i360°VR: an interactive 360-degree virtual reality approach for engineering education

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Abstract

Virtual Reality (VR) has demonstrated great promise in creating immersive learning environments across various educational domains. However, most VR learning modules are developed using entirely artificial environments, often constructed via game engines. While engaging, these virtual worlds may lack authenticity, which can detract from students' real-world learning experiences. On the other hand, VR modules based on 360º filming capture real-world environments but are often limited by the lack of interactivity. As a result, users can only passively review the media without interacting with the virtual world. In this study, we introduce a novel VR development framework—Interactive 360-Degree Virtual Reality (i360ºVR)—that combines the strengths of both game engine-based VRs and 360º filming. Our approach integrates real-world authenticity with interactive features, providing students with an engaging and immersive learning experience. To demonstrate its effectiveness, we developed an i360ºVR module focused on coastal erosion monitoring through the usage of a series of software packages across different domains including photogrammetry, computer graphics engines, and an online VR editing tool. We conducted an evaluation of this i360ºVR module with engineering students on four key metrics: immersion, interactivity, the creation of a tangible learning environment, and student perception of coastal erosion. The results of this study offer valuable insights into the role of interactive, authentic VR environments in enhancing student engagement and learning outcomes in engineering education. In addition, we discussed frameworks of applying the proposed i360ºVR approach into two other STEM education contexts, including proposing a remote VR lab for the mechanical engineering program; and enhancing student learning in physics education through an accident analysis of the August 2020 port explosion in Beirut, Lebanon.

1. Background and Motivation

Virtual Reality (VR) has become an emerging tool with broad applications in education [1], workplace training [2], healthcare [3, 4], and entertainment [5]. By replicating real-life situations in a virtual environment, VR offers a unique and efficient way to achieve various research goals. For instance, Marco et al. [6] studied behavioral therapy treatment for body image issues in eating disorder patients using various interactive virtual modules that represent therapeutic objectives. After one year of follow-up, all participants improved their body image under VR behavioral therapy treatment conditions. In another study performed by Tradeja et al. [7], a VR simulation was developed to replicate the working space of a mobile (Magnetic Resonance Imaging) MRI unit to improve operational cost-efficiency. Results demonstrated that, by implementing VR in a medical facility, staff can navigate more efficiently to access and organize various devices efficiently, optimizing space usage. Hong et al. [8] studied distraction behaviors among individuals with intellectual disabilities by creating an enhanced visual experience in various occupations using VR. Through the head and eye tracking data, the researchers correlated those data with VR experience for individuals with intellectual disabilities.

VR also plays a critical role in engineering education. Azzam et al. [9] conducted a study to test VR's effectiveness in mechanical engineering education by creating a virtual design laboratory that enabled students to perform robotic experiments. Results from student participants illustrated that the VR design laboratory improved students' learning experiences and engagement in the gripper design of robotic arms. Dither et al. [10] investigated the STEM motivation in chemistry education and found that students with VR experience showed increased STEM motivation and interest in learning chemistry compared with the control group. Similar findings in physics education were concluded from the study performed by Georgiou et al. [11]. VR is also found to be a great approach for the visualization of complex spatial concepts. For instance, Takac et al. [12] applied a VR module to student participants, allowing users to navigate and adjust various three-dimensional calculus concepts. As a result, the virtual module significantly increased students' interest in calculus.

Despite these successes in engineering education, most VR modules discussed above [9, 10, 11, 12] are based on entirely imaginary universes with artificial physics simulations developed through 3D game engines (e.g., Unity [13], or Unreal Engine [14]). If not well investigated, these game engine-based VRs are criticized for being unauthentic and unsophisticated [15]. Indeed, developing and maintaining realistic, high physical fidelity, virtual content is time-consuming and labor-intensive [16], as the developer(s) must consider multiple factors such as viewpoint selection, camera movement, the realism of the virtual environment, media mode, audio rendering, lighting condition, and display resolution [17]. To adopt these game engine-based VR approaches, engineering educators must carefully balance the substantial costs of VR modeling and the demands for authenticity.

Filming real-world authentic 360° media, on the other hand, can overcome these challenges and ensure that the virtual environment looks and feels grounded. When viewing 360° media (i.e., video, images) on VR-enabled devices, the accuracy of the virtual environment's measurements (e.g., dimensions, colors, textures) in instances from a real-world environment is high, hence providing the foundation for authenticity [17]. Furthermore, the efforts in developing VRs based on 360º media are significantly less compared to game engine-based VRs, as the virtual content can be directly obtained through 360° in-situ filming. Recently, research on educational VRs using 360° videos has started to develop [18, 19, 20, 21, 22, 23].

Nevertheless, a notable limitation of the above 360º video-based VRs is the lack of interactive functionalities. When viewing 360° videos in the virtual environment, users can only passively observe and hear the pre-filmed scene(s) without interacting with the virtual environment. This limitation can detract from the overall learning experience [24], especially in engineering education where strong user engagement would be required to demonstrate complex features. For example, Wall et al. [25] filmed 360° videos of the operation procedure for tire inspection performed by an experienced technician. While the participants felt the VR learning scenario was interesting, the authors were concerned about the benefit of this approach due to the lack of user interaction.

From the above discussions, it is critical to explore innovative VR approaches that combine authenticity and interactivity while remaining cost-effective. This study introduces Interactive 360-Degree Virtual Reality (i360ºVR), a new VR framework in engineering education. Table 1 highlights how the proposed i360ºVR addresses challenges faced by existing VRs. Game engine-based VRs face formidable challenges in balancing the authenticity of the virtual content and the cost of modeling VR scenes. VRs that are solely based on 360° videos, on the other hand, can offer an authentic experience but are less effective for creating comprehensive VR learning scenarios due to their passive learning mode (lack of interactions between the user and the virtual scene [26]). The proposed i360ºVR addresses these limitations by integrating in-situ filming to deliver an authentic learning experience, incorporating interactive elements such as hotspots and multi-scene transitions to enhance user engagement. Furthermore, it leverages a user-friendly VR editing platform to significantly reduce development costs, making it a practical and accessible solution for higher educational institutions with limited resources.

Table 1: The proposed i360°VR vs. existing VRs in the field

	Game Eng.-VRs	360° Videos	i360° VR
Is the VR model based on in-situ real-world filming?	✗	✓	✓
Is the VR content authentic?	?[1]	✓	✓
Is the VR content interactive?	✓	✗	✓
Can the user explore and control the features in the virtual scenes?	?[1]	✗	✓
Is the cost of learning skillsets for VR development affordable?	✗	✓	✓
Can educators adapt this VR method to model complex scenes?	?[1]	?[2]	✓

1. Game engine-based VRs require extensive efforts in modeling to achieve these goals.
2. VRs that are solely based on 360° videos can only offer a passive learning experience without user interactions, hence it is difficult to demonstrate complex features.

The rest of the manuscript is structured as follows: Section 2 discusses the literature grounds in both education research and technology contexts for proposing i360°VR; Section 3 overviews the development and evaluation of the i360°VR module of this study; Section 4 details the efforts in developing the i360°VR module; Section 5 reports the protocols and findings of the evaluation of the i360°VR module; Section 6 further summarizes the research findings; Section 7 discusses potential frameworks to apply the proposed i360°VR approach in two other STEM education contexts; Section 8 concludes the manuscript.

2. Literature Grounds for Proposing i360°VR

2.1 Education Literature

The proposed i360°VR represents a transformative approach to engineering education by integrating authenticity (i.e., modeling real-world experiments) with interactivity (i.e., enabling an interactive virtual environment for engaging learning). These two core features align closely with Kolb's experiential learning theory [27], which outlines learning as a four-stage process initiated by a concrete learning experience and guided by the processing and perception continuums (see Figure 1). Traditionally, engineering education relies heavily on direct, hands-on experience in physical laboratories. However, as Godat et al. [28] have theorized, VR can serve as a "transitional interface", bridging conceptual understanding with experiential learning by leveraging a high-fidelity virtual environment to replicate a real-life experience. Furthermore, Kwon [29] highlighted that the combination of authenticity and interactivity within VR can render virtual experience nearly indistinguishable from real-world encounters.

When replicating a real-world environment, the accurate measurements obtained from high-fidelity imaging technology are crucial for establishing authenticity and realism in VR models [17]. Unlike game engine-based VRs, the i360°VR achieves this by using a photogrammetry-based technological framework that closely replicates real-world experience. These authentic scenarios foster immersion and presence [30], which have been shown to improve student engagement [31]. Additionally, the interactivity feature of the proposed i360°VR will enhance the internalization of information that is achievable beyond passive learning [32].

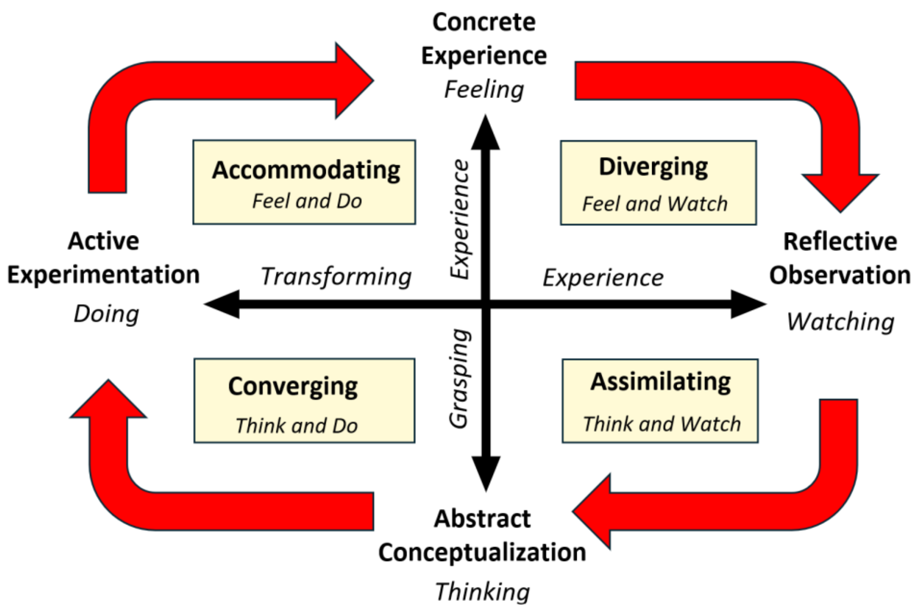


Figure 1 Kolb's experiential learning theory [27]

2.2 Photogrammetry Literature

Photogrammetry offers a promising alternative to traditional 360° video or image capture for VR production. Photogrammetry-based VR modules are manufactured to be more interactive, engaging, and authentic [33, 34, 35,36]. As Tucci et al. [36] highlighted, photogrammetry is an accessible tool for digitizing physical objects and simplifying 3D modeling processes, making it particularly valuable for educational applications. In a different study conducted by Fink et al. [34], the researchers compared educational responses to 3D bridge models created by photogrammetry and game-engine modeling software. Their findings showed that photogrammetry was not only preferred for its user-friendliness but also for its time and cost efficiency, requiring significantly less manual input than traditional methods. Burk et al. [35] conducted a study with no prior experience in configuring photogrammetry models and evaluated students' responses to an interactive 3D photogrammetry model of a human arm. Despite being configured by a novice, the model provided helpful visualizations and facilitated students' comprehension of anatomical structures. Similarly, Aridan et al. [33] found increased engagement among medical students when using a photogrammetry-based VR model of a brain. These studies illustrate that VR models built by photogrammetry technologies offer engaging and authentic learning experiences while being cost-efficient, making them an ideal solution for educational institutions seeking effective and immersive training tools.

3. Development and Evaluation of the i360°VR Module: An Overview

To evaluate the proposed i360°VR framework, a i360°VR module focusing on coastal erosion education was developed. The 3D cliff model featured in this module was created using datasets from the first author's prior research on coastal erosion monitoring [39]. Additionally, the development process of the i360°VR module in this study leveraged the best practices learned from the team's prior VR research in manufacturing education [37]. A comprehensive discussion of the development process is provided in Section 4. Once the i360°VR module was built, a user evaluation was conducted with engineering students at Coastal Carolina University. The evaluation focused on four key metrics: immersion, interactivity, tangible learning environment, and the i360°VR module's potential to shift participants' perceptions regarding coastal erosion. Detailed protocols and findings from this evaluation are reported in Section 5.

4. Development of the i360°VR Module

4.1 Methodology

Figure 2 illustrates the workflow for establishing the i360°VR module which includes four major components. As shown in Figure 2a, the framework starts with collecting digital images of a coastal cliff via Unmanned Aerial Vehicles (UAVs) under different camera angles. These digital images are then processed under a photogrammetry workflow for creating the 3D dense point cloud of the cliff, based on which a textured 3D cliff model can be generated. A detailed explanation of this photogrammetry workflow will be shown in Section 4.2. Once the textured model is obtained, this model then is loaded into Blender [38], a free and open-source 3D computer graphics engine, for developing the VR model of the cliff. As illustrated in Figure 2b, efforts are mainly focused on two aspects to make the VR model authentic. These efforts are: 1) adding sky texture to the cliff model; and 2) configuring a realistic lighting condition. Technical details of these investigations will be explained in Section 4.3.

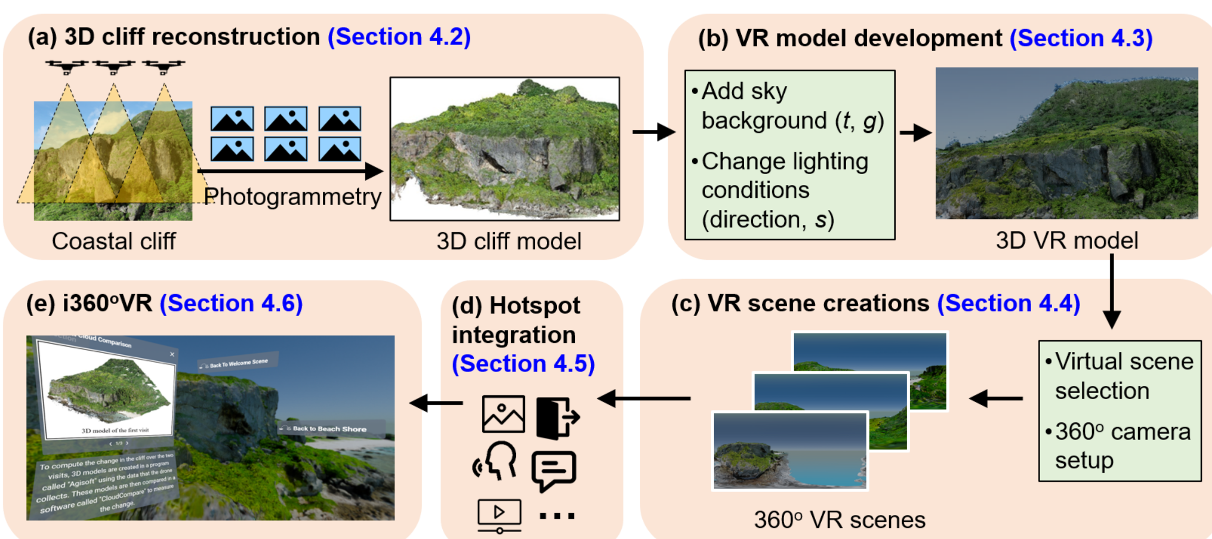


Figure 2. The proposed i360°VR framework: (a) 3D reconstruction; (b) VR model development; (c) VR scene creations; (d) hotspot integration; and (e) i360°VR.

Once the VR model of the cliff is developed, the next step is to create 360º virtual scenes as shown in Figure 2c. To this end, a virtual 360º camera is placed at pre-selected locations in the VR model of the cliff. Camera parameters are tuned such that 2:1-ratio 360º images of the cliff model can be rendered for each camera location. The demonstration of VR scene creation will be illustrated in Section 4.4. Thereafter, the rendered 360º images are integrated with multiple hotspots for producing the final i360ºVR module (Figure 2d). These hotspots, such as virtual texts, speech, 2D video clips, and transitional hotspots that enable viewers to navigate between different VR scenes, can increase the interactivity of the VR experience. The summary of the hotspot integration will be explained in Section 4.5. Finally, the established i360ºVR module for this study (Figure 2e) will be presented in Section 4.6.

4.2 3D Cliff Reconstruction

The coastal cliff (Figure 3a) studied in this research is located at Tagachang Beach on the island of Guam, a United States Territory in the Western Pacific. Consumer-grade UAVs (*i.e.*, DJI Air and DJI Phantom 4 Pro + V2.0) were deployed at the cliff site to collect digital images of the cliff from different camera angles. A detailed description of the image collection procedure can be found in [39]. Thereafter, photogrammetry technology was employed to generate a 3D dense point cloud of the cliff using the off-the-shelf software Agisoft Metashape [40]. This photogrammetry workflow is grounded in advanced computer vision algorithms, specifically structure-from-motion with multi-view stereo (SfM-MVS) [41, 42], which is a robust technique that has been widely utilized in coastal surveying [43], civil infrastructure inspection [44], and historic preservation [45, 46].

To further explain SfM-MVS, the process begins with the detection of 2D features in each image, which are small patches containing distinctive intensity distributions. For example, Figure 3 illustrates the use of the Shi-Tomasi [47] feature detection algorithm to identify such features within a cropped region (50 x 50 pixels) of a sample cliff image (Figure 3b). These features, marked as red crosses in Figure 3c and shown as individual patches in Figure 3d, are designed to remain consistent across multiple images. This consistency enables the matching of features across different images. During this procedure, both extrinsic parameters (e.g., camera positions and orientations) and intrinsic parameters (e.g., focal length and sensor dimensions) are also estimated. This alignment further serves as the basis for reconstructing a 3D dense point cloud of the cliff, which consists of millions of data points within a 3D coordinate system, capturing both geometric details and color (i.e., texture) information of the cliff.

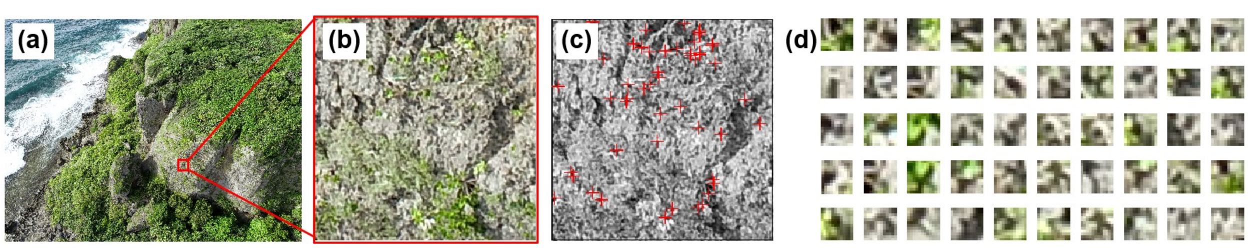


Figure 3. Feature detection illustration: (a) a sample UAV image, (b) a small image patch from (a), (c) the 50 strongest features extracted from (b), and (d) a close-up view of these features.

Figure 4a shows the established 3D dense point cloud. A closer examination of the dense point cloud under a predefined region of interest (ROI) is provided in Figure 4b. Due to the scattered arrangement of the 3D points, the dense point cloud is not ideal for direct visualization in the VR environment. To enhance the visual clarity of the cliff model, the point cloud undergoes further processing to generate wireframe and mesh models, as illustrated in Figure 4c and Figure 4d. Using the refined mesh model, a high-resolution textured model is finally created as shown in Figure 4e, serving as the basis for VR model development.

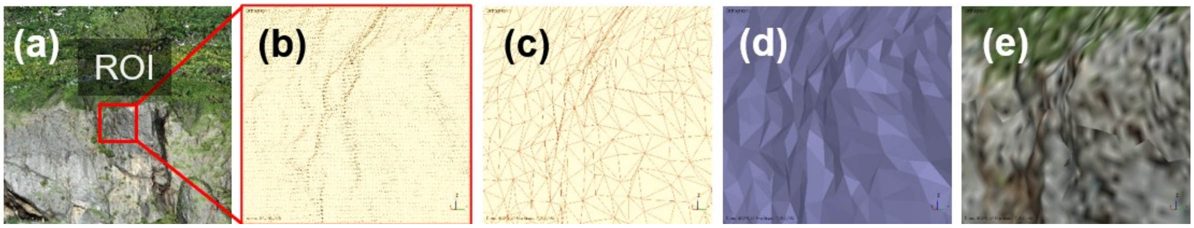


Figure 4. (a) ROI selection; (b) to (e): dense point cloud, wireframe model, mesh model, and textured model under the selected ROI.

4.3 VR Model Development

To enhance the authenticity of the textured model of the cliff, making it more realistic for being viewed in the virtual world, we utilized Blender [1] to manipulate the sky background and the lighting conditions. Figure 5 illustrates the initial considerations in Blender to properly import the cliff model. To elaborate, we first exported the textured model derived from SfM-MVS into two files (Figure 5a), including the DAE (i.e., COLLADA) model which represents the geometric features of the cliff, and a high-resolution image file (in the tiff format) containing texture information of the cliff. Through this image file, the color information of the cliff can be mapped back to the DAE model. Moving to Blender, we first loaded the DAE cliff model into the workspace. Subsequently, we loaded the image file of the cliff's texture via Image Texture and linked it to the DAE model. The outcome of applying these settings is shown in Figure 5b.

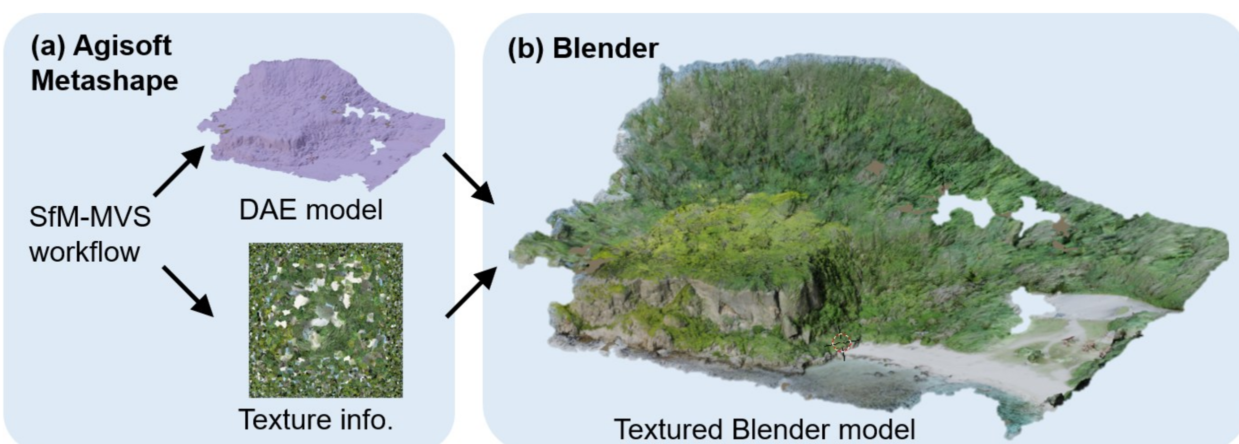


Figure 5. Initial configuration in Blender.

After initially configuring the cliff model in Blender, we proceeded to manipulate the sky background via Sky Texture within in Blender. To explain, the computer graphics model proposed by Wikkie and Hosek [48, 49] was adopted to simulate the sky background. To achieve the desired result, we first tuned the turbidity parameter, denoted as t, which influences the atmospheric conditions. According to [49], $t = 2$ yields a very clear, arctic-like sky; $t = 6$ represents a sky on a warm moist day; and $t = 10$ leads to a slightly hazy day. The results of the sky background under different t values are shown in Figure 6a to c. Next, we tuned the ground albedo parameter, denoted as g, which measures the reflective properties of the Earth's surface. Lower values of g produce a darker sky background; higher values create a brighter or white texture in the sky [49]. Figure 6d to e show the results under different g values. For the i360ºVR module of this study, we ultimately selected $t = 2.2$ and $g = 0.3$ as the final configuration of the sky background (see Figure 6a).

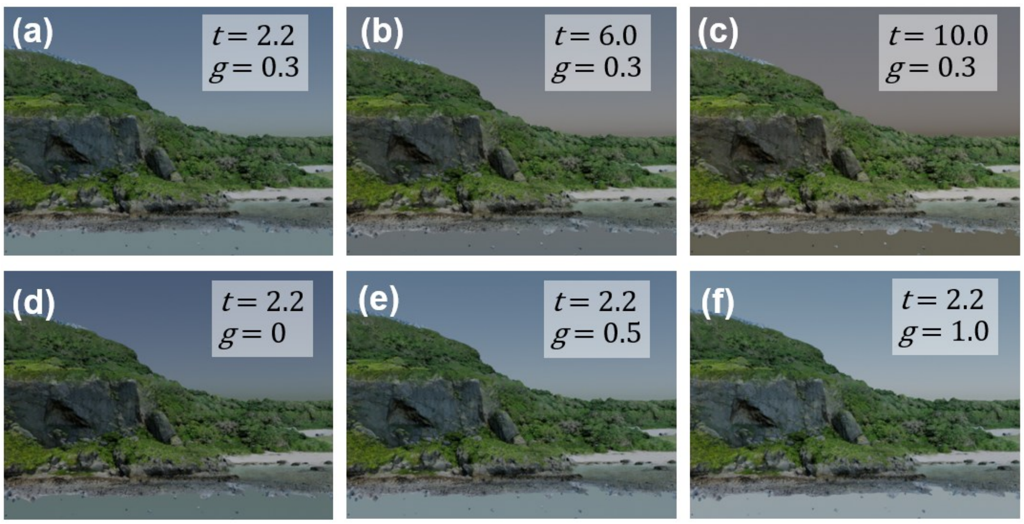


Figure 6. The cliff model under different configurations of the sky background where *t* refers turbidity; *g* refers ground albedo.

Next, we researched various light source options in Blender and determined sunlight as the most realistic choice for the outdoor environment such as coastal cliffs. Alternative lights such as point light, area light, or spotlight were deemed less suitable for capturing the natural lighting conditions of the scene. After selecting sunlight, we focused on optimizing the direction and strength of the sunlight to achieve the desired visual effect.

To achieve an optimal sunlight direction, we simulated three different scenarios, as shown in Figure 7a. Scenario 1 represents the sunlight directed vertically downward; Scenario 2 illustrates inward sunlight, perpendicular to the cliff plane (shown as the yellow dashed line in Figure 7a); while Scenario 3 refers to outward sunlight, also perpendicular to the cliff plane. Using a virtual camera positioned perpendicular to the cliff plane, we rendered images for each scenario, shown in Figure 7b to d. The results indicate that Scenario 3 (Figure 7d) leads to a darkened cliff façade due to insufficient sunlight. Scenario 2 (Figure 7c) improves brightness on the cliff plan but creates shadows on the backside of the cliff. Based on these observations, we selected Scenario 1 (Figure 7b) for the cliff model in this study.

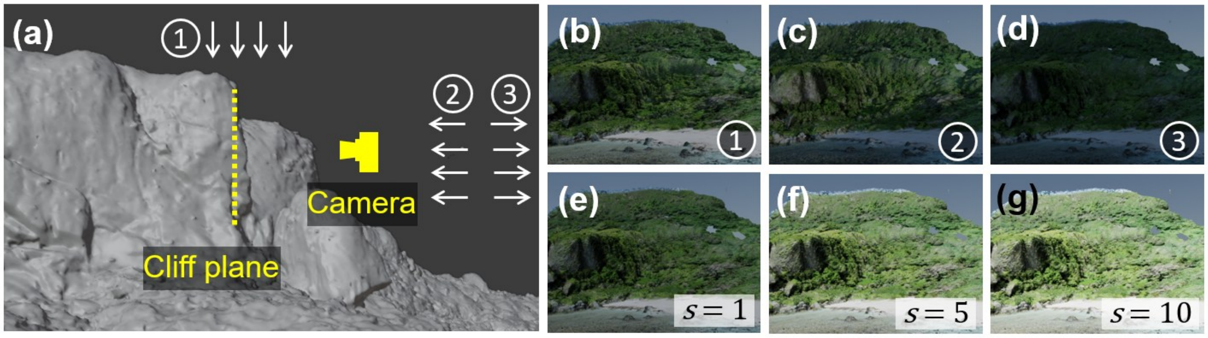


Figure 7. (a) Defines three sunlight simulation scenarios. (b) to (d) show results for Scenarios 1, 2, and 3. (e) to (g) present results under varying sunlight strengths, using Scenario 1. *s* refers to sunlight strength.

To further refine the lighting conditions, we explored different values of sunlight strength. Denoted as s, strength is a parameter to control the brightness of the light source with a scale from 0 to 10. It is worth noting that high values of s lead to an unrealistic level of brightness for the cliff. Therefore, we used $s = 1.2$ in this study. Figure 7e to g represents the impact of s values on the visual appearance of the cliff under the same virtual camera position defined in Figure 7a.

Notice that the textured model of the cliff obtained through the SfM-MVS workflow inherently incorporates lighting conditions from field UAV images. This includes the presence of shadows and sunlight on the cliff façade, which accurately reflect the lighting conditions on the day of field UAV image collection. The simulations of the direction and strength of the sunlight in Blender described in this subsection serve to augment the lighting conditions of the cliff rather than override the original lighting conditions.

4.4 VR Scene Creation

Once the VR model was developed, we proceeded to render three 360° images in Blender to serve as the virtual scenes for the i360°VR module. Figure 8 provides an overview of this process. First, we configured an equirectangular panoramic 360° camera and aligned it horizontally to replicate a human field of view. The 360° camera was then positioned at three distinct locations on the cliff, marked by yellow dots in Figure 8. These locations were strategically chosen: Location A near the beach, Location B at the plateau, and Location C close to the cliff façade.

To render the 360° images, we used the Cycles Render Engine and set the image resolution to 2000 × 1000 pixels, the standard 2:1 aspect ratio commonly used for panoramic 360° imagery. The rendered images, referred to as Scenes A, B, and C, are shown in Figure 9b under Section 4.5. These high-resolution, immersive 360° images offer viewers a dynamic and comprehensive representation of the virtual environment. It is important to note that the sky background and lighting effects simulated in Section 4.3 are visible only in the rendered images and not in the 3D view of the cliff model. Consequently, these visual effects are not depicted in Figure 8.

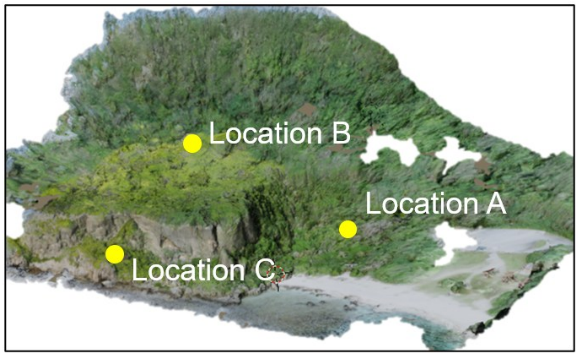


Figure 8. A virtual 360º camera is placed at Locations A, B, and C on the cliff.

4.5 Hotspot Integration

Once the VR scenes were rendered, we integrated multi-type hotspots into these scenes via VIAR360 [50], an online web-browser-based VR editing platform. A total of four VR scenes are included in this workflow, consisting of a welcome scene and three additional VR scenes built upon the rendered 360º images derived from the cliff model as described in Section 4.4. Figure 9 shows the VR editing flowchart which is re-created based on the manuscript in Appendix C. This flowchart in Figure 9 describes the navigation path between different VR scenes, the themes of VR scenes, and the contents of hotspots added to VR scenes. Additional information that is not included in the flowchart is illustrated below.

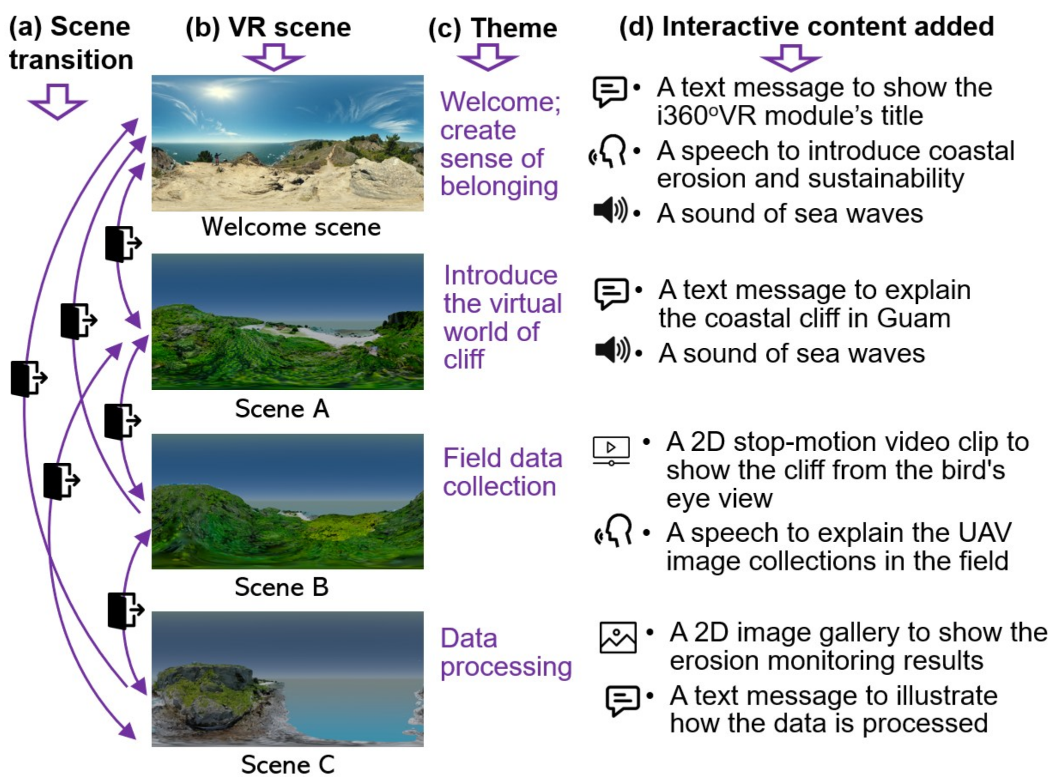


Figure 9. VR editing flowchart.

- **Welcome scene:** This VR scene was created using a copyrighted free 360º image of a coastal cliff downloaded from the internet [51]. This VR scene aimed to offer participants a sense of belonging to the i360ºVR module. A few interactive hotspots were added to this scene including a text message, a speech, and a repeatable sea wave sound. The speech was generated by a system-embedded artificial intelligence (AI) tool which can generate voices from a user-defined script. The script of this speech can be found in Appendix A.

- **Scene A:** This VR scene features a rendered 360º image taken from Location A in the cliff model, which is close to the beach area. A brief text message is added to the scene to explain the cliff model in Guam. Also, a repeatable sea wave sound is also added to this scene to enhance the authenticity of the virtual environment.

- **Scene B:** The topic of this VR scene is to introduce the UAV image collection in the field. To accommodate this, we added a stop-motion video to the scene to illustrate a sequence of sample UAV images collected in the field. The video clip is about 36 sec and is created by stitching together 99 UAV images in chronological order. This allows the viewer to see the cliff from the perspective of the UAV. A speech with an AI-generated voice was also added to the scene, explaining the procedure for UAV image collection. The script of this speech can be found in Appendix B.

- **Scene C:** In this VR scene, we added a 2D image gallery to show typical data processing results. This image gallery includes three images that were taken from the author's previous work on erosion monitoring of this cliff [39] which includes the cliff's point cloud from the first field visit, the cliff's point cloud from the second field visit, and the cloud-to-cloud comparison to highlight the differential changes caused by erosion. In addition, a text message was added to the scene to explain the procedure of data processing work.

To create a seamless and interconnected narrative, we added transition hotspots to all VR scenes to link them as one cohesive story. Shown in the purple arrows in Figure 9a, these transition hotspots allow the viewer to have the freedom to walk from one VR scene to another with multiple possible routes. For example, after the viewer completes the exploration in Scene A, the viewer has the option to explore Scene B, proceed to Scene C, or return to the welcome scene. These transition hotspots enable personalized exploration such that viewers can craft their own unique journey, engaging with the content according to their preferences and interests.

Figure 10 provides an overview of the layout in VIAR 360 [50], which is the VR editing platform in this study. The blue grid lines in the figure refer to the 360º coordinate system overlaid on the VR scene, facilitating the VR editing work. Two transition hotspots have been added to the VR scene. When the viewers interact with these hotspots using VR controllers, they can proceed to different scenes based on their choice. Also shown in the figure, a hotspot of the image gallery is established. Upon clicking this hotspot, a collection of 2D images showing the cliff monitoring results will appear within the virtual environment. This allows the viewer to access additional information. Next, POV (point of view) signifies the initial viewpoint once the viewer enters the scene, determining the perspective from which the VR experience begins. Lastly, the editing manual can be found on the left-hand side of the VR editing platform. The manual offers guidance and instructions on various hotspots that can be utilized in the VR scene.

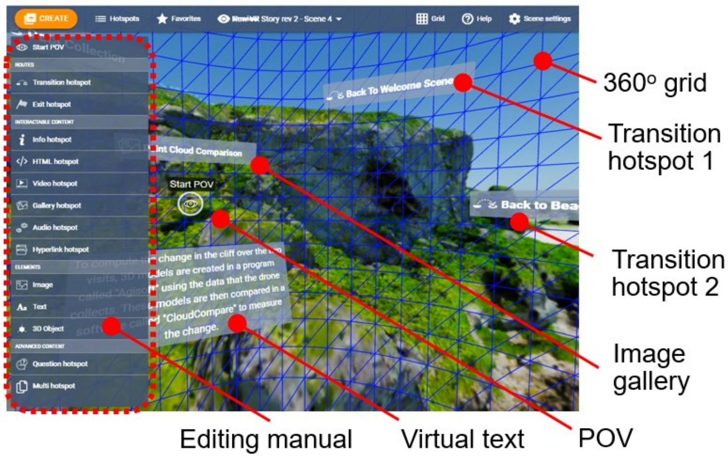


Figure 10. The layout of the VR editing platform

4.6 Established i360ºVR Module

Figure 11 shows the results of the developed i360ºVR module. Since the virtual world is presented in 360º coordinates, we captured screenshots from various viewing angles. In total, four screenshots (labeled a to d) are taken for the welcome scene, Scene A, and Scene B. Each screenshot approximately covers a viewing angle of 90º (360º as a whole). Scene C only contains three screenshots (labeled a to c); while the last screenshot is not provided. The missed screenshot only captures the sky and sea and does not contain any hotspots or the cliff model.

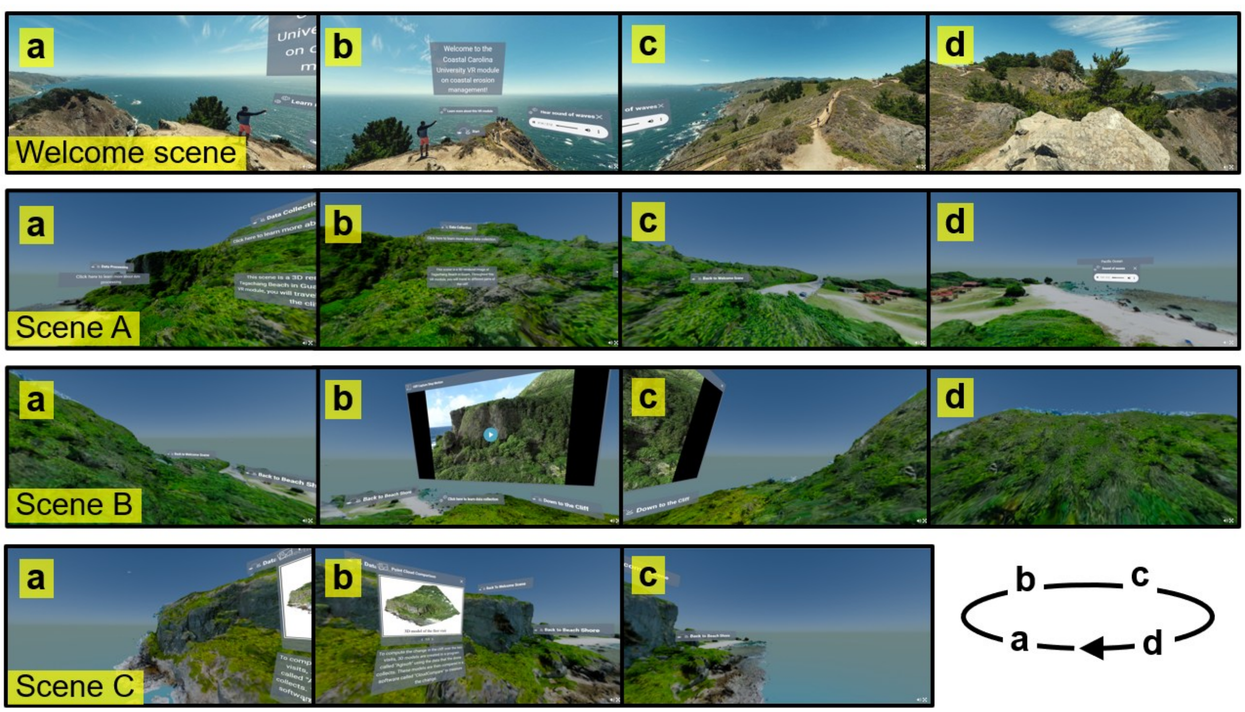


Figure 11. Screenshots from four scenes of the established i360ºVR module.

Notice that the inclusion of transition hotspots within the VR scene, as described in the map of Figure 8a, provides viewers with the flexibility to choose their own distinct routes while exploring the virtual world. For example, one viewer might choose a route such as the welcome scene → Scene A → Scene B → Scene C. On the other hand, another viewer may opt for a different path such as the welcome scene → Scene A → Scene C → the welcome scene → Scene A → Scene B. By offering multiple options for scene transitions, the i360°VR module caters to individual preferences and allows viewers to personalize their exploration of the virtual environment. This approach enhances user engagement and offers a more tailored and immersive experience within the i360°VR module.

5. Evaluation of the i360°VR Module

5.1 Overview

Several goals of the assessment were established (see Table 2) before designing the experiment protocol evaluating: a) immersion and interactivity of the established i360°VR module, b) whether or not the i360°VR module can offer a tangible learning environment, and c) whether or not the i360°VR module can change the participants' perception about coastal erosion. Based on these goals, we then reviewed and selected suitable assessment instruments and the assessment method from the literature. The selections of assessment instruments are summarized in the third and last columns in Table 2.

The rest of this section is structured as follows: Section 5.2 summarizes the participants for this experiment; Section 5.3 illustrates the software and hardware needed for this experiment; Section 5.4 reports the experimental procedure; Section 5.5 explains the rationale for selecting assessment instruments and methods (*i.e.*, the last two columns in Table 2) for this study; and Section 5.6 reports the findings from assessment data.

Table 2: Assessment goals, questions, instruments, and methods.

Assessment goal	Assessment question	Instrument	Method	Results
Immersion	To what extent does the established i360°VR module offer an immersive virtual experience to the participants?	F1, G2, and G6 of EduVR rubric (**Sec. 5.5.3**)	Post survey	Sec. 5.6.1
Tangible learning environment	To what extent does the established i360°VR module provide a tangible learning environment that relates to coastal erosion?	Sense of Presence Questionnaire (**Sec. 5.5.2**)	Post survey	Sec. 5.6.2
Interactivity	To what extent does the established i360°VR module allow a user to navigate and interact with the virtual environment?	F2, F3, and F4 of EduVR rubric (**Sec. 5.5.3**)	Post survey	Sec. 5.6.3
Perception of coastal erosion	To what extent does the established i360°VR module change the participants' perception of coastal erosion?	Attitudes Toward Coastal Erosion (**Sec. 5.5.1**)	Pre & post survey	Sec. 5.6.4

5.2 Participants

The participants (*n* = 15) of the experiment included a mixture of cisgender men (12) and women (3). The participants' ages ranged from 18 to 50 (*M* = 22.47, *SD* = 8.70). The participants included first-year students (6), sophomores (5), juniors (2), and seniors (2). The participants identified as African/African American/Black (5), Caucasian/European American/White (8), Asian/Asian American (1), and Middle Eastern or North African (1). These participants completed all surveys as illustrated in Table 2, as well as other activities as described in Section 5.4.

5.3 Materials

The implementation of the VR activities was achieved through Meta Quest 2 [52], a VR headset designed and manufactured by Meta (Figure 12). The headset weighs 503 g and has a display resolution of 1832 pixels by 1920 pixels per eye. The headset also comes with 128 GB of internal storage and two hand controllers. The Meta Quest 2 utilizes a Meta-developed VR system that allows the user to enter a virtual lobby to perform common operations using hand controllers, such as browsing the internet, accessing a variety of VR apps, and configuring the system settings.

After the i360°VR module was developed via the online platform VIAR360 [15], the module was then published on VIAR360.com. This allows users to access the i360°VR module from the VR headset. To view the module, participants used the VIAR360 Virtual Player app, which was installed through Meta Store in the headset. This app was developed by VIAR360 to enable users to view the established i360°VR module in the virtual environment.

Figure 12. Meta Quest 2

5.4 Procedure

Figure 13 illustrates the experimental procedure, which contains two major components: recruitment of participants (Figure 13a) and implementation of the VR activities (Figure 13b). Each component will be explained in detail in the rest of this section.

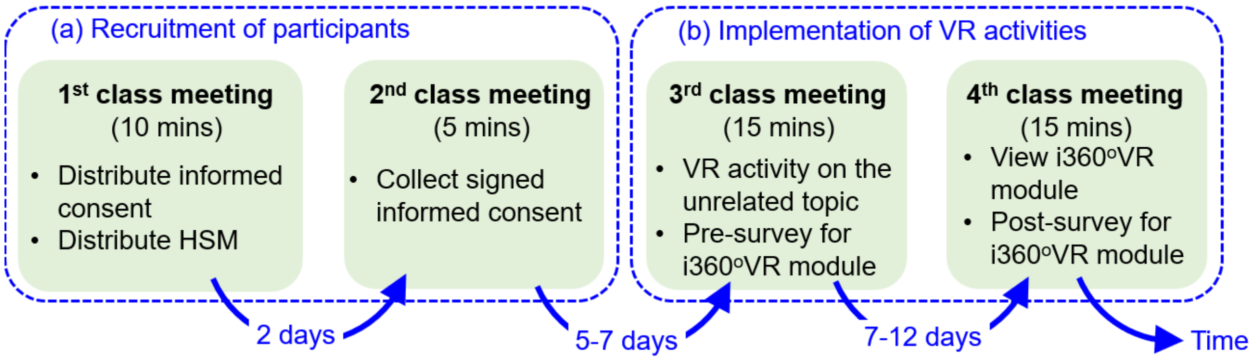


Figure 13. The procedure of the experiment.

5.4.1 Recruitment of Participants

We recruited the participants from two undergraduate engineering courses at Coastal Carolina University including 1) two class sections of Engineering Problem Solving which is an entry-level course that focuses on programming, robotics, sensing technologies, and engineering report writing [53]; and 2) one class section of Engineering Mechanics I: Statics which is an entry-level engineering mechanics course. Most of the students in these courses are Engineering Science majors; while a small portion of them are in other majors or non-degree-seekers. An incentive for a $10 Amazon gift card was given to the participant who completed all required activities.

As shown in Figure 13a, we first visited two class sections of Engineering Problem Solving. During this meeting, we distributed the informed consent forms to the students, showed a promotional Microsoft PowerPoint slide on the concept and applications of VR, explained the benefits and risks of participating in the experiment, and answered questions from the students. During our visits, we also distributed hard copies of the Health and Safety Manual (HSM) of the Meta Quest 2 [54], in which the potential health risks of engaging the VR headset have been illustrated. These health risks are associated with any VR activities in general and are not specifically tied to this experiment. The students were then asked to bring informed consent and HSM back home and reflect on this participation opportunity at their own pace. After two days, we met the students again in the second class meetings, addressed additional questions from the students, and collected signed informed consent forms from those who agreed to participate. In total, 3 out of 7 students in one class section and 11 out of 17 students in another class section signed the forms.

The recruiting procedure for one class section of Engineering Mechanics I: Statics was the same, except for the fact that no promotional PowerPoint slide was displayed during the first visit. This might be the cause of a lower participation rate compared with the other two sections of Engineering Problem Solving mentioned above. Only 1 out of 13 students signed the informed consent. Combining all three sections from two engineering courses, a total of 15 participants were recruited for the experiment.

5.4.2 Implementation of VR Activities

In the third class meeting (see Figure 13b), all participants who signed the informed consents were invited to view a VR demonstration that was unrelated to the i360°VR module we developed. The purposes of this arrangement are two-fold: 1) test the VR headset outside the lab environment; and 2) ensure our developed i360°VR module is not the participant's first VR experience, as studies in literature reported potential fear associated with the first VR experience [55]. Such an experimental design strategy was also adopted by [56]. To implement this VR activity, we first briefly instructed the participants on how to use the VR headset and hand controller. Then the participant wore the headset and spent 5 to 8 minutes on a VR app called First Steps, a game engine-based VR module developed by Meta [57]. During this VR demonstration, participants learned how to use headsets and controllers and became familiar with a typical virtual environment. Next, participants were asked to exit the VR module and complete the pre-survey on Attitudes Toward Coastal Erosion as illustrated in the last row of Table 1. Notice that this questionnaire is for assessing the upcoming i360°VR experience, not related to participants' first VR experience on the same day.

To ensure participants had enough time to reflect on their first VR experience, the fourth (and the last) class meeting was held 7 to 12 days later, as illustrated in Figure 13b. During this class meeting, we first invited the participants to view our developed i360°VR module. Although participants already obtained their first VR experience in the third class meeting, the layouts of virtual scenes are quite different between the game engine-based VR module (i.e., First Steps they already viewed) and the i360°VR module (i.e., the module to be viewed in this class meeting). To accommodate this, we printed two typical virtual scenes of the i360°VR module onto a letter-size paper and briefly instructed the participants about typical hotspots they were about to experience. Then, the participants spent 5 to 8 minutes experiencing the i360°VR module. This allowed the participants to navigate into different virtual scenes and interact with the virtual environment through hotspots. Once completed, we distributed the survey instruments to the participants to conclude the experiment. These instruments included the post-survey questionnaire on Attitudes Toward Coastal Erosion, Sense of Presence questionnaire, F1, G2, and G6 of EduVR rubric for immersion, and F2, F3, and F4 of EduVR rubric for interactivity.

5.5 Instrument

5.5.1 Attitudes Toward Coastal Erosion

Changes in participants' perceptions about coastal erosion were measured with a researcher-modified version of the Attitudes Towards the Urgency of Climate Change subscale of the Attitudes Towards Climate Change and Science Instrument (ACSI) [58]. Only one six-item subscale (Table 3) was selected from this instrument due to its alignment with the research questions. Modifications were made to the items in this subscale (*e.g.*, the words "coastal erosion" were substituted for the original instrument subscale's language of "climate change" for each item). Participants completed six survey questions on a five-point Likert-type scale from strongly disagree to strongly agree on the pre-survey before viewing the i360°VR module, and the post-survey immediately after.

Table 3: Attitudes toward coastal erosion instrument

	Statement
S1	People should care more about coastal erosion
S2	Coastal erosion should be given top priority
S3	It is annoying to see people do nothing for the coastal erosion problems
S4	People worry too much about coastal erosion
S5	The seriousness of coastal erosion has been exaggerated
S6	Coastal erosion is a threat to the world

5.5.2 Sense of Presence

A modified version of Nichols et al's [59] Sense of Presence Questionnaire was used as a post-survey (Table 4). The Sense of Presence Questionnaire is a nine-item instrument that was developed to assess participants' sense of presence in a virtual environment. Two items from the original questionnaire were removed for this study because those items assessed the game features of a virtual experience, which did not align with the research questions of this study. Participants rated their feelings of presence on varying seven-point scales (*e.g.*, 1 [not at all/no more enjoyable/at no time] to 7 [very much/a great deal more enjoyable/almost all the time]). While neither the reliability nor validity of the instrument has been conclusively determined, the instrument is widely used to evaluate presence in virtual environments. Schwind et al. [60] have noted that the instrument had been cited more than 158 times in their study's publication.

Table 4: Modified Sense of Presence Questionnaire

	Question
Q1	In the virtual world, I had the sense of "being there"?
Q2	How flat and missing in depth did the virtual world appear?
Q3	Do you think of the virtual world as…?
Q4	How disturbing was the lag or delay between your headset movements and the response in the virtual world?
Q5	Whilst you explored the virtual world, background voice and sound were played in the background. How much attention did you pay to it?
Q6	Did the virtual world become more real or present to me compared to the "real world"?
Q7	How interested did you feel after the experience?

5.5.3 EduVR Rubric

Six dimensions from Fegely and Cherner's [61] comprehensive rubric (see Appendix D) for evaluating educational VR experiences were chosen to evaluate the immersive and interactive qualities of the i360^{o}VR module. Immediately after their VR experience, participants rated the i360^{o}VR module on a 5-point criterion-referenced Likert-type scale for each of the six dimensions.

The six dimensions were specifically selected from this rubric because it is the only criterion-referenced and research-supported rubric currently in existence for evaluating educational VR experiences. While other methods of evaluation, such as star or number ratings are subjective in nature, criterion-referenced instruments help to ensure consistent, reliable, and valid evaluations. Criterion-referenced instruments attach specific guidance for the rater as well as purposefully tiered criteria that the rater must observe within the subject under evaluation for the subject to receive a specific rating [62].

To evaluate immersion, the rubric dimensions chosen included F1 Authenticity and Realism, G2 Pathways, and G6 Immersion. These three dimensions were chosen as they are all essential tenants for evaluating the immersive nature of a VR experience. Authenticity in this context refers to the environment appearing grounded in an accurate representation of a real-world location [61]. The Authenticity and Realism dimension was selected because the fact-and-measurement-based accuracy of a VR environment's digital copy of a physical environment is essential for fostering immersion [17]. Pathways refer to the number of options users have while moving through VR experience. This includes both the number of complex paths and pacing (either computer-regulated or self-paced). Movement in a VR environment that is similar to the real world can help foster feelings of immersion within a digital experience [63]. Users' sense of immersion within a VR environment is built on presence - "the sense of being there" [64] - and is fostered by rich sensory inputs. The Immersion dimension measures how absorbed users become within the VR experience through its sensory inputs (e.g., visuals and audio).

To evaluate interactivity, F2 Content Presentation, F3 Navigational Aids, and F4 Multimedia Elements were chosen from the rubric. These three dimensions were chosen to evaluate interactivity as they align with the interactive features offered by the VR environment. Content Presentation evaluates how users interact with multimedia elements through active and/or passive engagement strategies. Similarly, Multimedia Elements assesses the quality of integration and organization of the text, graphics, video, images, sounds, etc. within the user experience. Another way users interact in VR is with the environment itself. Navigational Aids measures intuitiveness and supports in place to ensure users can maneuver throughout the VR environment efficiently.

5.6 Results

5.6.1 Immersion

Table 5 shows the results for assessing immersion of the established i360ºVR module on a 5-point Likert scale. The lowest-scoring element of the i360ºVR module across all dimensions was Authenticity and Realism. This dimension garnered a score of 3.13/5.00, which according to the rubric, indicates that participants found the VR environment to have minor flaws which disturbed the overall user experience. While the digital version of the coastal environment was based on accurate camera scans documenting a real-world environment, participants did not find it indistinguishable from reality. Therefore, the graphics resolution, field of view, and other aspects that contribute toward the authenticity and realism of the i360ºVR module can be improved.

The Pathways dimension measured the number of options available to learners as they move within the i360ºVR module. Because of the nature of the camera capture of 360º VR, participants were tied to a linear, predetermined path. Therefore, a score of 3.80/5.00 is noteworthy for this dimension because of the inherent limitation of 360º-captured VR.

The Immersion dimension measures how present and absorbed learners become within the VR environment through sensory richness. The score of 3.49/5.00 indicates that some of the participants' senses were stimulated, but the sensory experience could be improved to strengthen the module. Overall, the immersive aspects of the i360oVR module show promise, but can be improved, which may impact the effectiveness of the i360oVR module overall. For example, learners' perceptions of immersion can lead to enhanced engagement [31] and more active learning compared to textbooks or videos [65, 66, 67]. Immersion has also been indicated to help improve learners' attitudes and achievements related to STEM subjects [68, 69, 70].

Table 5: Immersion results

Dimension	*M*	*SD*
F1 Authenticity and Realism	3.13	0.64
G2 Pathways	3.80	0.41
G6 Immersion	3.53	1.19
Total	3.49	0.34

5.6.2 Tangible Learning Environment

Table 6 summarizes the results of assessing the tangible learning environment of the established i360ºVR module on a 7-point Likert scale. The questions in the table are the same as those in Table 4. Presence, simply explained as "the sense of being there" [64], is the learners' perception that a digital environment is real [71].

Participants' ratings of their sense of presence in Table 6 revealed that the highlights of the i360ºVR module were the lack of lag in the VR experience (M = 5.87, SD = 1.19) and the quality of sound elements within the VR experience (M = 5.33, SD = 0.82). Furthermore, participants' ratings indicate that the authenticity of the i360ºVR module made them feel as though they were actually in the location that they were virtually placed in (M = 4.47, SD = 0.99), and the was interesting to them (M = 4.80, SD = 1.32). However, participants' positive perceptions of the authenticity and interest they experienced in the i360ºVR module were tempered by their average ratings of the depth of the virtual world (M = 3.87, SD = 1.46), which impacted their perceptions of presence. The nearly one-and-a-half point standard deviation of participants' ratings on the depth question suggests that there were varying viewpoints on how flat or deep the i360ºVR environment was. While discordant, the large standard deviation for this question is encouraging since depth is inherently limited in the i360ºVR approach described. Despite participants being restricted to predetermined spots without the ability to freely roam the environment, some still rated the depth as moderate or high. Overall, the participants experienced a moderate level of presence within the VR experience (4.55/7.00).

Table 6: Results of tangible learning environment

	M	*SD*
Q1	4.47	0.99
Q2	3.87	1.46
Q3	4.00	1.60
Q4	5.87	1.19
Q5	5.33	0.82
Q6	3.53	1.19
Q7	4.80	1.32
Total	4.55	0.27

5.6.3 Interactivity

Table 7 summarizes the results for assessing interactivity on a 5-point Likert scale, measuring the i360ºVR module's content presentation, navigational aids, and multimedia elements. The highest-scoring elements across all rubric dimensions were in navigational aids and multimedia elements (see Table 7). Navigational aids support learners' movement within a VR environment, helping ensure that they do not become frustrated or lost while maneuvering between learning areas [61]. A score of 4.20/5.00 in this dimension indicates that participants found the navigational aids to be mostly intuitive and logically placed, which helped them maneuver through the environment at their own pace. A score of 4.33/5.00 indicates that the i360ºVR module's text, iconography, graphics, colors, and other multimedia elements were positioned intuitively for user interaction and did not enhance nor detract from the VR experience. The lower-scoring content presentation dimension (3.53/5.00) aligns with the limitations of the VR platform used, which does not allow for communication between users. Therefore, this indicates that the multi-model elements (text, images, audio, video) within the VR experience earned as high a score as possible for this module given its platform limitations.

Table 7: Interactivity results

Dimension	*M*	*SD*
F2 Content Presentation	3.53	0.92
F3 Navigational Aids	4.20	0.86
F4 Multimedia Elements	4.33	0.72
Total	3.67	0.99

5.6.4 Perception of Coastal Erosion

Table 8 summarizes the results for assessing the perception of coastal erosion on a 5-point Likert scale. Participants' average ratings increased on all statements except for "It is annoying to see people do nothing for the coastal erosion problems" which decreased slightly (-0.20). The data were found to be normally distributed for the pre- (p = .772) and post-surveys (p = .594) according to Shapiro-Wilk test results (p > .05) [72]. Therefore, a parametric paired samples *t*-test was used to analyze the survey data. A paired samples *t*-test was conducted to compare participants' survey responses on the pre- and post-surveys. The paired samples *t*-test ($p < .05$) revealed that while participants' post-survey ratings were higher than their pre-survey ratings, the participants' increases from the pre-survey ($M = 3.59$, $SD = 0.43$) to the post-survey ($M = 3.75$, $SD = 0.43$), $t(14) = -1.52$, $p = .150$ did not reach a statistically significant level. The effect size calculation (Cohen's $d = .51$) exceeded Cohen's [73] convention for a medium effect.

Table 8: Results of perception of coastal erosion

	Pre-survey		Post-survey	
	M	***SD***	***M***	***SD***
S1	4.07	0.46	4.33	0.49
S2	3.27	0.70	3.33	0.82
S3	3.67	0.82	3.47	0.74
S4	3.60	0.83	3.73	0.80
S5	3.53	0.83	3.87	0.74
S6	3.40	0.63	3.79	0.70
Total	3.59	0.27	3.75	0.35

6. Discussions

6.1 Summary of i360ºVR Development

The development process of the i360°VR module, as outlined in Section 4, demonstrated the feasibility of creating an interactive and immersive learning environment using accessible tools and innovative workflows. By employing photogrammetry technology, the framework achieved a high degree of authenticity in replicating the real-world coastal cliff. The resulting 3D textured model, enhanced through Blender for realistic lighting and sky conditions, served as the foundation for generating 360° virtual scenes. These scenes, integrated with interactive hotspots via VIAR360, provided an engaging user experience that allowed participants to navigate and explore virtual environments effectively.

Despite these achievements, certain aspects of the development process presented challenges that need further attention. While photogrammetry enabled accurate and visually compelling models, lighting and texturing could be improved to further enhance the realism of the VR environment. Additionally, the integration of interactive elements, though successful in adding engagement, was limited to pre-defined functionalities within the VIAR360 platform such as navigation and media playback. Expanding the range of interactions, such as enabling users to manipulate virtual objects or trigger scenario-based changes, could further enrich the educational value of the module. These extra features are not supported at this point.

6.2 Summary of i360ºVR Evaluation

The evaluation of the i360°VR module, as detailed in Section 5, highlighted its strengths and areas for improvement, offering valuable insights into its impact as an educational tool. Looking across the results with a normalized scale (out of 1.0), data indicated that participants experienced moderate levels of immersion (*M* = 0.70; *SD* = 0.34), presence (*M* = 0.65; *SD* = 0.27), and interactivity (*M* = 0.74; *SD* = 0.14) within the i360°VR module. The navigational aids, multimedia elements, and pathways dimensions received the highest ratings, with participants finding them intuitive and supportive of user interaction. The lowest-rated response was in the Tangible Learning Environment category's question 6: *Did the virtual world become more real or present to me compared to the "real world"?*

The results underscore a tradeoff between the authenticity provided by real-world 360° images and the freedom of movement available in game engine-based VR. While the i360°VR platform achieved a balance by offering authentic, photogrammetry-based scenes, its inherent limitations in user navigation and movement compared to fully computer-generated VR environments were apparent. Despite this, the evaluation revealed encouraging outcomes, with participants recognizing the module's potential to deliver meaningful first-person experiences that are difficult to replicate in traditional educational settings. Furthermore, while the module moderately influenced participants' perceptions of coastal erosion, fine-tuning the framework—such as extending the duration of use or introducing more immersive scenarios—may amplify its impact.

7. Broadening i360°VR in STEM Education

The proposed i360°VR approach in this study also shows great promise to be applied into other STEM education fields. In this section, we discuss the potential frameworks of using i360°VR in new contexts from two institutions including 1) proposing a remote VR lab for the mechanical engineering program at California State University Fresno (Fresno State) in Fresno, California; and 2) advancing physics education of non-STEM majors at Coastal Carolina University (CCU) in Conway, South Carolina.

7.1 Remote VR Lab for a Mechanical Engineering Program

The mechanical engineering (ME) program at Fresno State is a dynamic and rapidly growing hub, serving about 460 undergraduate students. However, as a result of a significant enrollment surge over the last four years, the program faces a critical challenge in meeting the demand for fluid mechanics lab sections due to limited lab space: the ME program must share its two fluid mechanics lab spaces (EW 130B and EW 122) with the Civil Engineering program. This constraint could negatively impact on student learning experience. For instance, in a typical lab group of five students in a pipe friction test, some students may struggle to observe critical details, such as changes in air pressure, due to the confined space and the small size of measurement gauges, limiting their ability to fully engage with and understand the experiment.

Establishing a remote VR seems to be an innovative solution to address these challenges. To evaluate the feasibility and likelihood of the success of this approach, we investigated the enrollment data of the program students. A data analysis revealed that most ME students are from local areas within San Joaquin Valley [74]. A substantial portion of these students are nontraditional learners who face daily commutes ranging from one to four hours, depending on their locations. For example, students from Bakersfield must travel over two hours to reach campus, as Fresno State is the only California State University (CSU) campus within 275,000 square miles of the San Joaquin Valley offering a BS degree in Mechanical Engineering (see Figure 14). Nearby four-year institutions, such as CSU, Bakersfield, do not have an ME program. This enrollment data analysis underscores the significant benefits of a remote VR lab, which would reduce the need for students to travel to campus, enhance accessibility, and offer greater flexibility in completing lab requirements.

Figure 14. San Joaquin Valley in California (the figure is modified from [75])

As the pilot study, we conceive a possible framework to adapt the proposed i360ºVR approach for developing an i360ºVR module of pipe friction lab section, serving as the basis for establishing a remote VR lab for the ME program over the long term. The proposed i360ºVR aims to replicate the pipe friction measurement experiment (see Figure 15), a critical part of the course that helps students understand concepts such as pressure drop, friction factor, and Reynolds number. Using the photogrammetry technology shown in this study, the experimental setup of pipe friction—including pressure gauges, flow meters, and the pipe network—would be captured in detail, along with real-time data like pressure readings and flow rates. These elements would then be integrated into an immersive virtual environment, where students can observe the changes in pressure drop at various flow rates and interact with hotspots that provide additional information and explanations. The module could also include dynamic visualizations, such as plotting the friction factor against the Reynolds number, allowing students to see how factors like pipe roughness affect design considerations for specific pressure losses in fluid systems. This could be done via a 2D video display in the virtual environment.

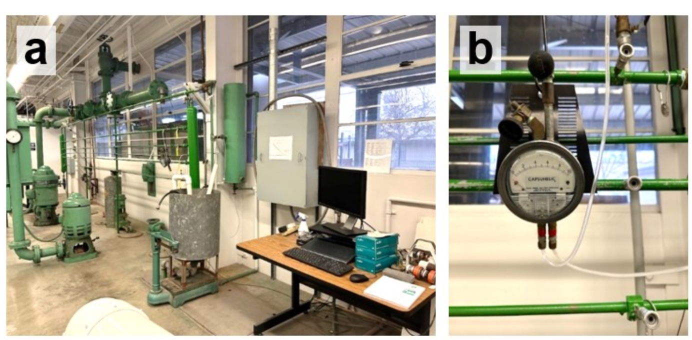


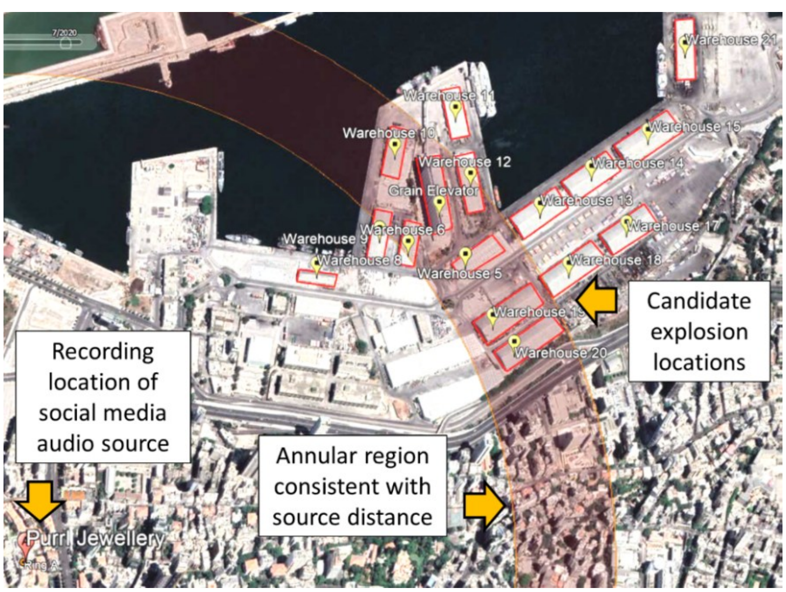
Figure 15. (a) Pipe friction lab equipment; and (b) detailed look of the water pressure gauge.

Interactive features enhance the learning experience by enabling students to manipulate parameters like flow rates and observe their effects on pressure and Reynolds number in real time. The inclusion of videos showing live changes in pressure and flow rate from gauges and monitors further enriches the authenticity of the VR module. This framework not only addresses the increasing demand for fluid mechanics lab sections due to limited lab space and rising enrollments but also provides a highly engaging and accessible learning tool. While this paper focuses on the framework for developing such a module without performing user testing, future iterations can incorporate student feedback and assessment data to continuously improve its effectiveness in achieving learning outcomes.

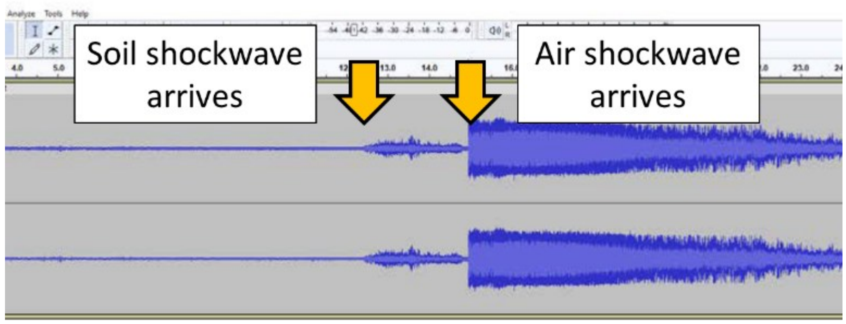
7.2 Integrating i360ºVR in Physics Education

The proposed i360ºVR approach in this study also shows potential to be integrated into physics education in PHYS 104 Science for Security at CCU. Offered by the Department of Physics and Engineering Science, PHYS 104 is designed for non-STEM students majoring in the Intelligence and Security Studies program. The course has ten two-hour-long laboratory configurations throughout the semester and is designed under the physics-based, open-source intelligence (OSINT) framework. OSINT applies physical principles and scientific methods to analyze publicly available data, such as videos, images, seismic readings, or audio recordings, to extract actionable insights.

To meet this goal, a new curriculum was developed and implemented in Fall 2023 with 24 non-STEM students based on the analysis of an industrial accident scenario of the August 2020 port explosion in Beirut, Lebanon [76, 77]. Figure 16 summarizes the current developed curriculum materials. For instance, students used the General Public License (GNU) software Audacity [78] to identify arrival times of shockwaves in the soil and air in social media audio to determine source distances (Figure 16b). In a different class meeting, students were instructed to apply Google Earth [79], range-ring plugin tool, and source distances to triangulate on the explosion epicenter (Figure 16a).



(a)



(b)

Figure 16. PHYS 104's class activities on (a) sourcing distances for the explosion epicenter; and (b) finding source distances in shockwaves.

For the above discussion, the PHYS 104 curriculum involves complex topics and skills that require students to perform spatio-temporal, 3-dimensional reasoning tasks, such as analyzing the differing wave speeds of soil and air shockwaves and triangulating the explosion location. These tasks demand a solid understanding of kinematics, including the relationships between position, velocity, and acceleration, as well as the dynamics of differently moving objects like wavefronts. The i360^{o}VR approach proposed in this study offers significant potential to enhance student learning in this context by providing an immersive and interactive environment where these abstract concepts can be visualized and explored in real time. Through virtual scenarios that replicate real-world phenomena, students can gain deeper insight into the interplay of physical principles, improving their conceptual grasp and engagement with the material.

Table 9 illustrates the proposed principles in developing the i360^{o}VR modules for PHYC 104 in the future. To this end, we adopt the embodied learning approaches [80, 81] along with research findings on embodied learning and mixed reality [82]. The learning strategies listed in the first column of the table are adapted from [82].

Table 9: Proposed i360^{o}VR principles

Learning strategies from [82]	**Implementation strategies in i360^{o}VR**
Sensory-motor activation of key processes	Interactive audio, video, and animations allow students to visualize wave propagation and wave speed concepts.
Congruency between the gestures the learning content	User movement and reorientation align gestures with the data analysis and event perspectives.
Perception of immersion in the relevant context	Interactive nested media immerse users in the event's context.
The augmentation of reality that is uniquely beneficial	Layered, interactive data sources highlight the spatial relationships critical for analysis.
Link unobservable phenomena with rapid feedback	Students can rapidly switch perspectives, enabling quick experiments and understanding of shockwave arrival times.
Appropriate assessment of outcomes attainment	Embedded assessments evaluate kinematic understanding, explosion source location, and yield estimates.

8. Conclusions

In this study, we first reviewed the literature work of VR research that is based on both game engines and 360º media by identifying the research needs to propose a novel interactive, authentic, and yet cost-effective VR solution in engineering education. Thereafter, we discussed the literature grounds in both education research and technology development for proposing our new i360ºVR framework. To validate the effectiveness of the proposed i360ºVR approach, we showcased the development of a i360ºVR module on the topic of coastal erosion education through the usage of a series of modeling and VR editing platforms, then reported a user testing study to assess four key metrics: immersion, interactivity, tangible learning environment, and the i360°VR module's potential to shift participants' perceptions regarding coastal erosion. The evaluation results demonstrated moderate to high levels of user engagement and learning effectiveness, highlighting the potential of i360ºVR to transform STEM education. Lastly, we discussed potential frameworks to apply i360ºVR into other STEM education contexts, including establishing a remote VR lab for a mechanical engineering program and enhancing physics-based analysis scenarios in physics education.

IRB Statement

The user test under Section 5 was approved by the Institutional Review Board at Coastal Carolina University under protocol number 2023.193. All participants provided informed consent prior to their participation.

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Appendix A

The script of the speech in the Welcome Scene is shown below:

Welcome to the Coastal Carolina University module on coastal erosion management. To keep our coastal communities sustainable and improve their development, it is important that we are aware of erosion as it occurs. This module will serve to inform you on how we can monitor our coasts for erosion, which is a crucial part of improving our management of coastal erosion. Thank you for viewing this module!

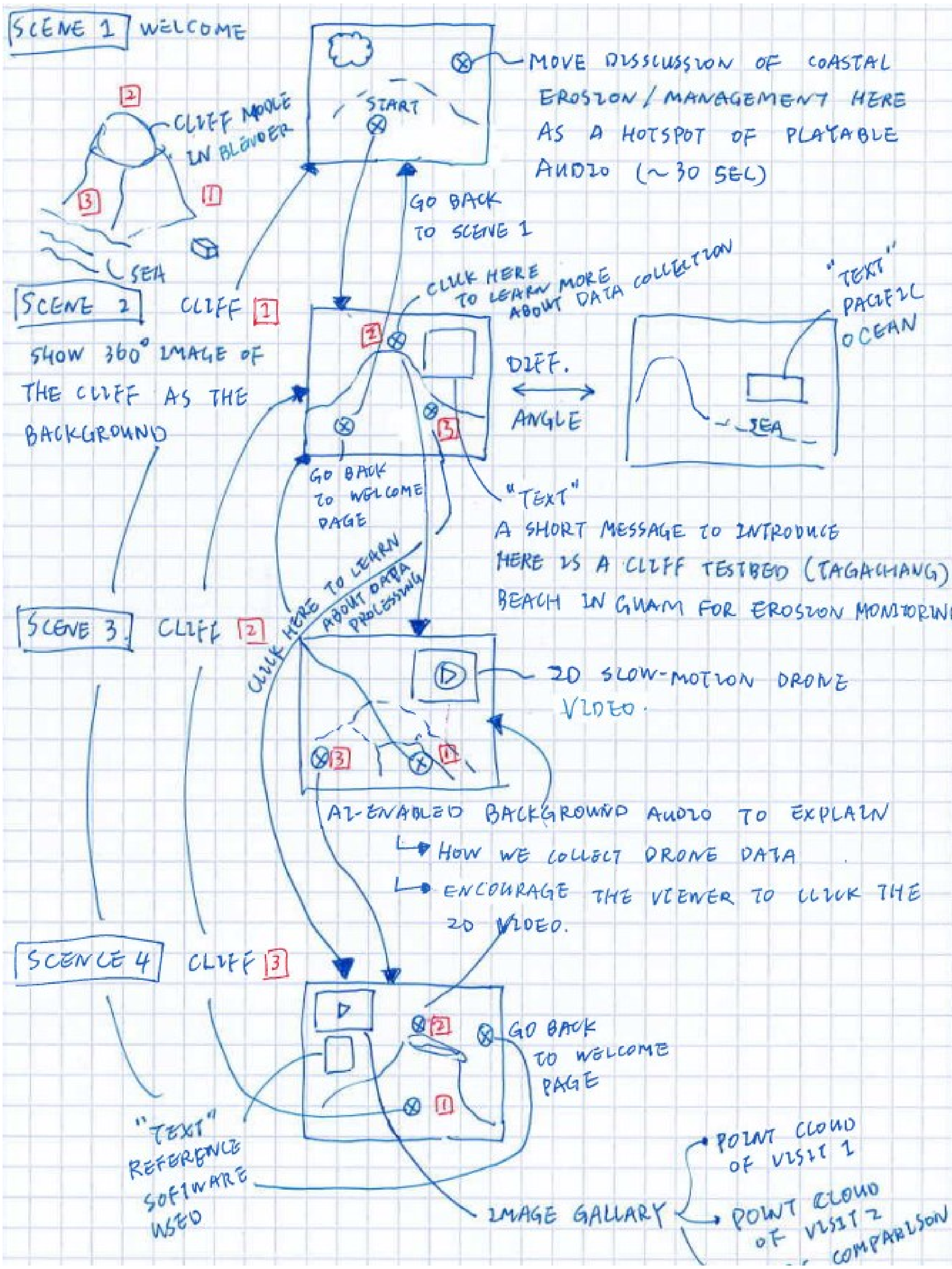
Appendix B

The script of the speech in Scene B is shown below:

To monitor for erosion, two data sets are required to detect changes in the cliff structure over time. These data sets are collected by a drone with a camera, sent on a path above and around the cliff. The drone continually collects images on two different runs, bringing back enough images to create an accurate model of the cliff. Click on the video in this scene to see a set of images a drone collected.

Appendix C

The original manuscript of the VR editing flowchart (Figure 9) is shown below. Arrows indicate navigation paths, and the numbers in red boxes represent transition hotspots. The missing text in the bottom-right corner refers to the C2C (cloud-to-cloud) comparison, which displays the results of the cliff monitoring analysis.



Appendix D

The six dimensions of the EduVR rubric adopted in this study are shown below.

Please evaluate the VR module by reviewing the criteria and circling a rating (5 – 1) below each question.

F1 Authenticity and Realism: Is the VR environment as authentic as possible?				
5	4	3	2	1
The VR provides a real-world environment in a way that is highly authentic and appropriately realistic, which enhances my experience.	The VR provides a real-world environment that is authentic and does not enhance nor detract from my experience.	The VR provides a real-world environment, but minor flaws exist with the authenticity of the environment that disturbs my experience.	The VR provides a real-world environment, but major flaws exist within the authenticity of the environment that significantly disrupts my experience.	The VR does not provide a complete environment of any kind that is suitable for any type of my experience.
G2 Pathways: What pathways through the VR environment are available to me?				
5	4	3	2	1
The VR provides seemingly infinite pathways through the environment that I can navigate at my own pace	The VR includes a set number of pathways through the environment that I can navigate at my own pace within set parameters.	The VR only includes one pathway through the environment that I can move along at my own pace.	The VR only includes one pathway through the environment, and I am moved through it at a pace that I can not control.	The VR only allows me to stand or be located in one place without any options for moving through the environment.
G6 Immersion: How immersive is the VR to me?				
5	4	3	2	1
The VR stimulates many of my senses to create a completely interactive experience that results in me making an emotional investment in the experience and blurring my physical and virtual worlds.	The VR stimulates my senses to create an interactive experience but lacks a strong enough emotional appeal needed for me to blur my physical and virtual worlds.	The VR only stimulates some of my senses, which precludes the experience from being interactive or emotional.	The VR allows me to interact with space, trigger events, or engage with manipulatives, but little else.	The VR only consists of a 360^{o} environment that does not allow for interaction outside of viewing the content.

Please evaluate the VR module by reviewing the criteria and circling a rating (5 – 1) below each question.

F2 Content Presentation: How does the VR module leverage multimodal elements (e.g., text, images, audio, video, etc.) and utilize active and passive strategies to engage me in the content?				
5	4	3	2	1
The VR combines multimodal elements along with active and passive strategies that utilize synchronous, person-to-person interaction to engage me in the content.	The VR combines multimodal elements along with active asynchronous strategies that do not include person-to-person interaction to engage me in the content.	The VR combines multimodal elements along with active and passive strategies to engage me in the content.	The VR combines multimodal elements but relies mostly on passive strategies to present content to me.	The VR largely utilizes one element with passive strategies to present content to me.
F3 Navigational Aids: Does the VR include indicators to aid navigation?				
5	4	3	2	1
The VR provides intuitive navigational aids that are logically placed to support me in maneuvering through the environment at my own pace.	The VR provides navigational aids that are mostly intuitive and logically placed to support me in maneuvering through the environment at my own pace.	The VR provides navigational aids that are intuitive to me but placed illogically, which limits the ease at which I can maneuver through the environment.	The VR provides few navigational aids that are not intuitive to me and illogically placed, which severely limits the ease at which I can maneuver through the environment.	The VR provides no navigational aids whatsoever and I must employ landmarks and a trail-and-error strategy for maneuvering through the environment.
F4 Multimedia Elements: How well does the VR integrate multimedia elements (e.g., text, graphics, videos, sound, live streaming, etc.) to engage me within the experience?				
5	4	3	2	1
The VR's multimedia elements are seamlessly integrated and organized in a way that enhances my experience.	The VR's multimedia elements are integrated and organized in a way that does not enhance or detract from my experience.	The VR's multimedia elements are well-integrated, but their organization detracts from my overall experience.	The VR's multimedia elements are integrated and organized in a way that reduces the quality of my experience.	The VR's multimedia elements are jumbled, confusing, and/or poorly organized, which significantly reduces my experience.

References

[1] Kavanagh, S., Luxton-Reilly, A., Wuensche, B., & Plimmer, B. (2017). A systematic review of virtual reality in education. *Themes in Science and Technology Education*, 10(2), 85-119.

[2] Abich IV, J., Parker, J., Murphy, J. S., & Eudy, M. (2021). A review of the evidence for training effectiveness with virtual reality technology. *Virtual Reality*, 25(4), 919-933. https://doi.org/10.1016/j.resuscitation.2019.06.139

[3] Pensieri, C., & Pennacchini, M. (2016). Virtual reality in medicine. In *Handbook on 3D3C Platforms: Applications and Tools for Three Dimensional Systems for Community, Creation and Commerce* (pp. 353-401). Cham: Springer International Publishing.

[4] Cieślik, B., Mazurek, J., Rutkowski, S., Kiper, P., Turolla, A., & Szczepańska-Gieracha, J. (2020). Virtual reality in psychiatric disorders: A systematic review of reviews. *Complementary Therapies in Medicine*, 52, 102480. https://doi.org/10.1016/j.ctim.2020.102480

[5] Lee, S., El Ali, A., Wijntjes, M., & Cesar, P. (2022, April). Understanding and designing avatar biosignal visualizations for social virtual reality entertainment. In Proceedings of the *2022 CHI Conference on Human Factors in Computing Systems* (pp. 1-15). https://doi.org/10.1145/3491102.35174

[6] Marco, J. H., Perpiñá, C., & Botella, C. (2013). Effectiveness of cognitive behavioral therapy supported by virtual reality in the treatment of body image in eating disorders: one year follow-up. *Psychiatry Research*, 209(3), 619-625. https://doi.org/10.1016/j.psychres.2013.02.023

[7] Tadeja, S. K., Bohné, T., Godula, K., Cybulski, A., & Woźniak, M. M. (2024). Immersive presentations of real-world medical equipment through interactive VR environment populated with the high-fidelity 3D model of mobile MRI unit. *Computers & Graphics*, 120, 103919. https://doi.org/10.1016/j.cag.2024.103919

[8] Hong, S.; Shin, H.; Gil, Y.; Jo, J. Analyzing Visual Attention of People with Intellectual Disabilities during Virtual Reality-Based Job Training. *Electronics* 2021, 10, 1652. https://doi.org/10.3390/electronics10141652

[9] Azzam, I., Breidi, F., & Soudah, P. (2023, June). Virtual Reality: A Learning Tool for Promoting Learners' Engagement in Engineering Technology. ASEE Conferences. https://peer.asee.org/44605

[10] van Dinther, R., de Putter, L., & Pepin, B. (2023). Features of immersive virtual reality to support meaningful chemistry education. *Journal of Chemical Education*, 100(4), 1537-1546. https://doi.org/10.1021/acs.jchemed.2c01069

[11] Georgiou, Y., Tsivitanidou, O., & Ioannou, A. (2021). Learning experience design with immersive virtual reality in physics education. *Educational Technology Research and Development*, 69(6), 3051-3080. https://doi.org/10.1007/s11423-021-10055-y

[12] Takac, M. (2020, October). Application of web-based immersive virtual reality in mathematics education. In *2020 21th International Carpathian Control Conference (ICCC)* (pp. 1-6). IEEE. http://doi.org/10.1109/ICCC49264.2020.9257276

[13] Unity, https://unity.com/

[14] Unreal Engine, https://www.unrealengine.com/en-US

[15] Zhao, D., & Lucas, J. (2015). Virtual reality simulation for construction safety promotion. *International Journal of Injury Control and Safety Promotion*, 22(1), 57-67. https://doi.org/10.1080/17457300.2013.861853

[16] Bükrü, S., Wolf, M., Golovina, O., & Teizer, J. (2020, November). Using field of view and eye tracking for feedback generation in an augmented virtuality safety training. In Construction Research Congress 2020: Safety, Workforce, and Education (pp. 625-632). Reston, VA: American Society of Civil Engineers.

[17] Schofield, D. (2014). A Virtual Education: Guidelines for Using Games Technology. *Journal of Information Technology Education*, 13, 25.

[18] Arents, V., de Groot, P. C., Struben, V. M., & van Stralen, K. J. (2021). Use of 360° virtual reality video in medical obstetrical education: a quasi-experimental design. *BMC Medical Education*, 21(1), 1-9. https://doi.org/10.1186/s12909-021-02628-5

[19] Ardisara, A., & Fung, F. M. (2018). Integrating 360 videos in an undergraduate chemistry laboratory course. *J. Chem. Educ*. 2018, 95, 10, 1881–1884. https://doi.org/10.1021/acs.jchemed.8b00143

[20] Ferdig, R. E., & Kosko, K. W. (2020). Implementing 360 video to increase immersion, perceptual capacity, and teacher noticing. *TechTrends*, 64, 849-859. https://doi.org/10.1007/s11528-020-00522-3

[21] Lee, S. H., Sergueeva, K., Catangui, M., & Kandaurova, M. (2017). Assessing Google Cardboard virtual reality as a content delivery system in business classrooms. *Journal of Education for Business*, 92(4), 153-160. https://doi.org/10.1080/08832323.2017.1308308

[22] Choi, K., Yoon, Y. J., Song, O. Y., & Choi, S. M. (2018). Interactive and immersive learning using 360 virtual reality contents on mobile platforms. *Mobile Information Systems*, 2018. https://doi.org/10.1155/2018/2306031

[23] Panchuk, D., Klusemann, M. J., & Hadlow, S. M. (2018). Exploring the effectiveness of immersive video for training decision-making capability in elite, youth basketball players. *Frontiers in Psychology*, 9, 2315. https://doi.org/10.3389/fpsyg.2018.02315

[24] Vergara, D., Rubio, M. P., & Lorenzo, M. (2017). On the design of virtual reality learning environments in engineering. *Multimodal Technologies and Interaction*, 1(2), 11. https://doi.org/10.3390/mti1020011

[25] Kruskal, W., & Wallis, W.A. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association*, 47(260): 583–621.

[26] Gavrielidou, E., & Lamers, M. H. (2010). Landmarks and time-pressure in virtual navigation: Towards designing gender-neutral virtual environments. In *Facets of Virtual Environments: First International Conference, FaVE 2009, Berlin, Germany, July 27-29, 2009, Revised Selected Papers 1* (pp. 60-67). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-11743-5_5

[27] Kolb, D. A. (2014). Experiential learning: Experience as the source of learning and development. FT press.

[28] Godat, M. (2007). Virtual golden foods corporation: Generic skills in a virtual crisis environment (a pilot study). *Journal of Educational Multimedia and Hypermedia*, 16(1), 67-84.

[29] Kwon, C. (2019). Verification of the possibility and effectiveness of experiential learning using HMD-based immersive VR technologies. *Virtual Reality*, 23(1), 101-118. https://doi.org/10.1007/s10055-018-0364-1

[30] Slater, M. (2018). Immersion and the illusion of presence in virtual reality. *British Journal of Psychology*, 109(3), 431-433. https://doi.org/10.1111/bjop.12305

[31] McKenzie, S., Rough, J., Spence, A., & Patterson, N. (2019). Virtually there: the potential, process and problems of using 360 video in the classroom. *Issues in Informing Science and Information Technology*, 16, 211-219. https://doi.org/10.28945/4318
[32] Galizzi, M. (2014). Bringing Adam Smith's Pin Factory to Life: Field Trips and Discussions as Forms of Experiential Learning. *Journal of the Scholarship of Teaching and Learning*, 14(5), 27-47.
[33] Aridan, N., Bernstein-Eliav, M., Gamzo, D., Schmeidler, M., Tik, N., & Tavor, I. (2024). Neuroanatomy in virtual reality: Development and pedagogical evaluation of photogrammetry-based 3D brain models. *Anatomical Sciences Education*, 17(2), 239-248. https://doi.org/10.1002/ase.2359
[34] Fink, M. C., Sosa, D., Eisenlauer, V., & Ertl, B. (2023, January). Authenticity and interest in virtual reality: Findings from an experiment including educational virtual environments created with 3D modeling and photogrammetry. In *Frontiers in Education* (Vol. 8, p. 969966). Frontiers Media SA. https://doi.org/10.3389/feduc.2023.969966
[35] Burk, Z. J., & Johnson, C. S. (2019). Method for Production of 3D Interactive Models Using Photogrammetry for Use in Human Anatomy Education. *HAPS Educator*, 23(2), 457-463.
[36] Tucci, G., Conti, A., Fiorini, L., Panighini, F., & Parisi, E. I. (2018). Education and training resources on digital photogrammetry. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 45-50. https://doi.org/10.5194/isprs-archives-XLII-5-45-2018
[37] Kong, X., Fegely, A., De Backer, W., Gray, M., Hitt, G., & Kerns, R. (2022, August). Work-in-Progress: Developing an Interactive, Immersive, 360-Degree Virtual Media for Enhancing Student Learning in Additive Manufacturing. In *2022 ASEE Annual Conference & Exposition*. https://doi.org/10.18260/1-2--41843
[38] Blender (Version 3.5) (Software), 2023, Retrieved from https://www.blender.org/
[39] Kong, X. (2021). Identifying Geomorphological Changes of Coastal Cliffs through Point Cloud Registration from UAV Images. *Remote Sensing*, 13(16), 3152. https://doi.org/10.3390/rs13163152
[40] AgiSoft Metashape Professional (Version 1.6.2) (Software). 2020. Retrieved from http://www.agisoft.com/downloads/installer/
[41] Ullman, S. (1979). The interpretation of structure from motion. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 203(1153), pp 405-426. https://doi.org/10.1098/rspb.1979.0006
[42] Andrew, A.M. (2001), "Multiple View Geometry in Computer Vision", Kybernetes, Vol. 30 No. 9/10, pp. 1333-1341. https://doi.org/10.1108/k.2001.30.9_10.1333.2
[43] Long, N., Millescamps, B., Pouget, F., Dumon, A., Lachaussee, N., & Bertin, X. Accuracy assessment of coastal topography derived from UAV images. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2016, 41, 1127. https://doi.org/10.5194/isprsarchives-XLI-B1-1127-2016
[44] Chaiyasarn, K., Kim, T. K., Viola, F., Cipolla, R., & Soga, K. Distortion-free image mosaicing for tunnel inspection based on robust cylindrical surface estimation through structure from motion. *Journal of Computing in Civil Engineering*, 2016, 30(3), 04015045. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000516
[45] Kong, X. and Hucks, R. G. (2023), Preserving our heritage: A photogrammetry-based digital twin framework for monitoring deteriorations of historic structures, *Automation in Construction*, 152C, 104928. https://doi.org/10.1016/j.autcon.2023.104928

[46] Kong, X. (2024). Monitoring Time-Varying Changes of Historic Structures Through Photogrammetry-Driven Digital Twinning. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 48, 181-186. https://doi.org/10.5194/isprs-archives-XLVIII-2-2024-181-2024
[47] Shi, J. (1994, June). Good features to track. In 1994 Proceedings of IEEE conference on computer vision and pattern recognition (pp. 593-600). IEEE. https://doi.org/10.1109/CVPR.1994.323794
[48] Wilkie, A., & Hošek, L. (2013, May). Predicting sky dome appearance on earth-like extrasolar worlds. *In Proceedings of the 29th Spring Conference on Computer Graphics* (pp. 145-152). https://doi.org/10.1145/2508244.2508263
[49] Hosek, L., & Wilkie, A. (2012). An analytic model for full spectral sky-dome radiance. *ACM Transactions on Graphics (TOG)*, 31(4), 1-9. https://doi.org/10.1145/2185520.218559
[50] VIAR360, https://www.viar360.com/
[51] Gratisgraphics, https://gratisgraphics.com/
[52] Meta Quest 2 headset, https://www.meta.com/quest/products/quest-2/
[53] Kong, X., Guo, S., & Gray, M. (2021). Hands-on STEM education during the pandemic: A fully-engaged, remote learning approach using Lego Mindstorms EV3.
[54] Health and Safety Manual, Meta Quest 2, https://www.oculus.com/safety-center/quest-2/
[55] Bricken, M. (1991). Virtual reality learning environments: potentials and challenges. *ACM Siggraph Computer Graphics,* 25(3), 178-184. https://doi.org/10.1145/126640.126657
[56] Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive virtual reality field trips facilitate learning about climate change. *Frontiers in Psychology*, 9, 2364. https://doi.org/10.3389/fpsyg.2018.02364
[57] First Steps, https://www.oculus.com/experiences/quest/1863547050392688/
[58] Dijkstra, E. M., & Goedhart, M. J. (2012). Development and validation of the ACSI: Measuring students' science attitudes, pro-environmental behaviour, climate change attitudes and knowledge. *Environmental Education Research*, 18(6), 733-749. https://doi.org/10.1080/13504622.2012.662213
[59] Nichols, S., Haldane, C., & Wilson, J. R. (2000). Sense of Presence Questionnaire [Database record]. Retrieved from PsycTESTS. doi: https://dx.doi.org/10.1037/t67800-000
[60] Schwind, V., Knierim, P., Haas, N., & Henze, N. (2019). Using presence questionnaires in virtual reality. *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019)*. https://doi.org/10.1145/3290605.3300590.
[61] Fegely, A., & Cherner, T. (2021). A comprehensive rubric for evaluating EduVR. *Journal of Information Technology Education: Research,* 20, 137-171. https://doi.org/10.28945/4737
[62] Crusan, D. (2010). *Assessment in the second language writing classroom*. The University of Michigan Press
[63] Alghofaili, R., Sawahata, Y., Huang, H., Wang, H., Shiratori, T., & Yu, L. (2019). Lost in style: Gaze-driven adaptive aid for VR navigation. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019)*, May 4–9, 2019, Glasgow, Scotland UK. ACM, New York, NY. ACM. https://doi.org/10.1145/3290605.3300578
[64] Heeter, C. (1992). Being there: The subjective experience of presence. *Presence: Teleoperators and Virtual Environments*, 1(2), 262-271. https://doi.org/10.1162/pres.1992.1.2.262

[65] Allcoat, D., & Von Mühlenen, A. (2018). Learning in virtual reality: Effects on performance, emotion and engagement. *Research in Learning Technology*, 26. https://doi.org/10.25304/rlt.v26.2140
[66] Fegely, A., Hagan, H., & Warriner III, G. (2020). A practitioner framework for blended learning classroom virtual reality inquiry lessons. *E-Learning & Digital Media*, 17(6). https://doi.org/10.1177/2042753020926948
[67] Wang, Y., & Braman, J. (2009). Extending the classroom through second life. *Journal of Information Systems Education*, 20, 235-247.
[68] Jitmahantakul, S., & Chenrai, P. (2019). Applying virtual reality technology to geoscience classrooms. *Review of International Geographical Education Online*, 9(3), 577-590. https://doi.org/10.33403/rigeo.592771
[69] Sarioglu, S., & Girgin, S. (2020). The effect of using virtual reality in 6th grade science course the cell topic on students' academic achievements and attitudes towards the course. *Journal of Turkish Science Education*, 17(1), 109-125. https://doi.org/10.36681/tused.2020.16
[70] Stranger-Johannessen, E. (2018) Exploring math achievement through gamified virtual reality. In V. PammerSchindler, M. Pérez-Sanagustín, H. Drachsler, R. Elferink, & M. Scheffel (Eds.) Lifelong technology-enhanced learning. EC-TEL 2018. *Lecture Notes in Computer Science*, vol 11082. Springer. https://doi.org/10.1007/978-3-319-98572-5_69
[71] Archer, D., & Finger, K. (2019). Walking in another's virtual shoes: Do 360-degree video news stories generate empathy in viewers? Tow Center for Digital Journalism. New York: Columbia University. https://doi.org/10.7916/D8669W5C
[72] Gibbons, J. D., & Chakraborti, S. (2011). *Nonparametric statistical inference* (5th ed.). Boca Raton, FL: Taylor & Francis Group, LLC.
[73] Cohen, J. (1988). Statistical power analysis for the behavioral sciences. Nature (2nd ed., Vol. 506). Lawrence Erlbaum Associates. https://doi.org/10.1038/506274a
[74] Local Areas of Admission for First Time Freshmen, Fresno State, https://studentaffairs.fresnostate.edu/are/futurestudent/freshmen/local.html
[75] California San Joaquin counties, https://commons.wikimedia.org/wiki/File:California_San_Joaquin_counties.svg
[76] Pilger, C., Gaebler, P., Hupe, P. et al. Yield estimation of the 2020 Beirut explosion using open access waveform and remote sensing data. Sci Rep 11, 14144 (2021). https://doi.org/10.1038/s41598-021-93690-y
[77] Aouad, C.J., Chemissany, W., Mazzali, P. et al. Beirut explosion: TNT equivalence from the fireball evolution in the first 170 milliseconds. Shock Waves 31, 813–827 (2021). https://doi.org/10.1007/s00193-021-01031-9
[78] Audacity, https://www.audacityteam.org/
[79] Google Earth, https://earth.google.com/
[80] Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction*, 60, 225-236. https://doi.org/10.1016/j.learninstruc.2017.12.007
[81] Johnson-Glenberg, M. C. (2018). Immersive VR and education: Embodied design principles that include gesture and hand controls. *Frontiers in Robotics and AI*, 5, 375272. https://doi.org/10.3389/frobt.2018.00081

[82] Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researcher*, 42(8), 445-452. https://doi.org/10.3102/0013189X13511661