Usability and motivational impact of a fast-paced immersive virtual reality lecture on international middle school students in geoscience education

Azim ZULHILMI[1], Yuichi S. HAYAKAWA[2], Daniel R. NEWMAN[2]

[1]Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan

[2]Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan

Correspondence to: Azim Zulhilmi (Azimzulhilmi@ees.hokudai.ac.jp)

Abstract. Immersive Virtual Reality (VR) offers educators an innovative tool to teach geoscience, addressing challenges in conveying the Earth's 3D characteristics traditionally taught through field visits and experiences that are often inaccessible to many due to socioeconomic, political, and logistical barriers. VR provides an alternative experience, allowing users to virtually explore geological sites beyond physical and situational constraints. Despite its potential, the implementation of geoscience-focused VR lectures remains largely unexplored. As a pioneering case study, this research investigates the usability and motivational impact of VR by developing a fast-paced virtual reality lecture on landslides for middle school students. Approximately 60 students from diverse cultural and educational backgrounds participated. Results revealed that the VR lecture was usable, with key strengths in its ability to engage students and deliver satisfaction. Compared to traditional teaching methods (lecture and hands-on), VR excelled in fostering interest, enjoyment, and perceived choice. This study provides valuable insights into the practical implementation of VR in geoscience education, demonstrating its potential to make geoscience topics more accessible and engaging for diverse student groups. Future research should explore strategies to address usability challenges and enhance the motivational attributes of VR, paving the way for its broader adoption in geoscience educational settings.

1 Introduction

Geoscience education can be referred as the structured teaching and learning that focuses on the earth's physical features, processes, and systems. It is important that when teaching geoscience, students may need to develop observational and spatial thinking skills, as it is an observational science. In particular, field experiences in geoscience require a level of thinking, mental visualization, and investigative skills not commonly found in other scientific fields (King, 2008; Liben et al. 2011). Therefore, it is necessary for educators of geoscience to emphasize on transferring these key skills to their students.

Conventional geoscience teaching methods using textbooks and lectures often fail to effectively convey the reality of the nature, including three-dimensional (3D) features of the Earth. These approaches tend to rely on pseudo-3D visualizations to express the earth which is challenging because it places additional cognitive burden on learners to mentally visualize complex 3D geometrical concepts that they may not be very familiar with (Fitzpatrick & Hedley, 2024; Havenith et al. 2019). Hands-on activities like fieldwork, museum visits, and lab activities help address this limitation, but access is often restricted due to practical issues like finance, health, socioeconomic, and logistical barriers. Addressing these challenges is vital for advancing geoscience education for all.

Immersive Virtual Reality (VR) offers a promising solution to tackle this issue. VR provides an immersive, interactive, and realistic 3D experience accessible through head-mounted displays (HMD) and their respective peripherals. It addresses the accessibility and visualization challenges of traditional geoscience teaching methods by enabling fully immersive realistic exploration of geological data in 3D, with intuitive motion-based interaction while also leveraging physical and cyber portability. Furthermore, it is well understood from meta-analyses studies and reviews that VR can yield improvements on students learning at the elementary, middle, and high school education (Merchant et al., 2014; Di Natale et al., 2020; Villena-Taranilla, 2022). This makes VR a potentially versatile and highly useful tool for geoscience education and communication.

1.1 Literature Review

One of the major global challenges today is ensuring quality education. As outlined by the Sustainable Development Goal 4 in United Nations (2015):

"Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all" (p. 14).

The geoscience community has made significant strides in communicating geoscience to the broader public, facilitating knowledge dissemination beyond the scientific community. While traditional communication methods, such as lectures, museums, and workshops, have been widely utilized, advancements in technology now provide more innovative outreach approaches.

Studies on 3D printing in geological education highlight its benefits: Gutierrez et al. (2023) demonstrated that 3D-printed models improve undergraduates' spatial and visualization skills while enhancing understanding of geological structures. Similarly, Chenrai (2021) found that integrating 3D printing into geoscience curricula bolstered structural interpretation and spatial visualization abilities.

Virtual Field Trips (VFTs) are effective tools for geological outreach: Watson et al. (2022) found personal computer (PC)-based VFTs engaging for teaching physical volcanology through 3D visuals and videos. Tibaldi et al. (2020) described VR approach using 3D digital outcrop models for teaching, learning, and research in volcanology suggest that VR is capable for engaging public and can be value to promote environmental site protection and development. De Paz-Álvarez et al. (2022) demonstrated VFTs' usefulness in teaching mapping skills but noted they cannot fully replace traditional courses. Klippel et al. (2019) showed immersive VFTs with VR headsets improved lab performance and enthusiasm compared to traditional field trips. Harknett et al. (2022) used VR for teaching students' structural geology fieldwork skills in structurally complex volcanic terrains noting its potential role to play in existing geoscience education curricula.

Other VR applications show promise in geoscience communication: Yamauchi et al. (2022) used VR to visualize underground heritage (Taya Cavern in Yokohama, Japan), boosting interest and encouraging potential real-world visits. Alene et al. (2024) developed "QuickAware," a VR tool raising awareness of quick clay landslides, effectively enhancing

hazard understanding. Graebling et al. (2024) introduced "VR-EX," a storyline-based VR application for learning geological electrical resistivity tomography experiments at Mont. Terri underground Laboratory (Switzerland), which fostered high engagement, immersion, and knowledge transfer. Jong et al. (2020) applied spherical video-based VR and found positive results on its pedagogical effectiveness on teaching physical geography.

As these studies demonstrate, geoscience outreach methods are expanding beyond traditional methods with the integration of innovative technologies and concepts like 3D printing, VFTs, and immersive VR experiences. However, despite these growing strategies, a gap remains in evaluating the effectiveness of VR-based pedagogies (Jong et al. 2020; Harknett et al. 2022; Hagge, 2024) such as in formal geoscience education. Further contribution is necessary, especially in integrating the lecture component of traditional geoscience education with VR. By combining the interactive nature of VR with the structured learning of lectures, a more dynamic and immersive approach to geoscience education could be achieved, potentially enhancing both engagement, knowledge retention, while ideally, improving communication to a wider audience.

1.2 Objectives

This paper explores the effectiveness of VR-based geoscience lectures in teaching middle school students, addressing the limited focus on this demographic in VR-related geoscience research. Additionally offering an opportunity to introduce the students to geoscience concepts typically inaccessible at their educational level. The study emphasizes geoscience topics related to the 2018 Hokkaido Eastern Iburi Earthquake (HEIE). A fast-paced, portable, VR lecture was developed for this purpose, and its effectiveness is compared to traditional teaching methods. To the author's knowledge, this approach using VR lectures in geoscience education has not been explored before. This study is part of a larger project examining the feasibility of VR in geoscience education. In this paper the focus primarily addresses the motivational and usability aspects of the VR application.

This study narrows on these key objectives:

i)   Evaluate the usability of the fast-paced VR lecture format and how it compares to the traditional teaching methods in terms of motivational preference by the participants at this educational level
ii)   Explore the ability of the VR experience to incite interest and curiosity of the geological environment
iii)   Identifies the strengths and limitations
iv)   Outlines potential directions for further development of such teaching approach

2 Methodology

2.1 Participants and Setting

The VR outreach program was conducted on the morning of September 19, 2024, at Hokkaido International School (chosen for its diversity of students), running from 9:00 AM to 11:45 AM. The session engaged middle school students (11-14 years old) from grades 6 (G6) through 8

(G8), with a total of 60 participants: 18 from G6, 21 from grade 7 (G7), and 21 from G8. The students came from a variety of international backgrounds, including: East Asia, North America, Oceania, Europe, and Eurasia. This ensures that any bias toward a single perspective in the results is minimized. Hokkaido International School, a private institution, follows a Western-style education system with English as the medium of instruction.

The research workflow consists of three key stages: VR lecture development, survey formulation, and outreach execution. The VR lecture was designed to replicate traditional lectures within a VR environment while leveraging VR-specific advantages, such as visualizing 3D VR models, and animated contents. The survey aimed to evaluate middle school students' motivation and usability experience of the VR lecture, and comparison between traditional teaching methods. The traditional teaching methods are the lecture and hands-on session. The entire outreach program was strictly limited to 165 minutes by the school and accommodated 60 students.

2.2 VR lecture development

The VR lecture had to adhere to the limitations of time and participant numbers. Furthermore, the goal was to fully leverage the unique capabilities of VR for presenting geoscience materials. To the best of the author's knowledge, no existing applications met this specific need, so it was a requirement to develop a custom designed method that aligns with the principles of VR-based lectures.

This paper defines VR lecture as such only when it meets at least the following key attributes:

- Delivered in a fully immersive 3D VR environment primarily accessed through immersive VR technology
- Designed to teach in a structured manner with defined learning objectives
- Conducted by a lecturer represented as an avatar, featuring voice and expressive body language
- Participants must have the ability to listen, visualize, navigate using VR-based locomotion, and engage with the lecture and its content within the virtual space
- Incorporates teaching aids that is possible only in VR to enhance understanding
- Capability of being adapted to various instructional settings

The VR lecture is designed in this manner: At the beginning, students will spawn into the starting lobby and are guided to the lecture room after entering a doorway (Fig. 1a). After standing on a designated spot on the floor the lecture will commence. The lecture featured a dummy virtual lecturer delivering a ~5 min oral commentary on the geoscience topics (Fig. 1b). The lecture is fully voiced and showcased virtual teaching aids including images, 360-degree photospheres, animated models, and 1:1 scale field replica to enhance understanding (Fig. 1c-f).

The 3D models were prepared using photogrammetry in Agisoft Metashape and 3D modelling in Blender. Voice lines were recorded using Microsoft's windows sound recorder application. Unity game engine was used for implementing, animating, and displaying these assets, while VRChat served as the platform for hosting the lecture during the outreach day. The processing was performed on a desktop PC equipped with an RTX 3080 Ti graphics processing unit (GPU), AMD Ryzen 5 7600x central processing unit (CPU), and 16 GB of random-access memory.
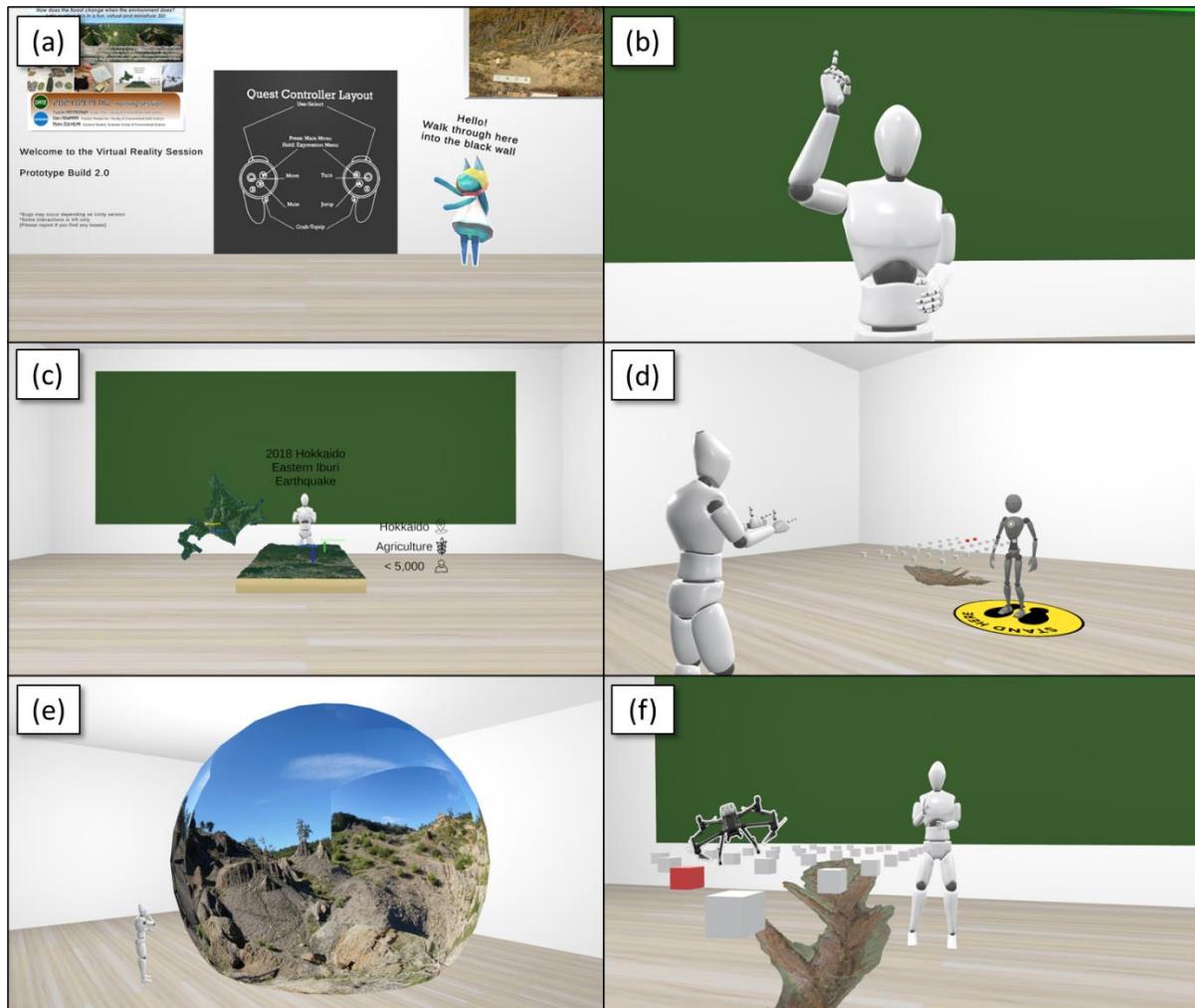
Figure 1. World setting for VR lecture (a) the starting lobby room with tutorial board (b) the VR lecturer (c) VR lecturer explaining about the 2018 HEIE (d) participant standing on the trigger zone (e) photosphere showcase of the deep-seated landslide (f) VR lecturer teaching about drones and 3D models

During the prototype phase, which is critical for smooth implementation (Novotny et al. 2019), the VR lecture was tested on graduate students from Hokkaido University's Graduate School of Environmental Science. This process identified technical and content-related issues, allowing the team to refine and finalize the lecture experience. The resulting optimized blueprint was used for the outreach program (Fig. 2).
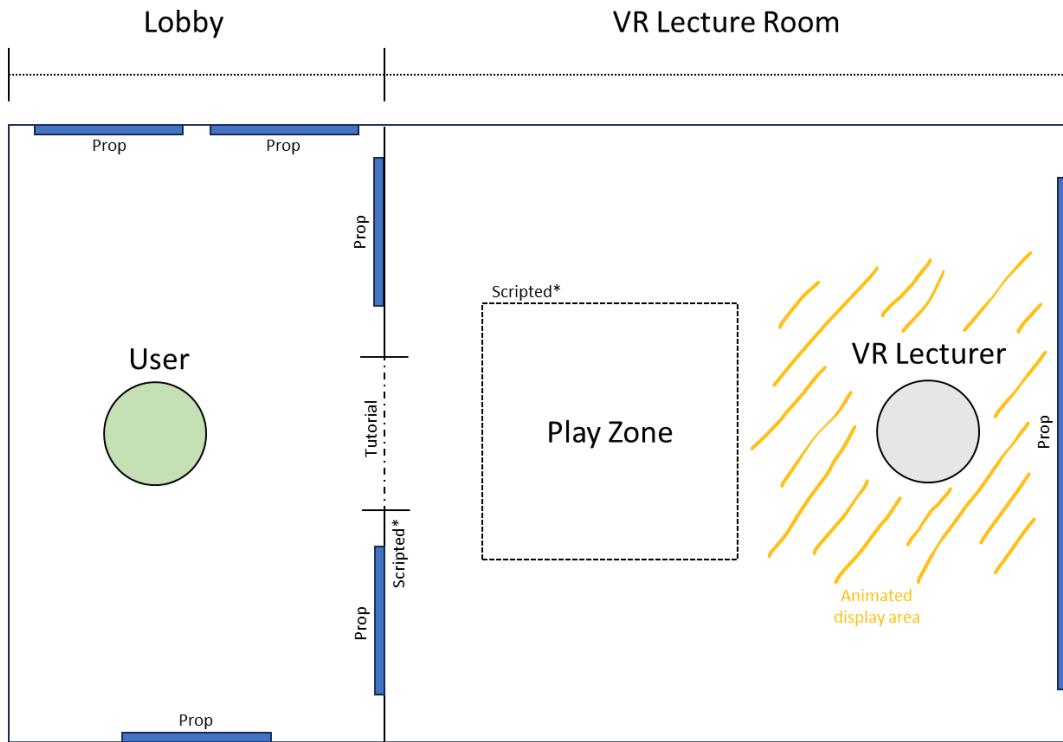
Figure 2. VR lecture world blueprint

2.3 Survey design

The survey design was inspired by the System Usability Scale (Brooke, 1996), which measures how easy a product is to use, and Intrinsic Motivational Inventory (Ryan & Deci, 2000) for measuring subjective experience of the user in relation to a specific target activity in laboratory experiments. These surveys have been used in previous studies (Carbonell-Carrera et al. 2021; Huang & Liu, 2024; Meulenbroeks et al. 2024).

The author's version of the survey was modified for the prepared VR lecture scenario and adapted to accommodate the time constraints and student amount of the outreach program. After the VR experience, students completed a 10-minute survey consisting of the following sections (refer Appendix A-C):

1. *VR Usability survey*: This section assessed five categories - Discomfort, Effectiveness, Satisfaction, Immersion, and Accessibility; using a 5-point Likert scale.

2. *VR/Lecture/Hands-on Motivational survey*: This section evaluated six categories – Interest/Enjoyment, Perceived Competence, Perceived Choice, Effort/Importance, Pressure/Tension, and Value/Usefulness; using a 7-point Likert scale.

3. *Open Comments*: Students could provide feedback on positives, negatives, and suggestions regarding the session.

To ensure reliable responses, Cronbach's Alpha (Cronbach, 1951; Gliem & Gliem, 2003) was used, with interpretations based on George & Mallery (2002) thresholds (≥ 0.9 excellent, ≥ 0.8 good, ≥ 0.7 acceptable, ≥ 0.6 questionable, ≥ 0.5 poor). The full questionnaires are provided in the Appendix section.

2.4 Outreach approach

The outreach program followed a structured schedule: early morning setup, student gathering and briefing, program initiation, and survey data collection (Fig. 3). Equipment deployed included four HMDs (Oculus Quest 2, Meta Quest 2, and two Meta Quest 3 units) supported by an Oculus Link and three third-party link cables. Four PCVR workstations (MSI GS65, HP OMEN, ASUS ROG Zephyrus G14, and HP ZBook Firefly 14 G8) were used, each running Windows OS with integrated CPUs and GPUs.

Figure 3. Pictures of the VR outreach session. a) students gathering for outreach briefing b) example of a VR workstation c) outreach staff setting up VR stations d) students at the VR stations e) the survey station

The VR sessions were conducted based on the prepared floorplan (Fig. 4). Each session lasted 55 minutes, allowing for three rotations between the three sessions to fit within a total timeframe of 165 minutes. The setup comprised four VR stations, a survey station, and a waiting area. Students were divided into four rows, with each experiencing the VR lecture for approximately five minutes before completing the surveys at the survey station (10 minutes). Those that completed the task moved to the waiting area.
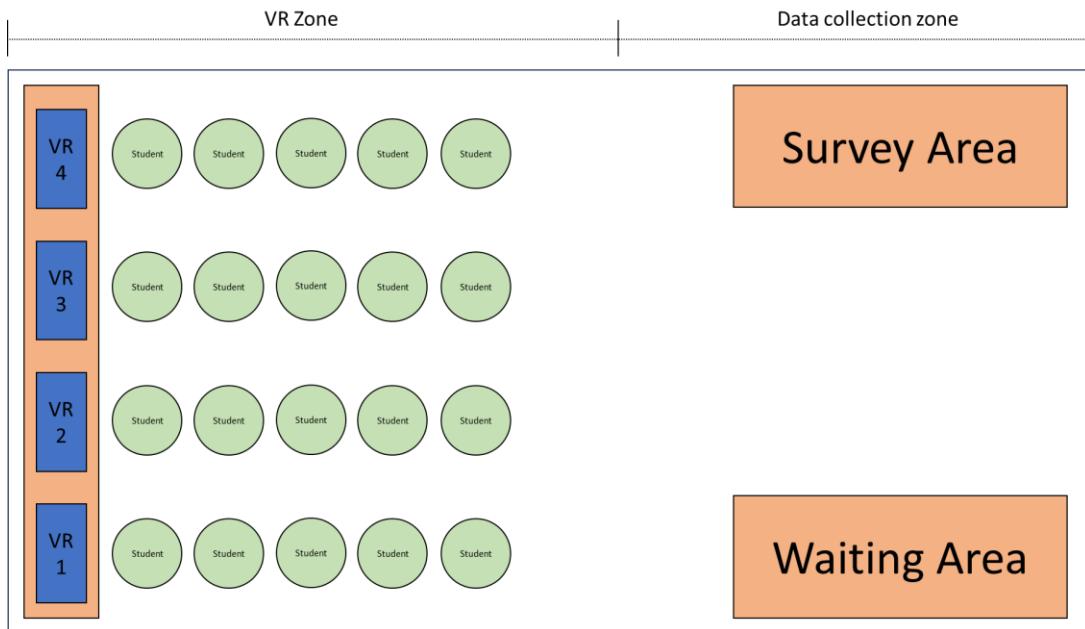
Figure 4. The floorplan for the VR outreach program

In the traditional activity sessions, students participate in a standard face-to-face lecture, allowing them to listen to and interact with the instructor in a typical classroom setting. For the hands-on session, they engage with 3D-printed models and even have the opportunity to watch and interact with the drones. The structure is 40 minutes allocated to activities or lectures and 15 minutes for surveys and transitions. This schedule enabled efficient coverage of all three grades within the allotted time, ensuring a streamlined outreach program.

3 Results

3.1 VR lecture Usability

The overall Cronbach's alpha value for VR usability was at 0.90, indicating excellent reliability. The VR lecture usability survey results were as follows (Table 1):

- Comfortability: Scored 3.81 (Standard Deviation (SD) = 1.23), reflecting a positive (reverse coded) outcome. This suggests that students disagreed with feeling discomfort during the 5-minute VR lecture.

- Effectiveness: Scored 4.01 (SD = 0.83), indicating a positive outcome. Students agreed that the VR lecture was easy to use and helped them understand the landslide and the authors' research.

- Satisfaction: Scored 4.45 (SD = 0.86), showing an overwhelmingly positive outcome. Students strongly agreed they were satisfied with the VR experience, enjoyed it, and would recommend it to others.

- Immersion: Scored 3.99 (SD = 1.03), resulting in a positive outcome. Students agreed they felt immersed in the experience and wanted to continue beyond the time limit.

- Accessibility: Scored 4.03 (SD = 0.93), demonstrating a positive outcome. Students agreed the VR application provided sufficient support and was easy to use, regardless of prior VR experience.

Table 1. *VR Usability Result of Middle School Students*

Subscale	G6 score		G7 score		G8 score		Total score	
	M	SD	M	SD	M	SD	M	SD
Comfortability	3.88	1.31	3.65	1.39	3.94	1.00	3.81	1.23
Effectiveness	3.84	1.05	4.18	0.71	3.97	0.70	4.01	0.83
Satisfaction	4.34	1.24	4.56	0.62	4.41	0.64	4.45	0.86
Immersion	4.00	1.37	4.00	0.93	3.97	0.79	3.99	1.03
Accessibility	3.78	1.10	4.23	0.97	4.03	0.65	4.03	0.93

Note. G = Grade; M = Mean; SD = Standard Deviation

3.2 Motivational Results

The overall Cronbach's alpha value for the VR lecture motivational survey was at 0.88, indicating good reliability. The survey results are summarized below (Table 2):

- Interest/Enjoyment: Scored 6.18 (SD = 1.27), indicating an overwhelmingly positive outcome. Students strongly agreed that the VR activity was interesting and enjoyable.

- Perceived Competence: Scored 4.97 (SD = 1.41), showing a slightly positive outcome. Students slightly agreed they understood the session, felt confident in their knowledge, and believed they performed better than their peers.

- Perceived Choice: Scored 5.50 (SD = 1.45), resulting in a positive outcome. Students agreed they participated willingly and felt a sense of freedom during the activity.

- Effort/Importance: Scored 4.44 (SD = 1.61), indicating a slightly positive outcome (effort item reverse coded). Students slightly agreed they put effort into the session and found the activity meaningful.

- Pressure/Tension: Scored 4.92 (SD = 1.92), showing a slightly positive outcome (both item reverse coded). Students slightly disagreed that the activity caused tension or anxiety.

- Value/Usefulness: Scored 5.23 (SD = 1.36), reflecting a slightly positive outcome. Students slightly agreed the activity was valuable for their future and useful for enhancing geological knowledge, improving their motivation in geoscience.

Table 2. *VR Motivational Results of Middle School Students*

Subscale	G6 Score	G7 Score	G8 Score	Total Score

	M	SD	M	SD	M	SD	M	SD
Interest/Enjoyment	5.71	1.93	6.42	0.72	6.33	0.79	6.18	1.27
Perceived Competence	4.27	1.54	5.37	1.33	5.16	1.14	4.97	1.41
Perceived Choice	5.44	1.93	5.78	1.21	5.26	1.15	5.50	1.45
Effort/Importance	4.53	1.61	4.45	1.72	4.33	1.51	4.44	1.61
Pressure/Tension	4.50	2.20	5.35	1.86	4.81	1.65	4.92	1.92
Value/Usefulness	4.81	1.68	5.62	1.15	5.19	1.13	5.23	1.36

Note. G = Grade; M = Mean; SD = Standard Deviation

The overall Cronbach's alpha value for the lecture session was at 0.86. Indicating good reliability. The survey results are summarized below (Table 3):

- Interest/Enjoyment: Scored 5.39 (SD = 1.36), indicating a positive outcome. Students agreed the lecture was interesting and enjoyable.

- Perceived Competence: Scored 4.67 (SD = 1.44), showing a slightly positive outcome. Students slightly agreed they understood the session, felt confident in their knowledge, and believed they performed better than peers.

- Perceived Choice: Scored 4.86 (SD = 1.15), resulting in a slightly positive outcome. Students slightly agreed they participated willingly and felt some freedom in their choices.

- Effort/Importance: Scored 4.45 (SD = 1.48), indicating a slightly positive outcome (effort item reverse coded). Students slightly agreed they invested effort and found the activity meaningful.

- Pressure/Tension: Scored 5.10 (SD = 1.57), showing a slightly positive outcome (both item reverse coded). Students slightly disagreed that the session caused tension or anxiety.

- Value/Usefulness: Scored 5.18 (SD = 1.51), reflecting a slightly positive outcome. Students slightly agreed the lecture was valuable for their future and useful for enhancing geological knowledge, improving their motivation in geoscience.

Table 3. *Lecture Motivational Results of Middle School Students*

Subscale	G6 Score		G7 Score		G8 Score		Total Score	
	M	SD	M	SD	M	SD	M	SD
Interest/Enjoyment	5.46	1.21	5.52	1.20	5.19	1.62	5.39	1.36
Perceived Competence	4.80	1.65	4.80	1.19	4.40	1.46	4.67	1.44
Perceived Choice	5.03	1.08	5.03	1.23	4.53	1.08	4.86	1.15
Effort/Importance	4.92	1.56	4.55	1.48	3.89	1.23	4.45	1.48
Pressure/Tension	4.58	1.86	5.75	1.19	4.89	1.43	5.10	1.57
Value/Usefulness	5.39	1.52	5.23	1.32	4.91	1.66	5.18	1.51

Note. G = Grade; M = Mean; SD = Standard Deviation

The overall Cronbach's alpha value for the hands-on session was at 0.95, demonstrating excellent reliability. On a 7-point Likert scale, the survey results are as follows (Table 4):

- Interest/Enjoyment: Scored 5.40 (SD = 1.27), indicating a positive outcome. Students agreed the hands-on activity was interesting and enjoyable.

- Perceived Competence: Scored 4.95 (SD = 1.25), showing a slightly positive outcome. Students slightly agreed they understood the session, felt confident in their knowledge, and believed they performed better than peers.

- Perceived Choice: Scored 4.91 (SD = 1.33), resulting in a slightly positive outcome. Students slightly agreed they participated willingly and felt some freedom in their choices during the hands-on.

- Effort/Importance: Scored 4.51 (SD = 1.61), indicating a slightly positive outcome (effort item reverse coded). Students slightly agreed they invested effort and found the activity meaningful.

- Pressure/Tension: Scored 4.91 (SD = 1.77), showing a slightly positive outcome (both item reverse coded). Students slightly disagreed that the session caused tension or anxiety.

- Value/Usefulness: Scored 5.21 (SD = 1.11), reflecting a slightly positive outcome. Students slightly agreed the hands-on activity was valuable for their future and useful for enhancing geological knowledge, improving their motivation in geoscience.

Table 4. *Hands-on Motivational Results of Middle School Students*

Subscale	G6 Score		G7 Score		G8 Score		Total Score	
	M	SD	M	SD	M	SD	M	SD
Interest/Enjoyment	5.39	1.50	5.73	1.07	5.07	1.18	5.40	1.27
Perceived Competence	5.18	1.45	4.95	1.21	4.73	1.07	4.95	1.25
Perceived Choice	4.97	1.53	5.48	1.30	4.18	0.67	4.91	1.33
Effort/Importance	4.58	1.80	4.58	1.65	4.37	1.35	4.51	1.61
Pressure/Tension	4.18	2.04	5.83	1.22	4.50	1.57	4.91	1.77
Value/Usefulness	5.39	1.23	5.35	1.04	4.79	0.92	5.21	1.11

Note. G = Grade; M = Mean; SD = Standard Deviation

Table 5 shows an overall comparison of the motivational impacts between the VR, Lecture, and Hands-on activity for all grades combined. The VR tends to score highest except for the Effort/Importance and Pressure/Tension, while the Hands-on often comes to the second.

Table 5. *Motivational Results of Middle School Students by activities*

Subscale	VR		Lecture		Hands-on	
	M	SD	M	SD	M	SD

	M	SD	M	SD	M	SD
Interest/Enjoyment	6.18	1.27	5.39	1.36	5.40	1.27
Perceived Competence	4.97	1.41	4.67	1.44	4.95	1.25
Perceived Choice	5.50	1.45	4.86	1.15	4.91	1.33
Effort/Importance	4.44	1.61	4.45	1.48	4.51	1.61
Pressure/Tension	4.92	1.92	5.10	1.57	4.91	1.77
Value/Usefulness	5.23	1.36	5.18	1.51	5.21	1.11

Note. M = Mean; SD = Standard Deviation

3.3 Open comments

The open comments provided valuable insights into the positive and negative traits of each session as perceived by the participants. Not to be mistaken for concrete frequency data pertaining these traits but only what was noticeable and mentioned by the participants. Students' feedback ranged from single words to more detailed responses, which required the author to code them individually according to a keyword-based guideline (Table 6). The frequency of responses for each code reflects the traits that were most mentioned, highlighting the strongest impressions of the sessions. While even a single mention indicates a positive or negative trait, the most frequently cited elements point to the most prominent experiences of the participants.

Table 6. *Coding procedure based on keywords*

Code	Example keywords
Accessibility	Difficulty, freedom, mobility, clarity, familiarity
Content	New knowledge, examples, materials, chapters, 3D materials, information, explanation, summary page, figures
Discomfort	Sickness, eye pain, cumbersome
Engagement	Style, fun, interesting, cool, enjoyable, satisfying, entertaining, interactive, positivity, delivery
Immersion	Presence, realism, visuals
Inaccessibility	Difficulty, lack possession, confusion, difficulty, equipability
Insufficient content	Lack content, simplicity, lack pictures, lack activity, lack explanation
Interaction	Hands-on, classroom interaction
Management	Distractions, lack instructions
Novelty	New experience, unique
Poor Engagement	Zoning out, boring, awkward, lack of interactions, lack participation, sitting, lack freedom, repetitive, passive
Technical Issues	Audio, bugs, glitches, lagging
Technology	VR device, drone
Time	Time limit, waiting time, long speech, long lecture
Value	Experience, usefulness, exposure

In terms of positive aspects, the VR session received the most positive feedback for its engagement, followed by the content, immersion, technology, accessibility, novelty, and interaction (Table 7). The lecture session was most appreciated for its content, with engagement, accessibility, value, and interaction also receiving positive mentions. Similarly, the hands-on session was praised for its content, engagement, and interaction, followed by technology,

accessibility, and value. The primary takeaway from the VR session was its ability to engage students, while the lecture and hands-on sessions were most valued for their content.

Table 7. *Open comments on positive aspects of the sessions*

Code	VR (from 47 response)	Lecture (from 45 response)	Hands-on (from 37 response)
Accessibility	4	10	2
Content	11	28	22
Engagement	32	17	12
Immersion	8	0	0
Interaction	2	3	10
Novelty	3	0	0
Technology	7	0	8
Value	0	4	1

330 On the other hand, the negative aspects identified in the feedback revealed areas for improvement. For the VR session, the most frequently mentioned negative aspects included technical issues, discomfort, inaccessibility/management, insufficient content, and time constraints (Table 8). For the lecture session, the main concerns were inaccessibility, poor engagement, insufficient content, and time limitations. The hands-on session received similar

335 negative feedback, with inaccessibility, poor engagement, and insufficient content being the most common complaints. The key negative issue for the VR session was the presence of technical problems, while the lecture and hands-on sessions were predominantly affected by accessibility challenges.

Table 8. *Open comments on negative aspects of the sessions*

Item	VR (from 30 response)	Lecture (from 26 response)	Hands-on (from 13 response)
Inaccessibility	5	13	8
Insufficient content	3	4	1
Discomfort	7	0	0
Management	5	0	0
Poor Engagement	0	10	4
Technical Issues	13	0	0
Time	2	2	0

340

4 Discussion

4.1 VR usability impacts

Overall feedback on VR-related discomfort was positive (Table 1), with most middle school students reporting no significant issues during the 5-minute lecture. However, seven students
345 experienced discomfort, including eye strain, headset heaviness, and motion sickness (Table 8). Motion sickness, or cybersickness, is a known challenge in VR adoption (Chang et al. 2020; Chattha et al. 2020; Keshavarz et al. 2011). The positive experience likely resulted from the short lecture duration, minimal movement, simple design, and optimized performance, all of

which could have reduced discomfort triggers. Previous studies indicate that longer sessions, complex tasks, and unrealistic locomotion increase motion sickness risk due to sensory conflict (Dużmańska et al. 2018; Reason & Brand, 1975; Saredakis et al. 2020). By keeping the experience brief and straightforward, these issues were effectively minimized.

The effectiveness of the VR experience received positive feedback (Table 1), with students finding it easy to use, navigate, and effective for learning geoscience topics. The lecture was designed to be simple and time-efficient, requiring minimal interaction; students only needed to stand, look, and listen. Open comments confirmed that students gained new knowledge, with 3D models being particularly helpful for understanding and visualizing discussed concepts (Table 7). Research on penetrative thinking (Bagher et al. 2020) and spatial abilities (Gittinger & Wiesche, 2024) supports that VR can benefit low spatial ability learners. Therefore, strategically designed VR lectures with 3D models can enhance geoscience teaching and improve learning effectiveness.

The satisfaction category received overwhelmingly positive feedback, with students across all grades enjoying the VR experience (Table 1). Open comments emphasized the excitement of learning geoscience in an engaging way, enhanced by a variety of 3D geological examples (Table 7). Similar positive responses to VR in educational settings have been reported across age groups, from high school to university (Graebling et al. 2024; Visneskie et al. 2020; Yamauchi et al. 2022). These findings compliments those literature, suggesting that VR is well-received by students, even at the middle school level.

The immersion category also received positive feedback, with students feeling absorbed and expressing a desire for longer VR sessions (Table 1). The VR lecture's immersive design, featuring a scripted virtual lecturer, detailed 3D content, and animations, likely enhanced this effect. Students highlighted the visuals, sense of "being there," and freedom of movement as key contributors to their sense of immersion (Table 7). Similar findings have been observed in geological VR research, including simulations, role-playing, and visualization (Alene et al. 2024; Graebling et al. 2024; Klippel et al. 2019). These results support that VR effectively immerses students, fostering a sense of presence with the geoscience content.

The accessibility category received positive feedback, with students finding the VR lecture easy to use despite having no prior experience. The simple tutorial (hypothesized to pose some difficulties for students), featuring a single panel with basic instructions (Fig. 1a), was generally sufficient, though G6 students were more neutral, possibly needing additional guidance or time to consult it (Table S1; Supplementary data). Some negative feedback pointed to the tutorial's simplicity and lack of detail (Table 8). This aligns with literatures that had outline the need for a robust familiarization phase (Harknett et al. 2022; Papadopoulou et al. 2022; Wright et al. 2023). While the current tutorial was adequate for most of the students, improvements for younger audiences, like G6, are recommended. Future studies should explore ways to enhance the tutorial or familiarization process for younger audiences.

Overall, the VR usability of this VR lecture experience was positive with a strong level of satisfaction. With rooms for improvements for discomfort, effectiveness immersion, and accessibility to obtain a stronger opinion.

4.2 VR motivational impacts

The VR session outperformed the lecture and hands-on sessions in Interest/Enjoyment, receiving overwhelmingly positive feedback (Table 2, 3, and 4). Its immersive 3D content and interactive experience led to strong engagement, with no reports of poor engagement. This aligns with similar studies in geoscience education (Graebling et al. 2024; Visneskie et al. 2020). However, critiques of the VR session primarily focused on its limited duration. Lectures and hands-on sessions were praised for content delivery, with lectures benefiting from teacher interaction and hands-on sessions excelling in interactivity. Traditional methods, however, faced issues like poor engagement and excessive session length (Table 8), which could induce boredom (Mann & Robinson, 2009). While VR's immersion is effective for engagement, the novelty may diminish with repeated use, warranting further studies.

All sessions showed slightly positive outcomes in Perceived Competence, with no significant preference among students (Table 2, 3, and 4). Likely, VR's 3D models and immersive content supported comprehension and spatial reasoning (Bagher et al. 2020; Gittinger & Wiesche, 2024). Students reported that VR aided mental visualization of geological concepts, though the absence of subtitles, lack of interactivity, and fast pacing affected younger students (G6). Lectures achieved positive outcomes for their content and clarity, but some students desired more in-depth clarifications. Hands-on sessions benefited from interactive 3D models and drones but occasionally struggled with complex content. To improve confidence and comprehension, the VR activity could incorporate aiding elements (e.g. subtitles), interactive features, and slower pacing, while adjusting content based on grade level.

Perceived Choice was rated positively for all sessions, with VR slightly outperforming others (Table 2, 3, and 4). Students appreciated VR's novelty and the freedom to explore models from different angles. Individual presence in virtual worlds can foster a sense of freedom and agency, allowing users to explore and interact with objects in ways impossible in the physical world (Chirico et al. 2018). Lectures offered interaction with instructors, and hands-on sessions excelled in exploration and drone demonstrations. VR's lower score in this category stemmed from limited content, non-interactive models, and short session durations, compounded by having only four VR stations. VR's high cost could limit classroom implementation if resources are scarce. Nonetheless, VR's immersive environment provided a unique sense of autonomy, motivating engagement and fostering independence. Longer, more interactive sessions are recommended, possibly by increasing VR workstation availability.

All sessions received slightly positive outcomes for Effort/Importance, indicating slight importance without being too effort demanding (Table 2, 3, and 4). VR was praised for simplifying content with 3D materials but may have been seen more as a fun tool than a serious learning medium, reducing its perceived importance (Table 7). However, this fun factor may be important as it will encourage exploration which could lead to a feeling of self-ownership in learning (Paige et al. 2024). Lectures were appreciated for clear explanations and future potential relevance, while hands-on sessions excelled in interactivity but likely required more effort to understand the small-scale geology models. Emphasizing educational value in VR and incorporating more detailed interactive elements could enhance perceived effort and relevance.

Pressure/Tension outcomes were slightly positive across all sessions, reflecting minimal stress or anxiety (Table 2, 3, and 4). VR's immersive environment and low complexity may contribute to a relaxed experience, this aligns with research on virtual presence (Pavic et al. 2023). However, issues like peer interference and the 5-minute time limit occasionally caused frustration. Lectures and hands-on sessions benefited from engaging materials and supportive instructors, though content density with complexity could have contribute to increased perceived tension. Addressing timing, peer distractions, and content difficulty may reduce pressure and improve the perception of the VR lecture.

Finally, all sessions scored slightly positive for Value/Usefulness, with students recognizing benefits in geoscience knowledge and motivation but not finding them highly impactful (Table 2, 3, and 4). VR was praised for enhancing visualization of landslides through 3D models, but the short duration and limited real-world applications diminished its impact. Lectures were valued for content and clarity, while hands-on sessions excelled in interactivity. The entertainment-oriented perception of VR, stemming from its origins in the entertainment industry (Havenith et al. 2019; Hornsey & Hibbard, 2024), may have influenced their perception outcomes. Future studies should connect geoscience concepts to practical applications and try to extend VR session durations to increase perceived value and usefulness.

4.3 Advantages and disadvantages of the VR lecture

From the study it revealed that there are several advantages and disadvantages of delivering VR lectures in a school setting most evident from the open comment entries by the participants (Table 7 & Table 8) and the results of the survey (Table 1, 2, 3, & 4).

The project demonstrated VR's advantages for geoscience education. The fast-paced VR lecture was enough to engage middle school students showcasing its ability to attract and motivate effectively. Its short duration minimized VR-related discomfort. Its immersive nature offered a safe exploration of hazardous sites, enhanced understanding through 3D models, and bridged abstract and practical concepts not easily achievable through traditional means. Additionally, the novelty of VR technology in the geoscience curriculum excited and appealed to the students, while the freedom to explore the virtual environment, including free-roaming capabilities and interaction with the VR system, further enriched their learning experience.

Despite its strengths, the VR lecture presented several challenges. Although majority of students did not experience discomfort, there were still some that did (e.g., motion sickness, eye strain, HMD weight), and technical issues like individuals changing audio on shared headsets, glitches, and lag were common. VR experience can also vary depending on the developers' expertise, time, and budget, posing a potential challenge for standardized implementation. VR is also not yet widely adopted in current educational settings and requires time for users to learn the system for efficient usage. High costs limit headset availability, necessitating shared use, which leads to shorter sessions and extended wait times. Although VR can significantly improve accessibility for individuals with impaired mobility by offering virtual experiences that eliminate physical barriers, it remains largely unusable for individuals with highly impaired vision (those that cannot be fixed with prescription lenses), those with certain neurological or vestibular conditions, and for individuals who cannot afford these

devices due to financial limitations. Addressing these issues requires thoughtful planning, resources, and financial support especially considering implementation for quality and accessible geoscience education.

475 It should be noted that developing VR-based educational materials can be time and effort intensive which is quite unlike traditional lecture preparation. Practitioners looking into tackling such topic may currently require some proficiency in game/3D engines, troubleshooting, user testing, iterative refinement process and sufficient knowledge in the geoscience subject matter for successful development of VR geoscience educational materials.

480 These invisible workloads have highlighted the difficulties of VR approaches in prior research (Lütjens et al., 2019; Akbulut and Anani 2019; Novotny et al., 2019).

The time and cost factor may be a significant barrier for the global adoption of VR lectures in geoscience education. For example, creating and editing 3D data can be technically demanding and time-consuming for geoscience researchers and educators who may not have advanced

485 computational expertise, and financial constraints often limit access to high-performance computers and HMD devices. However, it can offer additional benefits that traditional methods often struggle to deliver as discussed (e.g., taking young students to dangerous field sites and various data presentation possibilities). Even if both VR and traditional methods yield similar learning gain in the short term, the long-term impact of VR should be considered as well, such

490 as improved retention, increased motivation, and the ability to intuitively grasp complex spatial relationships of geological subjects, may justify the additional time and cost. Furthermore, as VR development tools for geosciences become more standardized and user-friendly, and as the cost of necessary VR devices continues to decrease, the initial investment in content creation may be repaid over repeated use, making it a potentially viable long-term educational strategy.

495 Further research is still required for more definitive conclusions, leading to the next section.

4.4 Limitations of the approach and future studies recommendations

It is advised that readers understand the limitations of this work as it will be helpful when using it as a reference.

Researcher bias could influence the interpretation of qualitative open comments, despite

500 adherence to coding guidelines (Table 6), as student responses varied from vague to detailed. Additionally, the sample may exhibit some class bias, as the school is a private institution catering primarily to foreign clients. Furthermore, session delivery styles differed among chairs, potentially affecting student experiences. Additionally, the survey was adapted for a young audience and time constraints, limiting its comprehensiveness; future studies with fewer

505 constraints could address this. Moreover, while the sample was international, it lacked true global representation. These difference in a countries' learning culture may influence how individuals learn (Joy & Kolb, 2009). Also, not all students completed the questionnaire, especially open comment sections, due to factors like unwillingness to provide feedback or logistical issues. Although the VR session had the highest response rate, no session achieved

510 full participation. Lastly, the study's fast-paced design, while efficient for collecting data, compromised survey depth and the VR experience quality, which could have been enhanced with additional time.

Future research should expand the sample to include more countries, capturing cultural differences and offering a broader global perspective. Investigating the perceptions of students with extensive VR experience could provide insights into how familiarity influences outcomes, potentially through repeated exposure experiments to mitigate the novelty effect over time. Another promising avenue is testing VR in multiplayer settings, where students collaborate to learn geological concepts. Additionally, live, teacher-led VR lectures could be compared with scripted formats to explore how educators adapt to VR and how students benefit versus traditional methods. Hybrid approaches combining traditional and VR-based learning also warrant further exploration.

5 Conclusions

This study developed a 5-minute, fast-paced, automated VR lecture to evaluate its usability and motivational impacts on international middle school students learning geological topics. To the best of the author's knowledge, it is the first known attempt to assess VR-based geoscience lectures for this demographic, it also showcases an efficient method for gathering substantial data within a limited timeframe. Results demonstrated that the VR lecture was usable, with students reporting high satisfaction levels. Motivational impacts were positive, excelling in fostering interest and enjoyment, and perceived choice. Overall, students showed a clear motivational preference for VR when compared to the traditional teaching methods.

But regardless, there remains for more potential improvements in the VR lecture architecture particularly to further enhancing its usability and motivational aspects. Future research should address the limitations identified in this study to achieve consistently strong verdict across all survey categories. Additionally, insights from challenges in traditional teaching methods can also be used to guide the further refinement of VR implementation in middle school education. This study highlights the potential of VR as a potential platform for engaging diverse audiences and disseminating geoscientific knowledge.

Data availability

The expanded versions of the data used in this study are available as supplementary materials.

Authors contribution

All authors contributed to the study conception, design, material preparation, and data collection. The first draft of the manuscript was written by AZ and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing Interests

The authors declare no competing interests.

Ethical Statement

This study was conducted with the head of school consent, adhering to ethical guidelines. Any personal data collected was anonymized, and participation was voluntary, prioritizing students' well-being and educational benefit.

Acknowledgements

The authors would like to acknowledge the support of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese government for providing the scholarship that sponsored this study.

555   The authors extend their gratitude to Tim Schlosser, Head of School, and middle school teachers Nick Fazio and Tricia Calhoon, along with the dedicated staff members of the school, for their invaluable support and coordination in successfully initiating this project.

The authors also gratefully acknowledge the support provided by students Masafumi Inomata, Tomoki Onodera, and Shunsaku Matsumura for their valuable assistance.

560   The authors would like to express their sincere gratitude to the reviewers and to the editor for their valuable feedback and insightful comments, which have greatly contributed to the improvement of this manuscript.

Financial Support

This work is partially supported by Japan Society for the Promotion of Science (JSPS)
565   KAKENHI Grant Numbers 23K20541, JP21H00627, 23KF0180, JSPS Bilateral Program Number JPJSBP120233201, and 2023 Hokkaido University COI-NEXT fund.

570

575

580

Appendix A: Usability survey

Student ID: ___________

VR Usability (VR Activity)

For each entry below, **circle the response** that best characterized how you feel about the statement.

Discomfort

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I felt some discomfort (e.g. sickness, eye strain etc.)	1	2	3	4	5

Effectiveness (ease of learning and using)

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
It was easy to use and navigate in VR	1	2	3	4	5
VR helped me understand the landslides and research work conducted in Atsuma better	1	2	3	4	5

Satisfaction

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I was very satisfied with the VR experience	1	2	3	4	5
I would recommend the VR activity to other students	1	2	3	4	5
I liked the VR experience	1	2	3	4	5

Engagement

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I wanted to continue the VR activity beyond the time limit	1	2	3	4	5
During the VR activity, it felt like I was really there	1	2	3	4	5

600   Accessibility

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The VR application provided sufficient help and support	1	2	3	4	5
I easily understood how to use the features of VR regardless of prior VR experience	1	2	3	4	5

605

610

615 Student ID: ___________

Motivational Survey (__ Activity)

For each entry below, **circle the response** that best characterized how you feel about the statement.

Interest/ Enjoyment

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
The __ activity was fun & entertaining	1	2	3	4	5	6	7
The __ activity was enjoyable & satisfying	1	2	3	4	5	6	7
The __ activity was interesting & appealing	1	2	3	4	5	6	7

620

Perceived competence

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
I understood majority of the __ session	1	2	3	4	5	6	7
I felt I performed better than my peers	1	2	3	4	5	6	7
I felt more confident and capable about my newly acquired knowledge after the __ activity	1	2	3	4	5	6	7

Perceived choice

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
I was involved with the __ activity because I wanted to	1	2	3	4	5	6	7
I felt I had some freedom of choice during the __ activity	1	2	3	4	5	6	7

625   Effort/Importance

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
I had to put a lot of effort during the __ activity	1	2	3	4	5	6	7
It is important to me to do well during the __ activity	1	2	3	4	5	6	7

Pressure/Tension

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
The __ activity felt tense	1	2	3	4	5	6	7
I felt anxious during the __ activity	1	2	3	4	5	6	7

630

Value/Usefulness

	Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree
The __ activity will value me in the future	1	2	3	4	5	6	7
The __ session is useful for my geological knowledge	1	2	3	4	5	6	7
This __ experience improved my motivation in Geology	1	2	3	4	5	6	7

635

640

645

Appendix C: Open comments

650

Student ID: ___________

Open entry (__ Activity)

- In your opinion, what are the positive parts of the __ experience?

655

660

- In your opinion, what are the negative parts of the __ experience?

665

670

- Please provide some suggestion to improve the __ activity and experience

675

References

Akbulut, N., & Anani, A. (2023). *APPLICATION OF VIRTUAL REALITY IN THE MINING INDUSTRY – WHERE WE ARE NOW?* (Preprint 23-036) Paper presented at the SME Annual Conference, Denver, CO.

Alene, G. H., Depina, I., Thakur, V., Perkis, A., & Bruland, O. (2024). QuickAware: A virtual reality tool for quick clay landslide hazard awareness. *Natural Hazards*, *120*(2), 1869–1898. https://doi.org/10.1007/s11069-023-06274-6

Bagher, M. M., Sajjadi, P., Carr, J., La Femina, P., & Klippel, A. (2020). Fostering Penetrative Thinking in Geosciences Through Immersive Experiences: A Case Study in Visualizing Earthquake Locations in 3D. *2020 6th International Conference of the Immersive Learning Research Network (iLRN)*, 132–139. https://doi.org/10.23919/iLRN47897.2020.9155123

Brooke, J. (1996). SUS: A "Quick and Dirty" Usability Scale. In *Usability Evaluation In Industry*. CRC Press.

Carbonell-Carrera, C., Saorin, J. L., & Melián Díaz, D. (2021). User VR Experience and Motivation Study in an Immersive 3D Geovisualization Environment Using a Game Engine for Landscape Design Teaching. *Land*, *10*(5), 492. https://doi.org/10.3390/land10050492

Chang, E., Kim, H. T., & Yoo, B. (2020). Virtual Reality Sickness: A Review of Causes and Measurements. International *Journal of Human–Computer Interaction*, *36*(17), 1658–1682. https://doi.org/10.1080/10447318.2020.1778351

Chattha, U. A., Janjua, U. I., Anwar, F., Madni, T. M., Cheema, M. F., & Janjua, S. I. (2020). Motion Sickness in Virtual Reality: An Empirical Evaluation. *IEEE Access*, *8*, 130486–130499. https://doi.org/10.1109/ACCESS.2020.3007076

Chenrai, P. (2021). Case Study on Geoscience Teaching Innovation: Using 3D Printing to Develop Structural Interpretation Skill in Higher Education Levels. *Frontiers in Earth Science*, *8*, 590062. https://doi.org/10.3389/feart.2020.590062

Chirico, A., Ferrise, F., Cordella, L., & Gaggioli, A. (2018). Designing Awe in Virtual Reality: An Experimental Study. *Frontiers in Psychology*, *8*, 2351. https://doi.org/10.3389/fpsyg.2017.02351

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*, *16*(3), 297–334. https://doi.org/10.1007/BF02310555

De Paz-Álvarez, M. I., Blenkinsop, T. G., Buchs, D. M., Gibbons, G. E., & Cherns, L. (2022). Virtual field trip to the Esla Nappe (Cantabrian Zone, NW Spain): Delivering traditional geological mapping skills remotely using real data. *Solid Earth*, *13*(1), 1–14. https://doi.org/10.5194/se-13-1-2022

Di Natale, A. F., Repetto, C., Riva, G., & Villani, D. (2020). Immersive virtual reality in K-12 and higher education: A 10-year systematic review of empirical research. *British Journal of Educational Technology, 51*(6), 2006–2033. https://doi.org/10.1111/bjet.13030

Dużmańska, N., Strojny, P., & Strojny, A. (2018). Can Simulator Sickness Be Avoided? A Review on Temporal Aspects of Simulator Sickness. *Frontiers in Psychology*, *9*, 2132.

https://doi.org/10.3389/fpsyg.2018.02132

720   Fitzpatrick, M., & Hedley, N. (2024). Review of the state of practice in geovisualization in the geosciences. *Frontiers in Earth Science*, *11*, 1230973. https://doi.org/10.3389/feart.2023.1230973

George, D., & Mallery, P. (2002). SPSS for windows step by step: A simple guide and reference, 11.0 update (4th ed.). Pearson.

725   Gittinger, M., & Wiesche, D. (2024). Systematic review of spatial abilities and virtual reality: The role of interaction. Journal *of Engineering Education*, *113*(4), 919–938. https://doi.org/10.1002/jee.20568

Gliem, J. A., & Gliem, R. R. (2003). *Calculating, Interpreting, and Reporting Cronbach's Alpha Reliability Coefficient for Likert-Type Scales*. 2003 Midwest Research to Practice
730   Conference in Adult, Continuing, and Community Education, Columbus, 82-88.

Graebling, N., Ziefle, G., Furche, M., Nicol, R., Schefer, S., Ziegler, M., Jaeggi, D., Nussbaum, C., Annanias, Y., Goldstein, S., & Rink, K. (2024). VR-EX — An immersive virtual reality serious game for science communication about the electrical resistivity tomography measurements in the Mont Terri Rock Laboratory, Switzerland.
735   *Environmental Earth Sciences*, *83*(10), 318. https://doi.org/10.1007/s12665-024-11613-2

Gutierrez, J., Akciz, S. O., Bursztyn, N., Nichols, K., & Thurmond, J. (2023). Testing the efficacy of 3D-printed geologic models as tools for fostering spatial visualization abilities. *International Geology Review*, *65*(8), 1320–1330.
740   https://doi.org/10.1080/00206814.2022.2084647

Hagge, P. D. (2024). Metaverse in in the geography lecture classroom? Evaluating 'group VR' possibilities using the multiplayer 'Wooorld' VR app. *Journal of Geography in Higher Education*, *48*(5), 864–872. https://doi.org/10.1080/03098265.2024.2333290

Harknett, J., Whitworth, M., Rust, D., Krokos, M., Kearl, M., Tibaldi, A., Bonali, F. L., Van
745   Wyk De Vries, B., Antoniou, V., Nomikou, P., Reitano, D., Falsaperla, S., Vitello, F., & Becciani, U. (2022). The use of immersive virtual reality for teaching fieldwork skills in complex structural terrains. *Journal of Structural Geology*, *163*, 104681. https://doi.org/10.1016/j.jsg.2022.104681

Havenith, H.-B., Cerfontaine, P., & Mreyen, A.-S. (2019). How virtual reality can help visualise
750   and assess geohazards. *International Journal of Digital Earth*, *12*(2), 173–189. https://doi.org/10.1080/17538947.2017.1365960

Hornsey, R. L., & Hibbard, P. B. (2024). Current Perceptions of Virtual Reality Technology. *Applied Sciences*, *14*(10), 4222. https://doi.org/10.3390/app14104222

Huang, H., & Liu, G. (2024). Evaluating students' behavioral intention and system usability of
755   augmented reality-aided distance design learning during the COVID-19 pandemic. *Universal Access in the Information Society*, *23*(3), 1217–1231. https://doi.org/10.1007/s10209-022-00920-9

Jong, M. S., Tsai, C., Xie, H., & Kwan-Kit Wong, F. (2020). Integrating interactive learner-immersed video-based virtual reality into learning and teaching of physical geography.
760   *British Journal of Educational Technology*, *51*(6), 2064–2079. https://doi.org/10.1111/bjet.12947

Joy, S., & Kolb, D. A. (2009). Are there cultural differences in learning style? *International Journal of Intercultural Relations*, *33*(1), 69–85. https://doi.org/10.1016/j.ijintrel.2008.11.002

765 Keshavarz, B., Hecht, H., & Zschutschke, L. (2011). Intra-visual conflict in visually induced motion sickness. *Displays*, *32*(4), 181–188. https://doi.org/10.1016/j.displa.2011.05.009

King, C. (2008). Geoscience education: An overview. *Studies in Science Education*, *44*(2), 187–222. https://doi.org/10.1080/03057260802264289

770 Klippel, A., Zhao, J., Jackson, K. L., La Femina, P., Stubbs, C., Wetzel, R., Blair, J., Wallgrün, J. O., & Oprean, D. (2019). Transforming Earth Science Education Through Immersive *Experiences*: Delivering on a Long Held Promise. *Journal of Educational Computing Research*, *57*(7), 1745–1771. https://doi.org/10.1177/0735633119854025

Liben, L. S., Kastens, K. A., & Christensen, A. E. (2011). Spatial Foundations of Science
775 Education: The *Illustrative* Case of Instruction on Introductory Geological Concepts. *Cognition and Instruction*, *29*(1), 45–87. https://doi.org/10.1080/07370008.2010.533596

Lütjens, M., Kersten, T., Dorschel, B., & Tschirschwitz, F. (2019). Virtual Reality in Cartography: Immersive 3D Visualization of the Arctic Clyde Inlet (Canada) Using
780 Digital Elevation Models and Bathymetric Data. *Multimodal Technol. Interact.*, *3*(1), 9. https://doi.org/10.3390/mti3010009

Mann, S., & Robinson, A. (2009). Boredom in the lecture theatre: An investigation into the *contributors*, moderators and outcomes of boredom amongst university students. *British Educational Research Journal*, *35*(2), 243–258.
785 https://doi.org/10.1080/01411920802042911

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. *Computers & Education, 70*, 29–40. https://doi.org/10.1016/j.compedu.2013.07.033

790 Meulenbroeks, R., Van Rijn, R., & Reijerkerk, M. (2024). Fostering Secondary School *Science* Students' Intrinsic Motivation by Inquiry-based Learning. *Research in Science Education*, *54*(3), 339–358. https://doi.org/10.1007/s11165-023-10139-0

Novotny, J., Tveite, J., Turner, M. L., Gatesy, S., Drury, F., Falkingham, P., & Laidlaw, D. H. (2019). Developing Virtual Reality Visualizations for Unsteady Flow Analysis of
795 Dinosaur Track Formation using Scientific Sketching. *IEEE Transactions on Visualization and Computer Graphics*, *25*(5), 2145–2154. https://doi.org/10.1109/TVCG.2019.2898796

Paige, C., Haddad, D. D., Piercy, T., Todd, J., Ward, F., Ekblaw, A., & Newman, D. (2024). Development and user study of the Operational Geology in a Virtual Environment
800 (OGIVE) platform. *Acta Astronautica*, *224*, 17–36. https://doi.org/10.1016/j.actaastro.2024.07.043

Papadopoulou, E.-E., Papakonstantinou, A., Kapogianni, N.-A., Zouros, N., & Soulakellis, N. (2022). VR Multiscale Geovisualization Based on UAS Multitemporal Data: The Case of Geological Monuments. *Remote Sensing*, *14*(17), 4259.
805 https://doi.org/10.3390/rs14174259

Pavic, K., Chaby, L., Gricourt, T., & Vergilino-Perez, D. (2023). Feeling Virtually Present Makes Me Happier: The Influence of Immersion, Sense of Presence, and Video Contents on Positive Emotion Induction. *Cyberpsychology, Behavior, and Social Networking*, *26*(4), 238–245. https://doi.org/10.1089/cyber.2022.0245

810 Reason, J. T., & Brand, J. J. (1975). *Motion sickness*. Academic Press.

Ryan, R. M., & Deci, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist*, *55*(1), 68–78. https://doi.org/10.1037/0003-066X.55.1.68

Saredakis, D., Szpak, A., Birckhead, B., Keage, H. A. D., Rizzo, A., & Loetscher, T. (2020). 815 Factors Associated With Virtual Reality Sickness in Head-Mounted Displays: A Systematic Review and Meta-Analysis. *Frontiers in Human Neuroscience*, *14*, 96. https://doi.org/10.3389/fnhum.2020.00096

Tibaldi, A., Bonali, F. L., Vitello, F., Delage, E., Nomikou, P., Antoniou, V., Becciani, U., De Vries, B. V. W., Krokos, M., & Whitworth, M. (2020). Real world–based immersive 820 Virtual Reality for research, teaching and communication in volcanology. *Bulletin of Volcanology*, *82*(5), 38. https://doi.org/10.1007/s00445-020-01376-6

United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development* (A/RES/70/1). United Nations General Assembly. https://undocs.org/A/RES/70/1

825 Villena-Taranilla, R., Tirado-Olivares, S., Cózar-Gutiérrez, R., & González-Calero, J. A. (2022). Effects of virtual reality on learning outcomes in K-6 education: A meta-analysis. *Educational Research Review, 35*, 100434. https://doi.org/10.1016/j.edurev.2022.100434

Visneskie, H., Parks, J., & Johnston, J. (2020). Learning about Ontario's Paleozoic Geology 830 with Virtual Reality Google Expedition Tours.

Watson, A., Kennedy, B. M., Jolley, A., Davidson, J., & Brogt, E. (2022). Design, implementation, and insights from a volcanology Virtual Field Trip to Iceland. *Volcanica*, *5*(2), 451–467. https://doi.org/10.30909/vol.05.02.451467

Wright, P. N., Whitworth, M., Tibaldi, A., Bonali, F., Nomikou, P., Antoniou, V., Vitello, F., 835 Becciani, U., Krokos, M., & Van Wyk De Vries, B. (2023). Student evaluations of using virtual reality to investigate natural hazard field sites. *Journal of Geography in Higher Education*, *47*(2), 311–329. https://doi.org/10.1080/03098265.2022.2045573

Yamauchi, H., Tsuruoka, K., Ogura, T., Tamura, Y., Hayakawa., Y. S., Iizuka, K., & Oguchi, T. (2022). 三次元地理空間情報とVR技術を用いた遺構の散策アプリの試作と評 840 価—地理教育への応用に向けて—. *E-Journal Geo*, *17*(1), 169–179. https://doi.org/10.4157/ejgeo.17.169