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เรื่อง ขออนุญาตให้ครูเผยแพร่งานวิจัยในสถานศึกษา

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อธิการและผู้อำนวยการโรงเรียนเซนต์คาเบรียล

สิ่งที่แนบมาด้วย บทความงานวิจัยของครู

ด้วย มาสเตอร์ภัทรพล แย้มวงษ์ศรี ครูผู้สอน กลุ่มสาระการเรียนรู้สังคมศึกษา ศาสนา และวัฒนธรรม ระดับชั้นมัธยมศึกษาปีที่ ๔ ได้ดำเนินการจัดทำงานวิจัยในหัวข้อ “The Effects of Spherical Video-Based Virtual Reality in Inquiry-Based Learning on Student Learning Outcomes, Higher-Order Thinking, and Learning Experiences in Geography Education” ซึ่งเป็นงานวิจัยทางการศึกษา

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The Effects of Spherical Video-Based Virtual Reality in Inquiry-Based Learning on Student Learning Outcomes, Higher-Order Thinking, and Learning Experiences in Geography Education

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Abstract

Inquiry-Based Learning (IBL) is known to develop advanced cognitive skills, particularly in complex subjects like geography. However, integrating Spherical Video-Based Virtual Reality (SVVR) with IBL remains underexplored. This study proposed an SVVR-based IBL approach to enhance geography education for high school students in Thailand. A quasi-experimental design was used, with students divided into an experimental group (SVVR-based IBL) and a control group (IBL only). Results showed significant learning improvements in both groups, with the experimental group achieving notably higher gains. The SVVR-based IBL approach particularly boosted critical thinking, problem-solving, and creativity. Qualitative data from student interviews supported these findings, indicating that SVVR's immersive environment effectively captured attention, stimulated curiosity, and improved understanding of complex geographical concepts. The study emphasizes that combining SVVR's interactive virtual spaces with IBL's inquiry-based group discussions significantly boosts learning outcomes and higher-order thinking. It underscores the value of integrating technologies such as SVVR into

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education to create engaging, effective learning experiences. This approach not only enhances learning outcomes but also equips students with essential 21st-century skills. The study offers insights for educators and policymakers, advocating for the inclusion of advanced technologies in curricula to improve educational practices, especially in subjects that benefit from visualization and interactivity.

Keywords
SVVR, inquiry-based learning, geography education, higher-order thinking, learning outcomes

Introduction

The 21st century demands new skills due to rapid globalization, technological advancements, and information spread. To succeed in this evolving world, individuals must develop higher-order thinking skills such as critical thinking, problem-solving, creativity, communication, and collaboration. These skills are essential for navigating complex life and work environments (Almerich et al., 2020; Partnership for 21st Century Skills, 2009; Singh et al., 2017). Thailand is rapidly evolving due to technological advancements, an aging society, and shifts in global relations, necessitating new skills for the 21st century. The Thailand National Strategy 2018-2037 and the Thai National Education Act of B.E. 2542 (1999) underscore the importance of developing higher-order thinking such as critical thinking, problem-solving, and creativity. These skills are essential for personal success and national growth, enabling citizens to navigate complex challenges and contribute meaningfully to both local and global progress in an increasingly interconnected world. As Thailand adapts to these changes, enhancing students' higher-order thinking has become a crucial priority for achieving educational excellence and fostering innovation.

To cultivate higher-order thinking in line with the Thailand National Strategy 2018-2037 and the Thai National Education Act of B.E. 2542 (1999), geography is vital as it explores the environment and human interactions. Geography education, encompassing physical and human geography, fosters critical analysis, creativity, and problem-solving. It promotes interdisciplinary learning and helps students develop the ability to evaluate information critically. As noted by scholars, geography is crucial for enhancing students' cognitive abilities (Favier & van der Schee, 2012; Maude & Caldis, 2019; Virranmäki et al., 2021). Through geography, students engage deeply with real-world issues, making it a strategic field for nurturing Thai students' advanced cognitive skills. This active engagement is essential for equipping students to effectively address the dynamic challenges of the modern world. However, in Thailand, geography education faces challenges due to the extensive content, leading teachers to prefer lecture-based teaching.

When designing learning activities, it is crucial to choose models that align with geography content and that focus on enhancing higher-order thinking (Purwanto et al., 2024). Lu et al. (2021) found that inquiry-based learning significantly boosts these skills as students progress from confirmation to open inquiry. This model, collaborative inquiry-based learning, fosters deeper learning and conceptual understanding, enabling students to think and act like experts in geography (Kriewaldt et al., 2021). The 5 E model, a specific Inquiry-Based Learning (IBL) approach, also addresses practical gaps in geography education, enhancing real-world problem-solving skills (Karvánková et al., 2017). While one of the challenges of implementing IBL is the significant amount of time required for students to engage in the inquiry process and achieve its objectives (Thunyaphon et al., 2022), emerging technologies such as immersive Virtual Reality (VR) provide innovative solutions to address this issue. Studies have shown that VR can streamline inquiry-based learning by providing interactive, immersive environments in which students can explore concepts directly and receive instant feedback, reducing the time needed for conceptual understanding and experimentation (Georgiou et al., 2021).

Scholars have integrated technology into classrooms to enhance participation and learning outcomes (Chen & Hwang, 2020; Fuhrman et al., 2021). Almelweth (2022) highlighted the use of AI in geography education for fostering higher-order thinking and practical application. VR also enhances learning by providing immersive, realistic experiences (Chang et al., 2020). Studies by Gilliam et al. (2017) and Huang et al. (2024) showed that VR, coupled with feedback and reflection, significantly improves problem-solving and critical thinking, leading to deeper engagement and better cognitive outcomes. Within geography education, VR's immersive and interactive nature has the potential to transform traditional teaching methods (Chien et al., 2019). Spherical Video-Based Virtual Reality (SVVR), a subset of VR, introduces a new dimension by offering panoramic views, creating a unique and engaging learning experience. The integration of SVVR into geography education aligns with broader efforts to leverage technology for enhancing educational practices (Pang et al., 2021).

Integrating SVVR with IBL offers a promising method to enhance higher-order thinking and learning outcomes. This approach combines SVVR's immersive features with IBL's investigative nature, aiming to create a stimulating learning environment. Aligned with the Thailand National Strategy 2018-2037 and the Thai National Education Act of B.E. 2542 (1999), this study explored the potential benefits of SVVR and IBL in geography education, thus contributing to educational advancements in Thailand. The purpose of this study was to investigate the impact of the SVVR-enhanced inquiry-based learning model on high school students' geography learning outcomes, higher order thinking and learning experiences. This study attempted to answer the following questions

RQ1: What is the impact of SVVR-based inquiry learning on student learning outcomes in the context of geography education among high school students in Thailand?

RQ2: What is the impact of integrating SVVR-based inquiry learning on high school students' higher order thinking compared to traditional inquiry learning without SVVR in the context of geography education?

RQ3: How do high school students perceive their learning experiences when engaging in inquiry-based learning with and without SVVR?

Literature Review

Theoretical Framework

The present study is grounded in constructivist learning theory, which emphasizes that learners actively construct knowledge through experience, reflection, and interaction with their environment, rather than simply absorbing information passively (Vygotsky, 1978). According to this theory, meaningful learning occurs when learners engage in tasks that are authentic and collaborative, and that allow them to connect new information with prior knowledge. Knowledge acquisition is not about transferring facts, but about facilitating opportunities for learners to build their own understanding. Within this framework, inquiry-based learning (IBL) serves as a pedagogical approach that aligns with the constructivist emphasis on learner-centered, active engagement. IBL encourages students to explore problems, ask questions, and construct their own understanding through investigation and discovery.

To enhance this experiential process, Spherical Video-Based Virtual Reality (SVVR) is employed as a technological tool that provides immersive, authentic learning environments. SVVR supports constructivist principles by simulating real-world contexts that allow learners to engage in situated learning experiences (Makransky & Mayer, 2022). It promotes active exploration, supports multiple perspectives, and enhances cognitive engagement—all of which are central to both constructivist theory and IBL.

Together, these approaches form a cohesive framework in which constructivist theory provides the epistemological foundation, inquiry-based learning offers the instructional strategy, and SVVR serves as the enabling technology that facilitates meaningful, learner-driven exploration and knowledge construction. This combination leverages both the pedagogical structure of IBL and the experiential potential of SVVR, creating a powerful platform for knowledge construction and cognitive engagement.

Inquiry-Based Learning in Geography Education

IBL is an educational strategy that involves students actively participating in the learning process by exploring, questioning, and investigating to find solutions and construct knowledge (National Research Council, 2000). It is particularly effective in geography education as it enhances students' geographical understanding by connecting current experiences with new knowledge (Roll et al., 2018). IBL promotes essential skills such as communication, collaboration, creativity, and critical thinking (Kriewaldt et al., 2021), and fosters deep learning by encouraging students to think and act like professional geographers. Research has shown that IBL significantly improves environmental knowledge, spatial thinking, and analytical skills, making geography learning more engaging and meaningful (Refualu et al., 2022; Suwito et al., 2020). The 5 E model, a specific IBL approach, enhances students' ability to analyze and synthesize geographic information, leading to better academic performance (Suwito et al., 2020). IBL's emphasis on inquiry practices, where students formulate questions, collect, and interpret data, is crucial for developing independent thinking and problem-solving abilities in the 21stcentury curriculum (Kuisma, 2018). Additionally, IBL allows students to engage with real-world geographical problems, improving their critical observation and data interpretation skills. This method's focus on active investigation during and outside of class aligns with the needs of modern geography education, providing students with numerous opportunities to explore and understand complex geographical concepts (Adawiyah & Haolani, 2021; Adnan et al., 2024).

Virtual Reality in Geography Education

VR denotes computer technology that generates realistic environments, enabling users to engage with virtual objects (Chien et al., 2019). It allows users to engage with the environment in a manner that creates a sense of being physically present (Pang et al., 2021). VR is increasingly recognized as a significant tool in geography education, offering lifelike, three-dimensional environments that enhance students' spatial cognition and analytical skills. The literature highlights VR's effectiveness in various educational contexts, from enhancing spatial skills and engagement in cultural heritage studies to improving comprehension in climate change education. For instance, Wright et al. (2023) emphasized the positive impact of VR on students' landscape analysis skills, particularly when they have prior experience with technology. Similarly, studies by Argyriou et al. (2020) and Petersen et al. (2020) showed VR's potential to provide immersive learning experiences in fields such as cultural heritage and climate change.

However, despite the growing body of research on VR's applications in geography education, there remains a need for more empirical studies, particularly concerning physical geography topics such as flood plains. The existing studies often focused on specific applications, such as cultural heritage or environmental science, leaving a gap in the literature regarding how VR can be effectively integrated into broader geographical education. Roelofsen (2022) pointed out that while VR can stimulate geographic understanding, it also introduces spatial and perceptual challenges that need to be addressed. This calls for a more nuanced understanding of VR's role as a pedagogical tool, especially in underexplored areas such as flood plain education, where the potential of VR remains largely untapped.

Additionally, the effectiveness of VR in educational settings largely depends on the strategies employed to integrate it into learning. Prior studies have noted that students engaging with VR systems often focus on completing assigned tasks while neglecting the environmental or contextual information presented within the VR environment, particularly when clear instructional strategies are not in place (Chang et al., 2020). This suggests that incorporating well-designed learning frameworks and scaffolding is essential to ensure that VR not only improves students' learning outcomes and motivation, but also fosters their deeper cognitive processing and higher-order thinking.

Virtual Reality and Higher-Order Thinking

VR has emerged as a potent tool in education, particularly for enhancing higher-order thinking skills such as critical thinking, problem-solving, and creativity. VR's immersive environments engage learners in ways that traditional methods cannot, requiring them to analyze situations, make decisions, and reflect on their actions in real time. This process inherently promotes critical thinking and problem-solving skills, as learners must constantly evaluate and adjust their strategies to achieve desired outcomes (Hwang et al., 2022). For example, in hands-on VR tasks, students are challenged to assess the accuracy of their actions and make necessary corrections, which deepens their cognitive engagement and reinforces these skills.

Furthermore, research has shown that VR environments can enhance creativity by encouraging students to generate ideas, experiment with diverse solutions, and apply innovative thinking in complex scenarios (Wong et al., 2022). However, some studies have suggested that the effectiveness of VR in terms of fostering creativity may depend on specific features within the environment. For example, Huang et al. (2024) found that VR environments incorporating feedback and reflection improved critical thinking and problem solving but required additional elements, such as collaborative features or diverse stimuli, to fully support creative thinking. This highlights the need for further refinement of VR tools to maximize their potential in fostering creativity.

Engagement in VR learning environments plays a crucial role in promoting higher-order thinking. The inclusion of feedback and reflection is vital, as it allows learners to engage in a thoughtful, step-by-step process of evaluating their knowledge and actions. This reflective practice not only deepens understanding but also strengthens the overall cognitive engagement, enhancing critical thinking, problem solving, and creativity.

Despite the growing evidence of VR's effectiveness in terms of enhancing critical thinking, problem solving, and creativity, there is still a need for further research to optimize VR environments to support all aspects of higher-order thinking and to explore how VR can be designed to balance its immersive features with structured learning strategies to maximize its educational potential across diverse learning contexts.

The SVVR-Based Inquiry Learning 5E Model

SVVR, a subset of VR, allows for more interactive exploration of geographical concepts compared to traditional 2D visualization, enabling students to virtually visit distant locations and engage with complex spatial data. It has emerged as a powerful tool in educational research, particularly due to its integration into the inquiry-based learning model. The integration of SVVR with the 5E Inquiry-Based Learning model offers a dynamic approach to enhancing education, particularly in science. SVVR immerses students in interactive, realistic environments during the Engage phase, fostering curiosity and personalized learning experiences. In the Explore stage, SVVR facilitates hands-on experimentation, deepening students' understanding of complex concepts. The Explain stage benefits from SVVR's visualizations and simulations, aiding with concept comprehension. During the Elaborate stage, SVVR supports further investigation and application of new knowledge, while the Evaluate phase utilizes interactive assessments to gauge understanding. Although widely applied in science, this combination of SVVR and IBL is underexplored in geography education, where SVVR is often used independently without the IBL framework. This gap highlights the need for further research into the potential of SVVR-IBL integration in geography to enhance educational outcomes (Lin & Sumardani, 2022; Pang et al., 2021).

Method

Research Design

This study employed a quasi-experimental research design. This design was chosen due to its ability to compare the outcomes between groups that are naturally occurring or non-randomly assigned while controlling for certain variables to establish causal relationships (Shadish, 2002). By employing this design, the study aimed to explore the effects of the SVVR intervention on students' learning outcomes and higher-order thinking tendencies. A mixed-method approach was used to gather both quantitative and qualitative data. Quantitative data were obtained through pre- and posttests, while qualitative data, which helped to substantiate the quantitative findings, were collected using semi-structured interviews.

Participants

The participants in this study were 74 high school students in Thailand. A purposive sampling method was used to select participants with no prior experience of SVVR-based inquiry learning in geography, ensuring the study accurately measured its impact. Students with previous SVVR learning experience in any subject were excluded to avoid bias. Two classes from a public high school were chosen: one control group of 35 students which used IBL only, and one experimental group of 39 students which used the SVVR-based IBL approach. Before the intervention, both groups demonstrated comparable levels of geography proficiency and higher-order thinking skills. To confirm the comparability of the two groups, a pretest was administered. Analysis of the pretest results of the experimental and control groups revealed no significant differences in geography proficiency or higher-order thinking, confirming that the groups were similar prior to the intervention. Both groups were taught by the same certified high school teacher with over 8 years of teaching experience, who was proficient in delivering technology-enhanced lessons and inquiry-based learning approaches. The instructor played a critical role in ensuring the consistency of the teaching content, instructional methods, and classroom management for the two groups.

Experimental Procedure

This study used the 5E instructional model to evaluate the effectiveness of SVVR in teaching geography about flood plains. Uptale, an SVVR development tool, was employed to develop the course about flood plains, which could support smart mobile devices from a variety of systems. Students were required to download the Uptale application on their mobile phones. The teacher then provided each student with a unique code, which they entered before placing their phones into a head-mounted display. Both the control and experimental groups followed the 5E stages: Engage, Explore, Explain, Elaborate, and Evaluate, with content focused on comparing the Chao Phraya River in Thailand and the Tamsui River in Taiwan. The study emphasized human-environment interactions. In the initial stage, a pretest and pre-questionnaire were administered. After initial pretests, the experimental group was introduced to the use of SVVR and then participated in the Engage stage utilizing SVVR, while the control group started the Engage stage following the 5E IBL model.

In the Engage stage, both groups explored the topic of flood plains. The control group took part in a teacher-led discussion, then watched a PowerPoint presentation (Figure 1) featuring images and a video of the Chao Phraya River, which helped them understand the floodplain environment. Meanwhile, the experimental group used SVVR to virtually explore the Chao Phraya River. Upon entering the SVVR environment, students found themselves in a virtual classroom where they were prompted with thought-provoking questions and a review of floodplain geography through video clips. Next, they entered a scene set on a bridge over the Chao Phraya River, where they

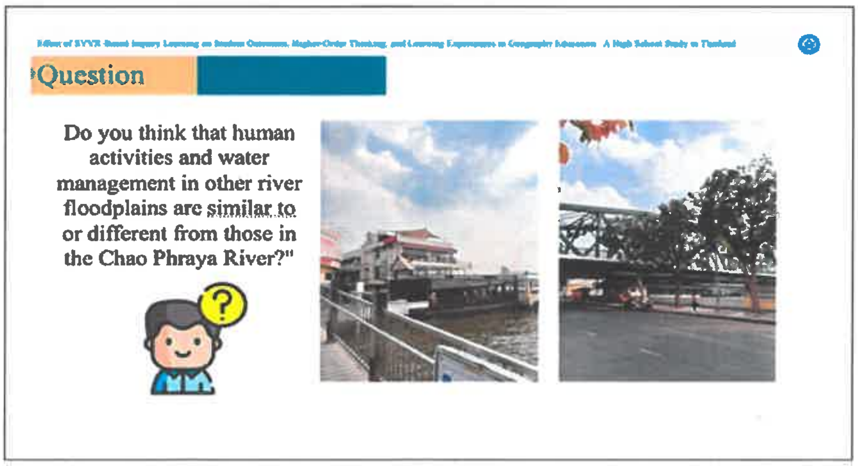

Figure 1. PowerPoint presentation in the Engage Stage for the control group.

were asked reflective questions such as, *"How is the land along the banks of the Chao Phraya River being utilized?"* Students then moved into riverside scenes that allowed them to observe human activities along both sides of the river more closely. Within SVVR, video clips were embedded into the scenes to provide students with enhanced visualizations. Figure 2 illustrates the riverside area along the Chao Phraya River, featuring a top-down view of the riverside communities. The text box feature was used to pose guiding questions, encouraging students to critically engage with the content. For example, after viewing the Chao Phraya River, students were asked, *"Based on what you've observed, how do you think flood prevention measures could be implemented if flooding were to occur?"*

During the Explore stage, both groups examined floodplain management, focusing on the Tamsui River floodplain. In the control group, the teacher provided an overview of Taiwan's geographical background, after which students watched a video about the Tamsui River and conducted online research on its water management methods. The teacher then used questioning techniques to stimulate students' critical thinking, posing questions via a PowerPoint presentation (as shown in Figure 3). For example: "How does the flood management practice in the Tamsui River valley differ from what you've learned about the Chao Phraya River? Consider factors such as pumping stations, sewage treatment, and riverbank dams." The experimental group used SVVR to introduce Taiwan's geographical background through an interactive map accompanied by narration within the SVVR environment. Next, students explored riverside scenes in the SVVR environment, where they investigated floodplain management systems such as pumping stations, riverbank dams, and green spaces along both sides of the river. They also observed human activities like cycling along the riverbanks, with supporting videos integrated into the environment (as shown in Figure 4). Throughout the 360-degree exploration, text box features were used to pose thought-provoking questions, prompting students to reflect on what they observed. These questions mirrored those posed to the control group, ensuring consistency across both learning experiences.

Figure 2. The Engage stage in the SVVR environment.

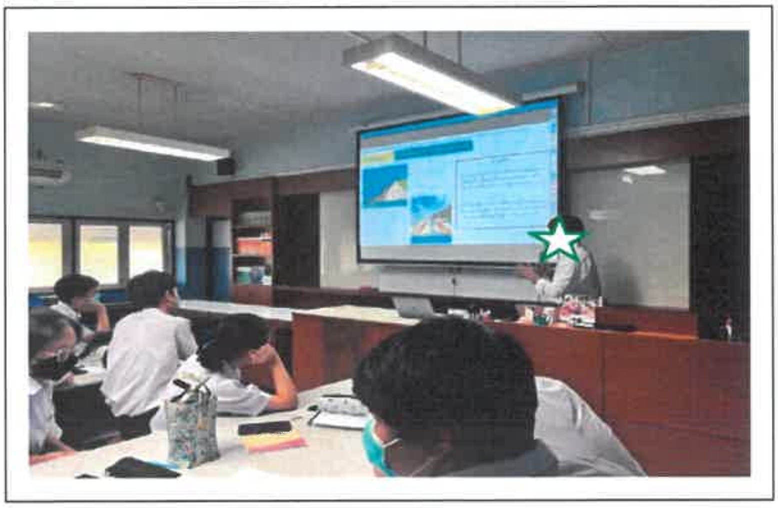

Figure 3. The Explore stage for the control group.

Figure 4. The Explore stage for the experimental group.

In the Explain stage, both groups worked in teams to discuss and articulate their understanding of flood plains. The control group relied on videos and internet research, while the experimental group shared insights from their SVVR experiences. Each group discussed their findings, with each team documenting their findings in notes, and the teacher facilitating discussions to ensure clarity and a comprehensive understanding of the material. Figure 5 illustrates the teacher assisting students during their discussions in the Explain stage. This stage lasted for 50 minutes.

In the Elaborate stage, students applied their knowledge to solve flood management scenarios. Both groups participated in the same activity, where they discussed potential solutions. The teacher posed questions such as "Given your role as a household, government entity, or business, how would you address the challenges of flood

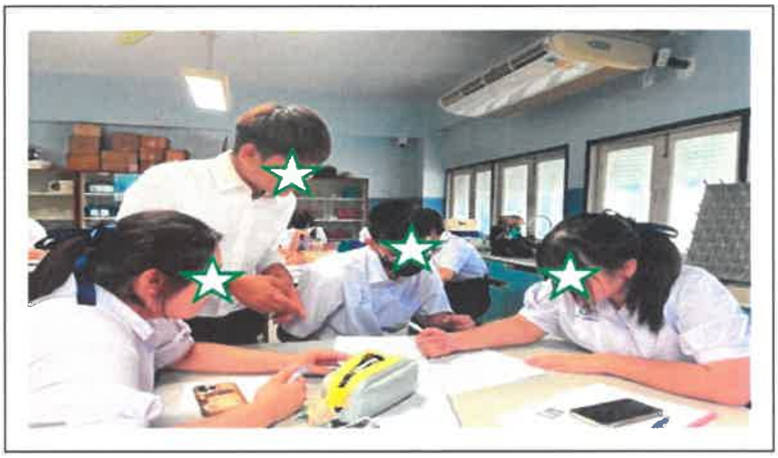

Figure 5. Student discussion in the Explain stage.

management along the Chao Phraya River?" and "Consider the impact of your actions on the river's ecosystem and the local community. What specific strategies or solutions would you propose to balance environmental concerns with urban development needs?" After brainstorming, each group presented their solutions on posters. Additionally, students in the experimental group had the opportunity to revisit the SVVR environment to refine their ideas.

In the Evaluate stage, students assessed other groups' flood management solutions by commenting on posters and voting on the most effective method, explaining their choices. This stage aimed to compare the effectiveness of SVVR versus conventional methods in understanding floodplain geography. Following this, both groups completed posttests and questionnaires via QR codes, taking 25 minutes. The research concluded with semi-structured interviews lasting 40 minutes each. Figure 6 illustrates the experimental procedure.

Instruments

Learning Outcome Test. A 25-min test, aligned with the 5E model, was administered to both groups, consisting of 15 multiple-choice questions with four answer options. The test items measured key learning objectives such as understanding, analysis, and problem-solving skills. For example, students were asked to describe physical characteristics of flood plains, evaluate the impact of human activities, and propose sustainable solutions to effectively manage flood risks. Specific examples of the questions include: "What is a floodplain?" (Understanding), "How does urban development impact flood management?" (Analysis), and "Propose a solution for mitigating flood risks in Bangkok" (Create). Items were formatted to align with Bloom's taxonomy, emphasizing higher-order thinking where possible. These questions were carefully aligned with the Thai curriculum's Standard So5.1, which emphasizes understanding the interaction between humans and the environment to create sustainable lifestyles. In particular, the test supported Indicator 1, focusing on analyzing environmental and

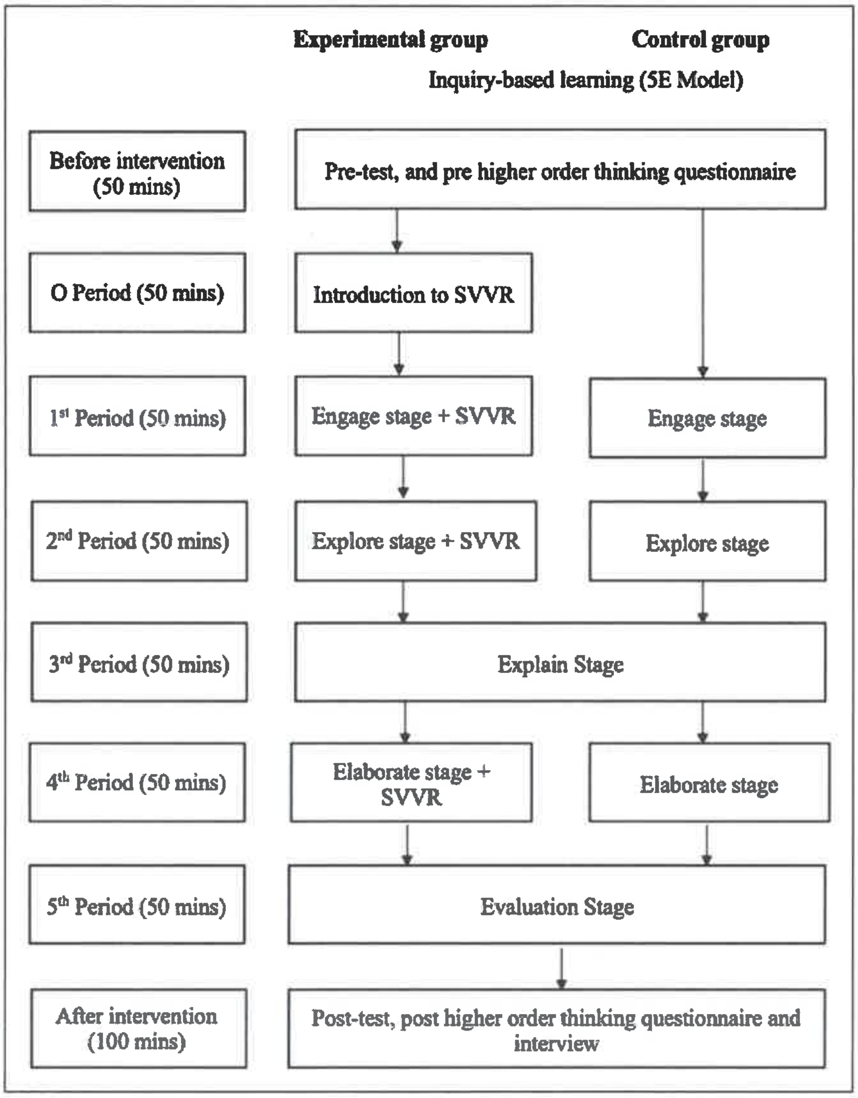

Figure 6. Experiment procedure.

human interactions to highlight their importance in daily life. Expert review and pilot testing further ensured the content's validity and reliability. The test showed strong reliability with a Cronbach's alpha of .81, ensuring consistency in measuring students' geography learning outcomes.

Questionnaires. To assess students' higher-order thinking tendencies, the study used a validated tool from Hwang et al. (2018), covering problem-solving, critical thinking, and creativity. The questionnaire included 11 items rated on a 5-point Likert scale, ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). The problem-solving dimension included items such as "When I face a problem, I believe I have the ability to solve it." The critical thinking section featured items such as "I ask myself periodically if I am meeting my goals." The creativity dimension contained items such as "I like to try something new." The reliability coefficients were 0.85 for problem-solving, 0.84 for critical thinking, and 0.80 for creativity, with an overall reliability of 0.86.

Interview. Semi-structured interviews were conducted with six students from the experimental group and five from the control group, each lasting about 40 minutes. The interviews explored students' learning experiences, focusing on the impact of SVVR on their understanding of geographic concepts, engagement, and challenges faced. The recorded and transcribed interviews aimed to differentiate the unique benefits of SVVR-based inquiry learning from traditional methods, providing a comprehensive analysis of its effectiveness in enhancing geography education.

Data Analysis. The study used non-parametric statistical methods such as the Wilcoxon signed-rank test and Quade's non-parametric ANCOVA to analyze within and between group differences respectively in learning achievement due to non-normal data distribution.

Regarding higher order thinking, paired sample *t* tests were performed to compare the changes from pre- to post-questionnaire scores within each group. Finally, ANCOVA was applied to evaluate the effect of SVVR-based inquiry learning on higher-order thinking, using pre-questionnaire scores as covariates to control for initial differences. Analysis was conducted using the SPSS software.

The qualitative analysis focused on exploring students' learning experiences through semi-structured interviews, which were recorded and transcribed using the SONIX AI software. Thematic analysis was then conducted on the transcribed data to identify and interpret key themes and insights regarding how SVVR-based inquiry learning impacted students' engagement, understanding, and overall learning experience compared to conventional methods. This analysis provided a nuanced understanding of the benefits and challenges associated with the use of SVVR for enhancing geography education.

Results

Analysis of Learning Outcome

We conducted the Mann-Whitney *U* test, a non-parametric statistical analysis, to compare the pre-questionnaire scores of students in the two groups, with the aim of

Table 1. The Mann-Whitney *U* Test Result for the Learning Outcome Test of the Two Groups.

Variable	Group	*N*	Mean-rank	Sum of ranks	*U*	*z*	*r*
Pre-learning outcome test	Control	35	37.53	1463	681	−0.111	−0.001
	Exp	39	37.47	1311			

assessing potential differences in the learning outcome test before intervention. Table 1 shows that the results of the Mann-Whitney *U* test indicated that students in both groups exhibited similar learning outcome test results before the intervention.

Analysis of Learning Outcomes Within Groups

As shown in Table 2, a Wilcoxon signed-rank test revealed that for both groups, the posttest learning achievement score was statistically higher than their pretest learning outcome. This finding implies that both the IBL and the SVVR-based IBL approaches could enhance students' learning outcomes.

Analysis of the Learning Outcomes Between Groups

Further analysis was employed to compare the two groups in terms of their learning achievement. We used a non-parametric test due to the violation of the normality distribution assumption. The non-parametric ANCOVA proposed by Quade (1967) was employed to compare the posttest scores of students' learning achievement in the control and experimental groups by incorporating pretests as the covariates.

Table 2. Wilcoxon Signed-Rank Test Results of Students' Learning Outcomes.

Group		*N*	Mean	*SD*	Wilcoxon W	*z*	*p*
Control group	Pre-test	35	6.09	2.00	401.00	−2.186*	0.029
	Post-test	35	6.76	2.00			
Experimental group	Pre-test	39	6.13	1.673	347.50	−4.249***	0.001
	Post-test	39	8.41	1.743			

$^{*}p < .05$, $^{***}p < .001$.

Table 3. The Quade's ANCOVA Results of Students' Learning Outcomes.

Dependent variable: Unstandardized residual

Source	Type III Sum of Squares	*df*	Mean Square	*F*	*p*
Corrected model	4696.499	1	4696.499	12.134	.001
Intercept	30.875	1	30.875	.080	.778
Group	4696.499	1	4696.499	12.134	.001
Error	27,868.921	72	387.068		
Total	32,565.421	74			
Corrected total	32,565.421	73			

R Squared = .144 (Adjusted R Squared = .132).

Table 3 shows the results of Quade's test of students' learning outcomes. The findings indicate a significant difference between the posttests of the two groups ($F = 12.134$, $p < .001$). The results imply that students in the experimental group, who learned using the SVVR-based inquiry-based learning approach, showed significantly higher learning outcomes compared to the control group, who learned using the conventional inquiry-based learning approach. These findings suggest that the integration of SVVR into inquiry-based learning in geography education had a notable impact on student learning outcomes.

Analysis of Higher-Order Thinking

To compare the pre-higher-order thinking questionnaire scores of the control and experimental groups, independent samples *t* tests were conducted for each variable: higher-order thinking, problem-solving, critical thinking, and creativity. The results showed no significant difference between the groups in terms of higher-order thinking ($t = -2.95, p > .05, d = -0.52$), problem-solving ($t = -2.38, p > .05, d = -0.42$), critical thinking ($t = -2.36$, $p > .05$, $d = -0.41$) or creativity ($t = -1.47, p > .05, d = -0.26$), indicating that both the control and experimental groups had similar higher-order thinking, problem-solving, critical thinking, and creativity before the intervention.

Table 4. Paired Samples *t*-Test Results of Higher-Order Thinking, Problem-Solving, Critical Thinking, and Creativity.

Variable	Group		Mean	*SD*	*t*	*d*	*p*
Higher-order thinking	Control	Pre-questionnaire	3.85	.37	−2.95	−.52	.004*
		Post-questionnaire	4.18	.52			
	Experimental	Pre-questionnaire	4.02	.53	−6.83	−1.15	.001***
		Post-questionnaire	4.54	.23			
Problem-solving	Control	Pre-questionnaire	3.75	.43	−2.38	−.42	.012*
		Post-questionnaire	4.13	.73			
	Experimental	Pre-questionnaire	3.93	.69	−3.96	−.67	.001***
		Post-questionnaire	4.47	.34			
Critical thinking	Control	Pre-questionnaire	3.88	.51	−2.36	−.41	.014*
		Post-questionnaire	4.25	.54			
	Experimental	Pre-questionnaire	4.07	.67	−3.43	−.58	.002*
		Post-questionnaire	4.52	.35			
Creativity	Control	Pre-questionnaire	3.93	.62	−1.47	−.26	.052
		Post-questionnaire	4.19	.73			
	Experimental	Pre-questionnaire	4.08	.76	−4.04	−.68	.001***
		Post-questionnaire	4.66	.26			

*$p < .05$, **$p < .01$, ***$p < .001$.

Analysis of Higher-Order Thinking Within Groups. The paired sample *t* test was conducted to compare the pre- and post-questionnaire scores of students in both the control and experimental groups, as summarized in Table 4. The analysis focused on four key variables: Higher-Order Thinking, Problem-Solving, Critical Thinking, and Creativity.

Higher-Order Thinking. The analysis of higher-order thinking showed significant improvement within both the control and experimental groups. For the control group, the mean score increased from 3.85 ($SD = .370$) in the pre-questionnaire to 4.18 ($SD = .529$) in the post-questionnaire, with a *t*-value of -2.836 ($p < .01$, $d = -0.52$). Similarly, the experimental group exhibited a notable improvement, with mean scores rising from 4.02 ($SD = .53$) to 4.54 ($SD = .23$), and a *t*-value of -6.83 ($p < .001$). This implies that both the conventional and SVVR-based inquiry learning approaches were effective in terms of enhancing students' higher-order thinking tendencies. The negative *d* values indicate that the post-questionnaire scores were higher than the pre-questionnaire scores within the same group, demonstrating improvement.

Problem-Solving. For problem-solving skills, the control group's mean score significantly increased from 3.75 ($SD = .43$) to 4.13 ($SD = .73$), with a *t*-value of -2.95 ($p < .05$, $d = -0.417$). The experimental group demonstrated a more substantial improvement, with scores rising from 3.93 ($SD = .69$) to 4.47 ($SD = .34$), yielding a *t*-value of -4.055 ($p < .001$). This implies that both conventional inquiry-based learning and SVVR-based inquiry learning can enhance problem-solving skills. The negative *d* values indicate a greater increase in scores from pre- to post-questionnaire within the groups.

Critical Thinking. Critical thinking skills also showed significant gains within both groups. The control group's mean score significantly increased from 3.88 ($SD = .51$) to 4.25 ($SD = .54$), with a *t*-value of -2.36 ($p < .05$, $d = -0.41$). In the experimental group, the mean score improved from 4.07 (SD = .67) to 4.52 (SD = .35), resulting in a *t*-value of -3.96 ($p < .001$). This implies that both the conventional and SVVR-based inquiry learning methods were effective in terms of enhancing critical thinking skills. The negative *d* values again reflect improvements within the groups from pre- to post-questionnaire.

Creativity. Lastly, the analysis of creativity scores revealed a significant improvement only within the experimental group. The control group's scores showed a slight increase from 3.93 ($SD = .62$) to 4.19 ($SD = .73$); however, this change was not statistically significant ($t = -1.67$, $p > .05$, $d = -0.296$). In contrast, the experimental group demonstrated a significant increase in creativity scores, from 4.08 ($SD = .76$) to 4.66 ($SD = .26$), with a *t*-value of -4.04 ($p < .001$). This suggests that the SVVR-based inquiry learning intervention had a notable positive impact on the creativity of students in the experimental group. The negative *d* values indicate that there was a higher increase in post-questionnaire scores compared to pre-questionnaire scores within the same group.

Analysis of Higher-Order Thinking Between Groups. Before conducting the ANCOVA, the assumptions of normality, homogeneity of regression slopes, and homogeneity of variance were tested and met. The Shapiro-Wilk test for normality indicated that the residuals were normally distributed ($p = .32$). The test for homogeneity of regression slopes showed that the interaction between the covariate and the independent variable was not significant ($p = .41$), confirming this assumption. Levene's test for equality of variances confirmed equal variances across the groups ($p = .27$). Then ANCOVA was conducted to compare the post-questionnaire scores of higher-order thinking between the experimental and control groups, with the pretest scores as covariates. This analysis was performed to determine the effectiveness of the SVVR-based inquiry learning intervention in comparison to the conventional inquiry learning approach.

The results indicated a significant difference between the two groups ($F = 12.94, p < .01$), with a large effect size ($\eta^2 = .168$), as shown in Table 5. This suggests that the experimental group, which received the SVVR-based inquiry learning, showed a greater improvement in higher-order thinking compared to the control group. Additionally, similar ANCOVA analyses were conducted for problem-solving, critical thinking, and creativity. The results revealed significant differences between the groups for problem-solving ($F = 6.14, p < .05, \eta^2 = .087$), critical thinking ($F = 7.10, p < .01, \eta^2 = .109$), and creativity ($F = 14.12, p < .001, \eta^2 = .157$), indicating medium to large effect sizes. These findings further corroborate the effectiveness of integrating SVVR into inquiry-based learning, demonstrating significant enhancements in students' higher-order thinking, problem-solving skills, critical thinking, and creativity in the context of geography education.

Table 5. The Analysis of Higher-Order Thinking Between Groups.

Variable	Groups	*N*	Mean	*SD*	Adjusted mean	*SE*	*F*	*p*	η^2
Higher-order thinking	Control	32	4.18	.52	4.18	.07	12.94	<0.001***	.168
	Experimental	35	4.54	.23	4.54	.06			
Problem-solving	Control	32	4.13	.73	4.12	.10	6.14	0.016*	.087
	Experimental	35	4.47	.34	4.47	.09			
Critical thinking	Control	32	4.25	.54	4.23	.11	7.84	0.007**	.109
	Experimental	35	4.52	.35	4.53	.11			
Creativity	Control	32	4.19	.73	4.20	.09	11.90	<0.001***	.157
	Experimental	35	4.66	.26	4.66	.09			

*$p < .05$, **$p < .01$, ***$p < .001$.

Analysis of Interview Results Regarding Students' Learning Experiences

Semi-structured interviews were employed to investigate students' learning experiences after the intervention. Six students from the experimental group, who experienced inquiry-based learning with SVVR, voluntarily participated in the interviews and were coded as E1, E2, E3, E4, E5, and E6. Additionally, five students from the control group, who experienced conventional inquiry-based learning, also volunteered, and were coded as C1, C2, C3, C4, and C5. Thematic analysis identified three core themes: SVVR Features Enhanced the Learning Experience, Active Engagement in Learning, and Implementation Challenges. As shown in Table 6, each theme encompassed several identified codes reflecting the saturated results.

SVVR Features Enhanced the Learning Experience. Students in the experimental group reported that SVVR significantly improved their understanding of complex geographic concepts. The immersive 360-degree environment allowed them to visualize and interact with landscapes, making the material clearer and more engaging. E1 mentioned that "Back in lower secondary when the teacher explained, it was always about imagining the picture yourself. It wasn't visible in reality. But now studying with a

Table 6. Summary of Themes and Codes From Student Interviews.

Themes	Codes	Description	Frequency EG	Frequency CG
SVVR features enhanced the learning experience	360-Degree environment	Learners have an immersive, panoramic view. This panoramic experience enriches students' understanding by allowing them to explore landscapes and environments in a more interactive way	47	0
	Learning prompts	Text boxes in SVVR environments combine informational content with questions to both stimulate critical thinking and captivate student attention. These prompts enhance cognitive engagement, fostering a deeper connection and understanding of the subject matter	12	0
	Interactive geographic visualization	The combination of immersive 360-degree environments, text overlays, and dynamic videos in SVVR. This tool allows students to actively explore and understand complex geographic concepts through visualization	6	0
Active engagement in learning	Explain stage	Students work together to discuss concepts, allowing them to construct a deeper collective understanding through shared dialogue and perspectives	3	30
	Elaborate stage	Students transition from theoretical learning to the practical application of concepts by undertaking projects that address real-world problems, enhancing their capacity for problem-solving and knowledge application	3	12
Challenge in implementation	Cyber sickness	The disorientation and discomfort experienced by students when engaging with virtual environments, which can impact their ability to participate fully in learning activities	3	0
	Device problem	Technical issues with the hardware that can disrupt the seamless use of educational technology, thus impeding the learning process	3	0
	Classroom problem	Disruptive dynamics within the classroom setting that can detract from a focused learning atmosphere and hinder effective implementation of instructional tools	3	0
	Lack of visualization	A shortfall in providing visual learning aids, which can limit students' ability to grasp complex concepts due to a lack of engaging and illustrative materials	0	4
	Limited time	The constraints of the instructional schedule, which may not provide sufficient time for the full utilization and integration of learning tools within the curriculum	0	6

teacher through virtual reality (VR) goggles it's like seeing the actual situation for what it is." Students appreciated the novel experience of VR glasses, feeling as if they were truly immersed in the environment. E2 highlighted that "VR glasses are something new to me; I've never studied in this way before. It feels like seeing real images as if we are actually there surrounded by the environment." The ability to see detailed geographic visualizations in an interactive format greatly benefited the students. E3 added "With VR you see more than just the city layout; you see how homes are placed, and their proximity to rivers, which helps when you put this information into a project." These features made learning more engaging and helped students retain information more effectively.

Active Engagement in Learning. Both groups of students reported increased engagement in the learning process. Students in both groups highlighted the effectiveness of group work and discussions in maintaining their interest and participation. For instance, C4 noted, "The group discussions and activities kept me interested and engaged with the material." Similarly, E6 shared, "Working in groups and discussing the topics helped me stay focused and engaged." The experimental group found that SVVR's interactive features, like virtual exploration and quizzes, provided an additional layer of engagement. E5 stated, "The VR quizzes and exploration activities made learning geography fun and exciting, which kept me engaged throughout the lessons." These interactive elements were particularly motivating and enhanced the overall learning experience.

Challenge in Implementation. Both groups faced challenges, but they differed. The control group struggled with a lack of visualization and insufficient time, as C1 noted, "It was difficult to imagine some of the geographical concepts without visual aids." This suggests that the abstract nature of the content, when presented without visual support, increased the cognitive load required for comprehension. C2 also added, "We often ran out of time to fully explore all the topics in depth, which left me feeling unprepared for the exams." This points to a time constraint that restricted students' ability to engage fully in inquiry activities, particularly during the Explore and Elaborate phases of the 5E model. Additionally, C3 commented, "Sometimes I felt like we were only scratching the surface of the topic, and I needed more time to ask questions or dig deeper." These experiences collectively highlight the limitations of traditional IBL when time and resources are insufficient to support extended exploration or multisensory learning.

On the other hand, the experimental group faced issues with SVVR, including cyber sickness, with E1 stating, "Wearing the VR headset for long periods made me feel dizzy and nauseous, which affected my concentration." E2 further stated, "Even after I took the headset off, I still felt disoriented and couldn't focus on the worksheet activity right away." These physiological effects suggest that while SVVR can increase immersion, it may also introduce discomfort that interferes with learning if not carefully managed. Technical difficulties were also frequently mentioned. E3 reported, "Sometimes the VR equipment would malfunction, and it took a while to fix, which disrupted the lesson." These malfunctions not only interrupted learning but also placed an added burden on the teacher to troubleshoot on the spot. E4 described occasional screen lag or visual distortion, which reduced the sense of presence and made it harder to follow spatial content. Classroom management was another noted challenge. E5 highlighted, "Managing the VR devices and ensuring everyone was using them correctly took a lot of time and effort from the teacher, which sometimes slowed down the class." This indicates that, although SVVR enhances the learning environment, it also requires significant instructional and logistical support to be used effectively.

Overall, the findings reveal that the control group's challenges were primarily cognitive and procedural, whereas the experimental group faced technological and physiological barriers. These insights suggest that while SVVR can provide rich and engaging learning experiences, successful implementation depends not only on pedagogical design but also on adequate infrastructure, time management, and teacher support mechanisms.

Discussion and Conclusion

In this study, we developed an SVVR-based inquiry-based learning approach to assist high school students in geography education. An experiment was carried out to evaluate the impact of this approach on students' learning outcomes, higher-order thinking skills, and overall learning experience. The findings suggest that SVVR enhanced student learning outcomes and their higher-order thinking.

Learning Outcomes

The results showed significant improvements within both the control and experimental groups, indicating that both approaches could enhance students' learning outcomes. This aligns with previous research on the effectiveness of IBL in geography education. (Jonassen, 2011; Kriewaldt et al., 2021; Mtitu, 2014; Roll et al., 2018; Schleicher, 2012). Moreover, IBL enhances geography education by helping students link their experiences with new knowledge for better understanding (Roll et al., 2018). This aligns with qualitative results showing that students in both groups valued the Explain stage as it deepened their understanding through discussions and collaboration. The Elaborate stage further helped them apply theory to real-world problems. These findings highlight the effectiveness of the IBL model in terms of helping students act as professional investigators, thinking and acting like geographers (Kriewaldt et al., 2021).

When comparing the two groups, the ANCOVA results revealed that the experimental group, which used SVVR-based inquiry learning, demonstrated significantly greater improvements in learning outcomes compared to the control group. This aligns with previous studies highlighting the advantages of SVVR in education (Liu et al., 2020; Netland et al., 2023). The enhanced outcomes suggest that SVVR fosters a more engaging and interactive learning environment, facilitating deeper understanding and the retention of complex geographic concepts. The immersive features of SVVR, particularly during the explore stage, allowed students to virtually visit and understand distant locations, aiding in visualizing landscapes and human activities. Qualitative data indicated that the experimental group experienced improved visualization, whereas the control group struggled with imagining unfamiliar landscapes, highlighting the importance of SVVR in geography education. Additionally, the experimental group reported that the SVVR's interactive questioning and 360-degree features reduced the time needed to understand content, contrasting with the control group, where students mentioned time limitations during the Explain stage. This suggests that integrating SVVR with IBL can streamline the learning process, making it more efficient and effective.

Higher-Order Thinking

Paired sample *t*-test analyses revealed significant improvements in higher-order thinking for both the control and experimental groups, indicating the effectiveness of IBL and SVVR-based inquiry learning. In the experimental group, all subdomains—critical thinking, problem-solving, and creativity—showed significant gains. The control group, however, exhibited improvements only in problem-solving and critical thinking, with no significant change in creativity. Previous research supports these findings. Qamariyah et al. (2021) noted significant improvements in critical thinking and problem-solving, suggesting that adding technology such as SVVR could further boost creativity, which IBL on its own may not fully develop. Similarly, Antonio and Prudente (2024) found that inquiry-based approaches enhance critical thinking and problem-solving, but creativity gains were less pronounced. This aligns with the observation that creativity did not significantly improve in the control group, indicating that IBL is more effective for critical thinking and problem-solving, but additional strategies may be needed for creativity.

When comparing the two groups, the experimental group using SVVR with IBL demonstrated significant improvements across all higher-order thinking sub-domains, including critical thinking, problem solving, and creativity. The integration of SVVR during the Engage and Explore stages helped students maintain focus and sparked their curiosity, fostering stronger higher-order thinking. Additionally, the 360-degree visualization during the Elaborate stage further enhanced their ability to apply their understanding to new situations. Interview responses indicated that students were able to analyze, compare, and adapt existing strategies to develop their own solutions. These findings align with Wong et al. (2024), who found that VR environments enable students to express creativity through analytical thinking and solution design. Similarly, these results are supported by Shivam and Mohalik (2022) and Suwito et al. (2020), further reinforcing the role of immersive VR environments in promoting cognitive engagement and creativity.

While earlier research has debated VR's ability to foster creativity, this study provides compelling evidence that SVVR, when integrated into IBL, significantly enhances creativity. Huang et al. (2024) previously argued that individual VR environments might not effectively stimulate creativity due to tool-based limitations. However, our findings contradict this assumption by demonstrating that SVVR, when structured to include interactive collaboration, problem adaptation, and multi-perspective engagement, significantly enhances creativity. Unlike individual VR settings that may limit creative exploration (Huang et al., 2024), the SVVR environment in this study incorporated group discussions and real-time scenario-based tasks, which are key factors in fostering creativity (Creech et al., 2022). This was particularly evident during the Elaborate stage, during which students developed flood management strategies in teams. Research has consistently shown that creativity is best stimulated through interactive methods such as group discussions and teamwork (Creech et al., 2022; Huang et al., 2024). In our study, students in the experimental group revisited the virtual environment, using data from their observations to refine their solutions. Moreover, these findings are further supported by Minas et al. (2016), who found that openness in virtual environments fosters more novel, feasible, and relevant ideas. This suggests that immersive and interactive virtual spaces, when designed to encourage exploration and collaboration, can significantly enhance creativity.

Learning Experiences

Students in the experimental group reported that SVVR significantly improved their understanding of complex geographic concepts by allowing immersive visualization, thus enhancing their problem-solving skills. This aligns with Wright et al. (2023), who found that VR deepens understanding of natural hazards in field investigations, helping students better grasp geographic phenomena and spatial relationships.

Both groups reported increased engagement in the learning process. Group work and discussions were highlighted as key factors in maintaining interest and participation, particularly during the Explain stage. Students found that group activities not only kept them engaged but also helped them better understand the material and reduce their misconceptions. In the Elaborate stage, group collaboration made it easier for students to connect concepts to real-world contexts and solve problems, with SVVR further enhancing these benefits for the experimental group. The experimental group, in particular, noted that the interactive elements of SVVR, such as the ability to explore environments and participate in quizzes, significantly boosted their engagement and motivation. Hwang et al. (2018) emphasized that the interactive nature of VR can sustain students' attention and interest, leading to more effective learning experiences. The active engagement facilitated by SVVR allows students to take an active role in their learning, leading to increased motivation and a deeper understanding of the material.

Students in the experimental group encountered challenges with SVVR, including technical issues and cyber sickness, echoing concerns noted by Renne et al. (2021) about VR in education. Addressing these issues with proper support and guidelines is crucial for successful implementation. In contrast, control group students struggled with maintaining engagement using traditional learning methods.

Conclusion

This study demonstrated that integrating SVVR with IBL significantly enhances students' learning outcomes and higher-order thinking in geography education. Both IBL and SVVR-enhanced IBL effectively improved students' learning outcomes, but the SVVR group showed greater progress. The immersive features of SVVR enhanced engagement, visualization, and understanding of complex geographic concepts, making the learning process more efficient. This highlights the potential of integrating SVVR with IBL to create more effective geography education experiences.

Both the control and experimental groups exhibited improvements in critical thinking and problem solving, highlighting the effectiveness of IBL. However, the experimental group utilizing SVVR showed greater improvements across all subdomains of higher-order thinking, particularly in creativity, which did not significantly improve in the control group. This indicates that while IBL alone is effective in terms of fostering critical thinking and problem solving, the integration of SVVR adds a unique dimension that significantly enhances creativity.

The immersive nature of SVVR, combined with the structured inquiry-based approach of the 5E model, provided an engaging learning environment that facilitated deeper understanding and active participation. SVVR's 360-degree visualization and interactive features enabled students to explore complex geographic concepts, visualize distant landscapes, and develop creative solutions for real-world problems, such as flood management strategies.

However, the novelty effect may have contributed to the observed improvements in engagement and learning outcomes. The initial fascination with immersive technology could have amplified student motivation during the early stages of the learning process. Future research should explore the long-term sustainability of SVVR's benefits, and determine whether the learning gains persist once the novelty of the technology diminishes.

While SVVR has already demonstrated significant educational benefits, addressing technical challenges—such as cyber sickness and equipment malfunctions—through improved technical support, teacher training, and the development of more user-friendly VR platforms will further enhance its effectiveness and ensure a smoother integration into classrooms.

Overall, the findings suggest that combining SVVR with IBL has significant potential to transform geography education by making learning more interactive, engaging, and effective. By leveraging SVVR's immersive capabilities alongside inquiry-driven pedagogies, educators can foster deeper learning and promote higher-order thinking skills. However, careful consideration of technical challenges and the novelty effect is essential to maximize the long-term impact of these innovative instructional methods.

Implications of the Study

The study results show that integrating SVVR with IBL significantly enhanced students' learning outcomes and higher-order thinking in geography. SVVR effectively captures attention and stimulates curiosity during the Engage and Explore stages, making it a valuable tool for teaching complex geographical concepts.

Educators should use SVVR to create realistic environments, particularly for visualizing unfamiliar geography, to enhance understanding. Combining SVVR with the 5E model supports deeper learning and helps develop critical thinking, problem-solving, and creativity. This approach provides richer learning experiences beyond conventional IBL methods, and presents innovative strategies for the Thai educational system to enhance student learning outcomes.

This approach could also be beneficial for other subjects that require visualization and real-world interaction. However, it is important to consider whether the content is well-suited for the IBL-with-SVVR approach. Certain topics may not fully align with inquiry-based methods and could benefit from alternative learning methods when combined with SVVR. Future research should explore how different pedagogical models can be integrated with SVVR to ensure the most effective learning experiences across a variety of subjects and content areas.

Although SVVR offers strong educational benefits, its application at scale presents further challenges that should not be overlooked. One major concern is scalability; implementing SVVR across different schools and grade levels requires careful planning and pilot testing to ensure that its use does not place excessive demands on existing educational resources. The cost of VR devices, the creation of instructional content, and system maintenance can also be prohibitive, raising questions about long-term cost-effectiveness when compared to other teaching tools. Infrastructural limitations—including unstable internet access, limited classroom space, and lack of technical support—may prevent some schools from fully adopting the technology. Furthermore, teacher readiness plays a critical role in effective implementation. Educators need appropriate training not only to use VR equipment, but also to integrate it meaningfully into their instruction. Future research should investigate professional development models that support both technical proficiency and pedagogical effectiveness, ensuring that SVVR enhances teaching and learning without increasing teachers' workloads.

Limitations and Recommendations

Despite its contributions, this study has highlighted several limitations. First, the sample size was relatively small and was limited to high school students from a specific region in Thailand, which may affect the generalizability of the findings. Future research should consider involving a larger and more diverse sample to enhance the applicability of the results.

Second, the study duration was relatively short, focusing on the immediate effects of SVVR and IBL on learning outcomes and higher-order thinking. While SVVR significantly enhanced student learning outcomes and higher-order thinking, it is important to consider the potential impact of the novelty effect. The initial fascination with immersive technology may have amplified student motivation and cognitive engagement during the early stages of the learning experience. This aligns with findings by Miguel-Alonso et al. (2024), who noted that the novelty effect could temporarily boost learning outcomes. However, as the novelty effect tends to diminish over time, the long-term sustainability of these learning gains remains uncertain. Therefore, longitudinal studies are recommended to examine whether the observed benefits of SVVR persist over extended periods or if engagement levels decline as the novelty wears off.

Third, the use of the same instructor for both the experimental and control groups was intended to ensure consistency in instructional content and delivery. This approach minimized variability in teaching style, language use, and classroom management, all of which could otherwise confound the results. However, it is acknowledged that using the same teacher may still introduce a potential bias, particularly if the teacher unconsciously exhibited more enthusiasm or engagement during the SVVR-integrated sessions.

Additionally, technical challenges such as cyber sickness and equipment malfunctions were noted during the study. These issues can affect students' learning experiences and outcomes. It is essential to provide adequate technical support and establish clear guidelines for using SVVR in the classroom to mitigate these challenges. Future research should also explore the development of more user-friendly and stable SVVR platforms to minimize technical disruptions.

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Ethical Statement

Ethical Approval

All the related parties approved this article's data collection and analysis processes throughout the informed consent process.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study are not publicly available due to personal privacy issues but are available from the corresponding author upon reasonable request.

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