high school learning and map directly to the expected outcomes in Table 3.

3.10.2. Satisfaction Questionnaire

A satisfaction questionnaire was used to evaluate three sections of user experience: content, usability, and value for specific tasks. The questionnaire was adapted from the System Usability Scale (SUS) [26]. User feedback data was collected via a Google form. The satisfaction questionnaires used a five-point Likert scale to measure user satisfaction. The lowest score indicates “Strongly Disagree”/ “Very Poor”/” Definitely Not”, and the highest score indicates “Strongly Agree”/ “Excellent”/” Definitely”.

3.10.3. Qualitative data

An emotional checklist was used to assess participants affective response during system usage and was collected from a Google form. Participants could also indicate additional emotional responses beyond the provided option. Open-ended responses were analyzed using qualitative content analysis [27]. Photography was also used to capture participants' gestures and engagement during the session, providing additional supportive data.

4. Results and Discussion

4.1. Tasks

In the data collection process with the target group, the researcher required participants to perform the following three tasks.

4.1.1. Task 1: User Assessment

The participants must take a pre-test before using the system to measure their knowledge. After participants completed tasks 2 and 3, they must take a post-test.

4.1.2. Task 2: Learning

The VR application consists of three levels, ranging from easy to difficult ecosystems. Participants must complete all three levels.

4.1.3. Task 3: Using the Application.

In this task, participants received instructions and watched a demonstration on how to use the application with the Oculus Quest 2 from the staff before actual usage.

Instructions

This mission involved learning how to use applications on the Oculus Quest 2 by reading instructions and guidance on interacting with objects using touch controllers, such as movement (warping), pressing buttons to interact with the UI, using the microphone to communicate with other players, and specific actions like growing algae, releasing a virtual shark, and collecting dead animal carcasses.

Tutorial

Users started in a tutorial room to learn details about organisms in the system, consisting of producers, consumers and decomposers. Afterward, they practiced interacting with the UI window, warping, collecting fish carcasses, and testing the release of virtual sharks to understand the interaction functions with the environment and familiarize themselves with the equipment.

Missions

Users had to explore and interact with organisms to complete the assigned missions/tasks in each level. They could consult with their partner via voice chat, but could not perform the other’s tasks. Users could not proceed to the next level without passing the previous one. Hints were provided in each mission to guide them.

Feedback

Once users have finished using the application, they must complete a satisfaction feedback form regarding system satisfaction and content satisfaction. During the test, the user’s view inside the Oculus Quest 2 was live-streamed to the staff in real time.

If users encounter problems with the system or usage, the staff will help. Each test session took approximately 50 minutes, depending on how quickly the participant was familiar with the device and solved the problems.

A potential risk from using this system was motion sickness. To mitigate this, the staff advised users to remove the Oculus Quest 2, sit down, and rest their eyes for 10 to 15 minutes if they felt unwell. No participants in this study experienced motion sickness.

4.2. Results

The system performance of the VR applications was measured by monitoring the frame rate while the system was running. The frame rate ranged from 45 to 70 fps, which is considered satisfactory and allows users to interact with the system smoothly.

The significance of system usage on participant scores was measured using pre-test and post-test results. Since two participants got full scores on both tests, the researcher excluded this data before calculation and analyzed only 33 participants who did not score full marks.

Table 4. Pre-test and post-test statistical scores

Statistics	Pre-test	Post-test
Mean	2.55	3.15
Median	3	3
S.D.	1.09	1.03
Min	0	1
Max	4	5

Table 4 shows statistical data of pre-test and post-test scores; the full score of these 2 tests is 5. The mean score increased from 2.55 (S.D. = 1.09) to 3.15 (S.D. = 1.03). The median scores were 3, statistically equal. The pre-test scores ranged from 0 to 4, while the post-test scores ranged from 1 to 5.

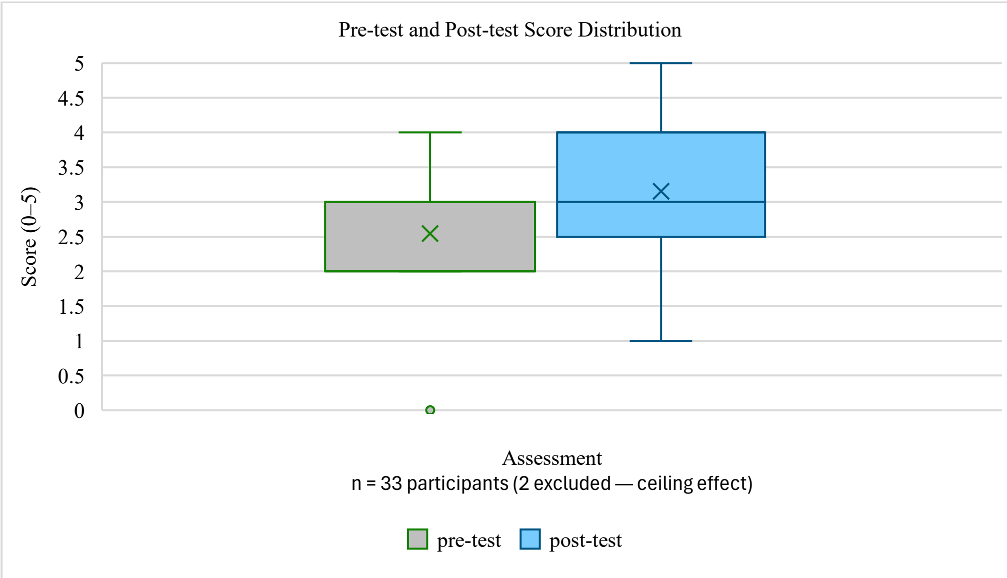

Fig. 9 Pre-test and post-test score distribution

As illustrated in Figure 9, the post-test distribution demonstrates a notable upward shift compared to pre-test scores. These statistical data demonstrated a statistically significant improvement in learner learning performance after using the VR system. However, these statistics did not yet show the significance of using this system before and after, based on the test scores. Additional inferential statistics were employed to analyze the data further.

Table 5. Statistical results of the Wilcoxon signed-rank Test

n	Positive Ranks	Negative Ranks	Ties	Z	p-value	r	95% CI
33	20	5	8	2.45	.014	0.49	[0.00, 1.50]

The researcher used the Shapiro-Wilk test to check for normal distribution of the data. The result showed a p-value < .001 for the pre-test scores, indicating that the data were not normally distributed.

Although the Shapiro-Wilk test on the differences indicated borderline normality (p = .078), the Wilcoxon signed-rank test was chosen due to the non-normality of the initial pre-test and post-test scores (p < .001).

From the results, the Wilcoxon signed-rank test indicated a statistically significant difference between post-test scores and pre-test scores (p = .014), with a medium effect size (r = .49). The 95% confidence interval [0.00, 1.50] was estimated using the Hodges-Lehmann estimator, indicating a positive shift in scores following system use.

Table 6. User satisfaction ratings across three sections (n = 35)

Sections	Mean	Median	S.D.
Content satisfaction	4.32	5	0.64
Usability	4.06	4	0.81
Value for specific task	4.21	4	0.76

There are 35 participants in total for the satisfaction, usability and value for specific task evaluation, while determining the significance of scores after using the system involved 33 participants, because two participants who received full marks were excluded. This method uses a five-level Likert scale to evaluate: definitions 1-Very Poor, 2-Poor, 3-Acceptable, 4-Good, 5-Very good.

As shown in Table 6, the present user satisfaction assessment consists of 3 sections. All sections received mean scores ranging from 4.06 to 4.32, indicating a 'good' to 'very good' level of satisfaction.

The content satisfaction yielded the highest mean scores (M = 4.32, S.D. = 0.64), indicating that learners agree that learning contents are clear, engaging, and appropriate for their level. Values for specific tasks scored (M = 4.21, S.D. = 0.76) reflect the users' perception that this system is useful in helping them to understand ecosystems.

The system usability yielded mean scores in a good level of satisfaction (M = 4.06, S.D. = 0.81).

However, when compared to the mean scores of other sections, the mean scores are slightly lower.

To further understand the user experience, qualitative data was collected through user observation during system usage. This involved taking photographs and analyzing behavior, emotions, attitudes, and interactions. It was found that users were interested in the VR system and displayed positive emotions, such as smiling, during use. This demonstrates a high level of emotional engagement and user accessibility. Furthermore, users were focused and attentive to the system's tasks, as evidenced by their stable grip on the touch controller and their focus on participating in the experiment. This shows their interest and concentration on the activity.

Fig. 10 Participant attentiveness during the learning session

This high concentration level also explains why participants tend to communicate less with each other while using the system. This behavior may stem from their lack of prior VR experience, as 34 out of 35 users had never used any VR equipment before. Even with the familiarization period, including introductions and demonstrations, the novelty of the virtual environment may have caused users to focus on completing tasks within the system rather than consulting with friends. Nevertheless, the open-ended feedback collected after the session revealed positive responses, with users identifying keywords from an emotional checklist, such as "enjoy" and "engaged", reflecting their feelings after using the system, as shown in Figure 11.

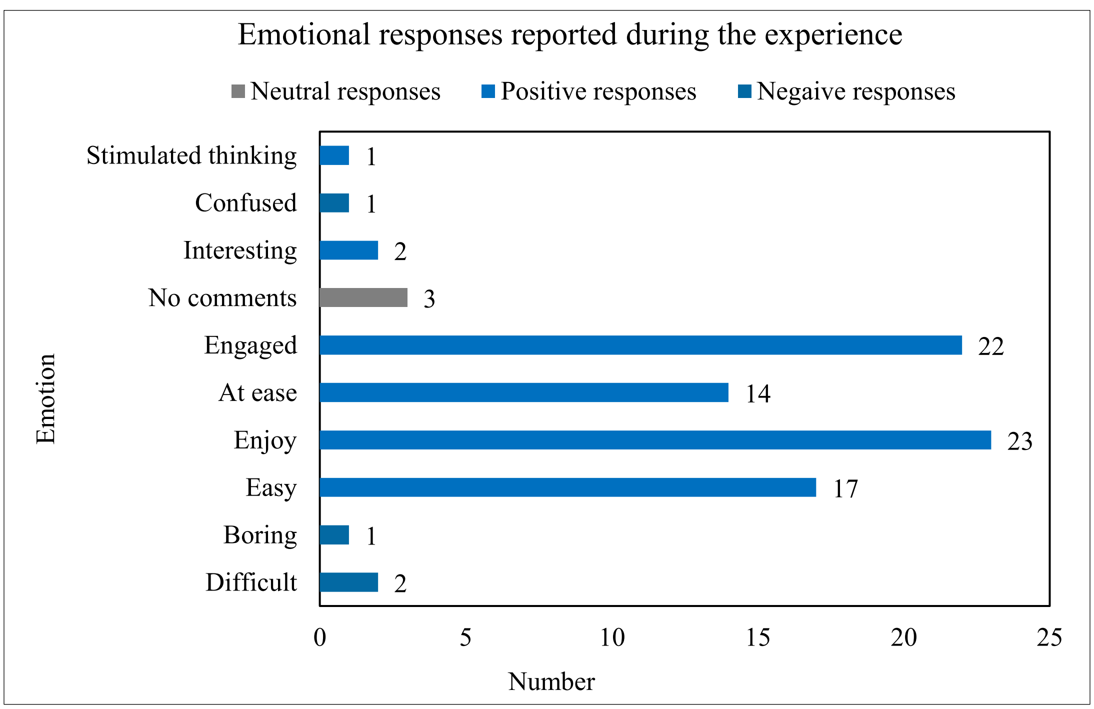

Fig. 11 Emotional responses of participants during system usage

Table 7. Summary of qualitative themes and representative user quotes

Themes	Quotes from users
Learning impact	"The predator-prey cycle was clearly demonstrated." "Analyzed why the fish died, and the water became polluted." "Enabled self -directed learning."
Social support	"Knowing others were doing the same task reduced my stress." "Friends helped guide me through points of confusion." "So much fun! Playing alone would be very lonely."
Hardware & Physicality	"The VR headset was difficult to wear and quite heavy." "Had to turn around to rotate in the system physically."

Qualitative data from open-ended questions were categorized into recurring themes and general consensus among the majority of participants, as shown in Table 6, to understand the user experience, in addition to the emotional checklist and photos.

According to the Learning impact, the findings indicated that the VR environment facilitated active knowledge construction, as participants reported being able to analyze ecological relationships independently. This finding aligns with the quantitative results showing significant improvement in post-test scores ($p < 0.05$) and the high ratings observed in the content section of the satisfaction feedback form, collectively supporting Constructivist learning theory [22], which emphasizes learning through direct experience.

Participants also mentioned that the friend-support function can reduce anxiety and enhance understanding, as reflected in comments, such as "playing alone would be very lonely" and "friends helped guide me through points of confusion", consistent with Vygotsky et al. (1978) Zone of Proximal Development (ZPD) [23]. The qualitative data reveal why the usability section score was slightly lower than other sections; the main reason is the hardware limitations, such as the headset's weight.

5. Conclusion

This study developed and evaluated a Collaborative Virtual Reality Learning Environment (CVLE) as a supplementary teaching tool for junior high school students. The content in this system covers the roles of organisms and their relationships within coral reefs. The system was developed by using Unity with Normcore for collaborative learning and was deployed on the Oculus Quest 2. The system performance was satisfactory with a frame rate of 45-70 FPS at a resolution of 1832x1920 per eye, which is sufficient for an immersive experience.

This paper collected data from 35 junior high school students after they used the system. The results showed that satisfaction scores for usability test, content and value for specific tasks ranged from good to very good. Users agreed that the system improved their understanding of ecosystems and was suitable for learning. These results seem to be consistent with other research, which found that VR enhances motivation, engagement and helps learners understand complex content [28]. In terms of user observation, the participants' positive emotions indicated that the system was interesting and enjoyable. The analysis of test scores from 33 participants showed a statistically significant increase after using the system.

The proposed system achieved these effective learning outcomes by aligning directly with the target group's science curriculum. Previous studies often relied on observational exploration to build ocean awareness [2, 5, 15, 19] and were solo explorations, which could cause users to feel isolated during the activities. [6]

This study utilized game-based learning missions to teach formal scientific content directly. The developed CVLE incorporated a voice chat feature that allowed users to receive support from their partners. This peer-support mechanism was intentionally designed without complex, full-collaborative tasks, aiming to minimize extraneous cognitive load according to Cognitive Load Theory. [22-25]

Finally, these outcomes are reinforced by the consistency between the quantitative and qualitative data—the statistically significant improvements in pre-test and post-test scores directly aligned with the high user satisfaction ratings. The positive user quotes corresponded with the active and engaged physical postures documented through observational photographs.

Limitations and Future Work

Several limitations to this study need to be acknowledged. The sample size was also minimal, although the sample size of 35 participants exceeded the minimum threshold of 30 required for statistical analysis. Future studies should recruit a larger sample to provide more insight into research trends.

Recruitment was a challenge for junior high school participants because they needed parental accompaniment, which constrained the total number of participants. The researcher plans to conduct a follow-up assessment to evaluate knowledge retention (a long-term retention test) and transfer effects, such as transferring the gained knowledge to other scientific topics. A long-term retention test should be conducted 2-4 weeks after the experiment.

In terms of system development, further work could focus on enhancing the content to be more challenging. The system's content should increase the biodiversity and create a more complex storyboard. The graphics should be improved for better visual quality.

The User Interface (UI) should be updated to provide a summary of the content after users finish each level, to review the content and identify any missed lessons. The task tracking should be enhanced in the system for easier visibility.

However, the current system was not designed for users with accessibility needs, for example, those with color blindness or physical limitations. The researcher plans to consult with accessibility experts and use universal design principles to ensure inclusivity. Testing with future versions of the system should also include users with diverse accessibility needs. As an additional suggestion, there might be an ice-breaking session before using the system to allow users to get to know others. The system should fully support multiplayer modes and allow users to choose between collaborative learning with friends or solo learning modes.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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