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Technology-enhanced digital game-based learning for environmental literacy: catalyzing attitude change in learners

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Recently, various approaches have been adopted to cultivate environmental literacy, and prior studies have confirmed the value of digital games in this domain. Nonetheless, concrete discussions of specific elements such as environmental sensitivity and attitude remain limited. Accordingly, the present quasi-experimental study investigates whether Digital Game-Based Learning (DGBL) can enhance the environmental literacy of Taiwanese elementary school students. Thirty-four sixth-graders were assigned to a DGBL group ($n = 17$) and a Web group ($n = 17$). Quantitative data were collected with an Environmental Literacy Scale covering knowledge, sensitivity, and attitude, while qualitative insights were gathered through semi-structured interviews. Post-test scores were analyzed via ANCOVA with pre-test scores as covariates. Results indicate that the DGBL intervention significantly improved students' environmental knowledge and attitude, whereas gains in environmental sensitivity, though evident, did not reach statistical significance. Qualitative responses echoed these findings, suggesting that immersive gameplay fosters deeper affective engagement with ecological issues even when measurable sensitivity improvements are modest.

KEYWORDS

digital game-based learning (DGBL), pro-environmental, behaviors, VR, environmental literacy

1 Introduction

American conservationist Aldo Leopold stated, "Without the requisite will and skill, conservation of natural resources is futile, and the role of education is to develop these capacities" (Coyle, 2005). This perspective underscores the critical role of environmental education in advancing sustainable development. In recent years, the United Nations has emphasized the importance of environmental literacy as a core educational goal within the framework of the Sustainable Development Goals (SDGs) (Allen et al., 2018). Environmental literacy refers to an individual's integrated capacity encompassing environmental knowledge, sensitivity, and values when addressing environmental issues (Disinger and Roth, 1992; Goldman et al., 2013). Learners who possess environmental literacy are able to identify the causes and consequences of environmental problems and are empowered to make responsible and sustainable decisions and take appropriate actions.

Against this backdrop, the integration of technology offers new opportunities for advancing environmental education. Recent studies have identified digital technology as a key driver in supporting the implementation of environmental education and have forecasted that Virtual Reality (VR) and Artificial Intelligence (AI) will become prominent trends in educational technology (Cao et al., 2024). In Taiwan, policy efforts have been actively promoting digital and intelligent learning environments. Since 2021, the Ministry of Education

has launched the 5G Smart Classroom initiative, encouraging the use of VR and other emerging technologies to enhance interactive learning experiences (Kuo et al., 2023). This development not only reflects the nation's commitment to integrating VR into pedagogical practices but also provides new instructional directions for environmental education. In the context of environmental education, VR-based immersive learning environments can effectively overcome the limitations of traditional outdoor learning, such as geographical constraints, weather conditions, or public health concerns (Markowitz et al., 2018). By simulating complex or hazardous scenarios that are difficult to recreate in real-life settings, VR enables learners to apply environmental knowledge in authentic contexts. Rather than remaining passive recipients of information, learners engage in interactive, experience-based learning within virtual environments (Ying et al., 2024). This enhanced interactivity not only increases learners' motivation but also allows for greater adaptability to diverse learning styles and individual needs. Although VR affords a high degree of interactivity and immersion that holds considerable pedagogical promise, studies caution that the accompanying learning burden should not be overlooked. Highly immersive virtual environments can overload learners with sensory stimulation and physical interaction, thereby imposing additional cognitive load that detracts from attention and learning outcomes (Albus et al., 2021; Makransky et al., 2019). Research has also documented dizziness, fatigue, and other discomforts that lower motivation and even lead some participants to withdraw from VR-based activities (Ozkan and Celikcan, 2023). Thus, a central challenge in VR instructional design is to strike an effective balance between presence and information simplification in order to keep cognitive load within manageable limits. Overall, numerous international studies have affirmed the pedagogical potential of integrating digital tools into environmental education. According to a meta-analysis by Hajj-Hassan et al. (2024), which reviewed 21 peer-reviewed journal articles published between 2013 and 2023, the use of digital tools in environmental education has demonstrated a positive impact on enhancing students' environmental awareness. However, compared to international trends, research in this field remains relatively limited in Taiwan.

Building on the aforementioned background and challenges, this study aims to empirically investigate the effectiveness of applying VR in environmental education at the elementary school level. Specifically, it examines how VR-based learning influences three key dimensions of environmental literacy, environmental knowledge, sensitivity, and attitudes and values as well as students' cognitive load. In addition, the study aligns with national digital learning policies and responds to practical needs in school settings by proposing concrete recommendations for integrating VR into environmental education. These insights are intended to support educators in effectively adopting innovative technologies to enhance teaching outcomes and increase student engagement.

2 Literature review

2.1 The evolution and framework of environmental literacy in Taiwan

The Tbilisi Declaration, issued by the United Nations Educational, Scientific and Cultural Organization in 1977, asserted that the primary

aim of environmental education is to cultivate individuals' awareness, concern, and capacity for action in order to preserve ecological balance (UNESCO, 1980). With the global rise of sustainability discourses, environmental education has evolved from a focus on nature conservation to an interdisciplinary, globally oriented, and action-driven approach. In Taiwan, environmental education has been promoted through an integrated instructional model since the introduction of the Grade 1–9 Curriculum Guidelines (Kao et al., 2017). The subsequent 12-Year Basic Education Curriculum Guidelines further emphasized the development of environmental literacy and critical thinking as key components of students' core competencies (Liu et al., 2015). Based on the above discussion, environmental literacy can be understood as a multidimensional construct. Beyond possessing fundamental environmental knowledge, it is crucial for individuals to recognize environmental issues in daily life, understand the interrelationship between human actions and environmental changes, and develop a sense of personal responsibility toward environmental challenges. However, cultivating environmental literacy remains a complex task. According to the literature, environmental education in Taiwan still primarily emphasizes the transmission of factual knowledge, with relatively limited instructional focus on students' environmental awareness and attitudes (Pan and Hsu, 2020). A nationwide survey on environmental literacy conducted by Taiwan's Environmental Protection Administration (EPA) among adults (including public officials and K–12 teachers) and students (from elementary to tertiary levels) revealed significant improvements in "environmental knowledge," indicating that environmental education has been effective in enhancing public understanding of environmental issues. Nonetheless, the findings also highlighted a notable gap between environmental knowledge and the actual practice of pro-environmental behaviors. This disparity suggests that the key to enhancing environmental literacy lies in enabling learners to translate knowledge into action. To bridge the gap between awareness and behavioral change, recent studies suggest that the appropriate integration of digital technologies can facilitate learners' engagement with the natural environment and strengthen their sense of environmental connectedness (Fauville et al., 2024; Zhang et al., 2024). In particular, under current curriculum frameworks that emphasize interdisciplinary learning and technology integration, DGBL has emerged as a promising pedagogical approach for environmental education (Monroe et al., 2019). DGBL not only conveys cognitive content but also emotionally engages learners with environmental issues, providing opportunities to experiment with new behaviors and experience their consequences within a simulated context (Janakiraman et al., 2021). Therefore, incorporating more interactive and immersive media into instructional design can enhance learner engagement, foster meaningful learning experiences, and support the development of responsible environmental attitudes and behaviors.

The concept of environmental literacy, which emerged from educational awareness initiatives in the 1990s, refers to the ability to recognize and understand environmental health issues, and to take informed actions aimed at maintaining, restoring, or improving environmental quality (Disinger and Roth, 1992). Environmental literacy encompasses three interrelated dimensions: knowledge, environmental sensitivity, and attitudes and values which collectively serve as the foundation for promoting pro-environmental behavior (Gibson et al., 2024).

2.2 Enhancing environmental literacy through DGBL and VR

DGBL has been proven to be an effective instructional tool. Mercer et al. (2017) argue that, to foster pro-environmental behaviors, educators must adopt more interactive, learner-centered approaches. DGBL meets this need: it can change behaviors and attitudes and even improve mental health thereby motivating learning (David et al., 2021; Tsai and Tsai, 2020). As a medium, digital games not only convey information but also allow learners to explore, understand, and engage with environmental issues and their consequences through interaction (Sun et al., 2021). Kawaguchi et al. (2018) built a game themed on Japan's Satoyama Initiative that lets students digitally simulate ecological plant-succession processes. Within a short period, learners can observe and participate in natural succession that would normally unfold over centuries. The study found significant gains in students' understanding and awareness of satoyama management, demonstrating that DGBL can boost motivation, environmental awareness, and hands-on skills. Multiple environmental-education studies show that embedding narrative in games enhances learners' environmental knowledge and even influences their attitudes (Curtis et al., 2013; Monroe et al., 2019). Narratives enable emotional projection learners feel like characters in the story (Pan and Hsu, 2020) and encourage them to explore and act to acquire knowledge (Prensky, 2001). Harker-Schuch et al. (2020) describe games as natural tools for climate-change education, providing "designed experiences" in which players learn through practice and participation rather than traditional reading or lectures. Likewise, Sun et al. (2022) and Kao (2019) note that the interactivity of digital games stimulates engagement and enjoyment, motivating players to explore and ultimately nurturing environmental awareness and understanding. In recent years, the development of VR technology has brought new dimensions to the field of DGBL (Al-Ansi et al., 2023). Due to its highly interactive nature, VR creates immersive virtual environments through Head-Mounted Displays (HMDs), offering learners a more intuitive and engaging learning experience (Huang et al., 2019). For instance, Markowitz et al. (2018) utilized a VR experience to immerse learners in an underwater exploration of ocean acidification. This approach transformed a traditionally costly and logistically challenging field investigation into an accessible virtual experience, and the findings indicated that VR can significantly enhance learners' awareness of environmental issues. The study further noted that one of the key advantages of using VR for environmental education lies in its ability to present environmental changes from a first-person perspective, making the experience psychologically more immediate and urgent. Learners were able to freely move to specific locations and observe details closely, which not only improved their understanding of environmental features but also enhanced their learning motivation.

In summary, while prior research has confirmed that both DGBL and VR technology are effective tools for promoting environmental education, the combined effect of these two approaches remains underexplored. Most existing studies tend to focus on the impact of a single instructional tool, with limited investigation into how the integration of "game interactivity" and "immersive experience" can holistically influence learners' environmental cognition, attitudes, and behaviors. Therefore, this study aims to design and evaluate a learning program that integrates the interactivity of digital games with the immersive qualities of VR to advance environmental education.

3 Methods

3.1 Methodology and participants

This study employed a quasi-experimental design involving 34 sixth-grade students from a southern Taiwan elementary school, randomly assigned to either a VR group or a Web group. The VR group used Oculus Quest 2 headsets to engage in VR Digital Game-Based Learning, while the Web group completed equivalent activities via a web-based multimedia platform. Prior to the instructional intervention, this study administered a digital literacy pre-questionnaire to both groups to assess their basic digital operation experience and usage frequency. The questionnaire consisted of seven items, including: 1. Whether they regularly use digital devices (e.g., computers, tablets, smartphones); 2. Average daily usage time (e.g., less than 30 min, 30 min–1 h, 1–2 h, more than 2 h); 3. Most frequently used digital tools (multiple-choice options such as online learning platforms, games, video streaming services, etc.); 4. Prior experience with educational games or apps; 5. Ability to independently open and operate basic applications; 6. Basic experience with internet use; 7. Typical problem-solving strategies when encountering digital device issues (e.g., asking family members, teachers, solving independently). Based on the aggregated results, the research team confirmed that the experimental and control groups demonstrated overall consistency in their digital usage habits and operational experience. Additionally, this study was conducted at a public experimental elementary school located in downtown Taiwan, selected for its representative educational setting characterized by equitable resource distribution. Public experimental schools in Taiwan typically allow for greater instructional flexibility and openness to pedagogical innovation, making them an ideal environment for implementing digital learning interventions. These factors were considered to help ensure the fairness and internal validity of the study. To evaluate learning outcomes, an environmental literacy questionnaire covering knowledge, sensitivity, and attitudes was administered before and after the intervention. Additionally, a cognitive load scale assessed students' perceived mental effort under the two digital learning environments. This study adopted a mixed methods approach. Quantitatively, environmental-literacy pre- and post-tests were collected for both learning groups and analyzed with a one-way analysis of covariance (ANCOVA), while descriptive statistics were used to summarize group performance. To further probe the cognitive demands imposed by each platform, a cognitive-load questionnaire was administered, and perceived load differences between the VR and Web groups were examined via independent-samples *t*-tests. Complementing these numerical data, semi-structured interviews were conducted immediately after the learning activities to capture students' experiences; the recordings were transcribed verbatim, coded, and thematically analyzed to reveal perceptions of the learning content, learning motivation, and sense of immersion. The coding process followed three stages: (1) open coding—reading transcripts and marking statements that reflected students' views, emotional responses, and behavioral tendencies; (2) axial coding—grouping related initial codes into higher-order categories; and (3) theme development—synthesizing categories into overarching themes that addressed the research questions. Two researchers independently coded the transcripts, compared their results, and resolved discrepancies through discussion to ensure

coding consistency and reliability. Representative quotations were selected to illustrate student experiences in different digital learning environments and to support the interpretation of quantitative findings.

3.2 Measuring tools

3.2.1 Environmental literacy scale

The Environmental Literacy Scale used in this study was adapted from the works of [Hsu and Huang \(2017\)](#). The scale consists of the following components: 1. Environmental Knowledge Test: This section comprises 15 items, each worth one point, for a total possible score of 15. Sample items include: “I am aware that my lifestyle habits can contribute to environmental problems,” and “I actively seek to learn about environmental issues (such as ecology and the interaction between humans and the environment) to enhance my understanding of nature.” 2. Environmental Sensitivity and Attitudes: This section includes 8 items measuring environmental sensitivity and 15 items assessing environmental attitudes, totaling 23 items. A five-point Likert scale was used, ranging from “strongly agree” (5 points) to “strongly disagree” (1 point). Higher scores indicate more positive environmental sensitivity and attitudes/values, while lower scores reflect a less favorable disposition. Sample items include: “We should care for the environment before natural ecosystems are damaged,” and “Proper waste sorting can effectively reduce environmental pollution.” The overall reliability of the scale, as measured by Cronbach’s α , was 0.86, indicating good internal consistency.

3.2.2 Cognitive load scale

To assess the cognitive load experienced in the two learning environments, this study employed the 25-item Cognitive Load Questionnaire developed by [Huang et al. \(2019\)](#), specifically designed for VR and digital reading contexts. The questionnaire utilizes a five-point Likert scale ranging from 1 (“strongly disagree”) to 5 (“strongly agree”), and comprises two dimensions: mental effort (12 items), which captures the subjective effort learners invest in accomplishing tasks, and mental load (13 items), which reflects the cognitive demands induced by instructional design and task complexity. Sample items for the VR group include, for the mental effort dimension: “It was easy to find relevant information while using VR,” and for the mental load dimension: “The reading process in the VR environment felt smooth.” To mitigate response bias, reverse-coded items were also included, such as: “I had to exert great effort to understand the content of the VR game,” and “The presentation format in VR made it difficult for me to concentrate on the game content.” The scale demonstrated high internal consistency reliability, with a Cronbach’s α of 0.939 for the mental effort dimension, 0.888 for the mental load dimension, and 0.915 overall, indicating that the questionnaire’s reliability reached an acceptable level. A structurally identical version of the questionnaire was administered to the Web group, with wording adapted to reflect the digital reading context, thereby ensuring equivalency across learning environments.

To enhance content validity, two experienced elementary school teachers were invited to review the questionnaire items and offer suggestions for wording revisions. Their feedback was incorporated to ensure that the content was age-appropriate and aligned with the comprehension levels and learning contexts of sixth-grade students.

3.2.3 Learning content of VR and web-based digital learning tools

In this study, both the VR digital game and the Web-based platform were utilized as digital learning tools aimed at enhancing learners’ understanding of environmental issues. Both formats adopted a role-playing approach to encourage learners to actively explore the causes of environmental changes and construct knowledge through clue analysis and information comparison. The VR-based digital game, learners assumed the role of the Taiwan Blue Magpie, a native species, to experience and investigate contemporary environmental issues in Taiwan, such as pesticide use, land development, and water pollution. The game was structured into three chapters, guiding learners progressively through changes in the ecological environment. Through interactions with non-player characters (NPCs), answering questions, and collecting clues, students identified key factors contributing to environmental changes and developed a comprehensive understanding of the issues. In contrast, the Web-based learning content adopted a detective-themed role-playing scenario. Learners analyzed the environmental impacts of land development projects by engaging with various sources such as news reports, online forum discussions, and video materials. The web interface integrated guiding prompts to assist learners in comparing diverse information sources such as differences in headlines, reporting perspectives, and credibility to develop information literacy and analytical skills. The learning content was delivered via a one-page website design, enabling students to sequentially browse and integrate information. Although the VR and Web groups utilized different platforms and interaction modalities, the core learning content remained aligned across the three key dimensions of environmental literacy: environmental sensitivity, environmental knowledge, and environmental attitudes. The primary differences lay in the delivery medium and user interaction methods, as summarized in [Table 1](#) and [Figures 1, 2](#).

4 Experimental results and discussion

4.1 Environmental knowledge

As shown in [Table 2](#), the means and standard deviations for the experimental (VR) and control (Web) groups on the environmental-knowledge pre- and post-tests. Levene’s test showed that the variance of the pre-test scores was equivalent across groups ($p = 0.994$), indicating homogeneity of variance for this covariate and supporting its inclusion in the subsequent ANCOVA.

[Table 3](#) presents the ANCOVA results. After controlling for pre-test scores, the main effect of instructional group on post-test environmental-knowledge scores was statistically significant ($F = 12.64$, $p = 0.001 < 0.01$), indicating that the type of learning environment meaningfully affected learning outcomes. Specifically, the VR group who learned through immersive virtual-reality game-based activities demonstrated gains in environmental knowledge than the Web group using a conventional multimedia platform.

4.2 Environmental sensitivity

To investigate how different digital learning tools influence students’ environmental sensitivity, an analysis of covariance

TABLE 1 Learning content in VR DGBL and web-based activities.

Game chapter	Environmental literacy	VR digital-game based learning activities	Web-based learning activities
Chapter 1	Sensitivity	Navigate an immersive ecosystem as a Formosan blue magpie, collect contextual clues on pesticide use, and examine resulting changes in insect populations, bird behavior, and water quality.	Explore curated news pages, videos, and images on the same pesticide issue, identifying how different outlets define the problem and foreground particular impacts.
Chapter 2	Knowledge	Investigate diverse virtual habitats, observe links between human land-development actions and ecological change, and articulate the causal chain from disturbance to biodiversity loss.	Compare reporting styles across media sources on an identical land-use case, pinpoint discrepancies between headlines and full texts, and discuss how narrative framing shapes public understanding.
Chapter 3	Attitudes	Draw on in-game data logs and NPC dialogues to analyze key drivers of degradation, solve mission-based puzzles that require trade-off reasoning, and reflect on personal responsibility for environmental stewardship.	Conduct systematic content analysis of news stories (text, imagery, audio) about the same topic, assess credibility and bias, and formulate evidence-based positions that inform pro-environmental intentions.

(ANCOVA) was performed with pre-test scores entered as the covariate. As displayed in Table 4, the VR group had a pre-test mean of 3.73 ($SD = 0.66$) on the environmental-awareness-sensitivity scale, whereas the Web group averaged 3.60 ($SD = 0.83$). Levene's test indicated homogeneity of variance between the two groups ($F = 0.143$, $p = 0.708$), thereby meeting the key assumption for ANCOVA.

As shown in Table 5, the ANCOVA yielded a non-significant group effect on post-test environmental awareness-sensitivity after controlling for pre-test scores ($p > 0.05$). Nonetheless, the VR group exhibited a greater pre- to post-test gain than the Web group, indicating the potential value of the virtual-reality intervention. To probe this possibility further, the study next drew on qualitative data to illuminate its instructional benefits.

4.3 Environmental attitudes

As shown in Table 6, both groups exhibited positive gains on the environmental attitudes scale. The VR group's mean score rose from 3.50 to 3.72, an increase of 0.22 points, whereas the Web group improved only slightly from 3.60 to 3.63, a gain of 0.03 points. Although the Web group held a 0.10-point advantage at pre-test, the VR group surpassed it at post-test, suggesting that the two instructional modalities may differ in their impact on learning gains.

To rule out baseline disparities, an ANCOVA was conducted with the pre-test score entered as a covariate (see Table 7). The test of homogeneity of regression slopes was nonsignificant, $F(1, 30) = 1.261$, $p = 0.270$, satisfying ANCOVA assumptions. After adjustment, the between-group effect was significant, $F(1, 30) = 25.75$, $p < 0.001$, indicating that even after controlling for pre-test differences the VR group outperformed the Web group on the post-test measure of environmental attitudes. Hence, the instructional modality exerted a meaningful impact on students' attitudes.

4.4 Cognitive load

To gain deeper insight into how each digital platform influenced learners' mental load, a dedicated mental-load scale was administered

at the post-test stage. The instrument captured participants' perceived mental effort while they engaged with either the VR or the Web version of the learning activities, and the two groups were compared with independent-samples t -tests. Because all reverse-scored items were recoded before analysis, higher scores reflect lower mental load that is, a smoother learning experience that demands less mental effort.

Table 8 indicates that the VR group achieved significantly higher scores than the PC group on the mental-effort dimension, $t = 2.82$, $p < 0.05$, suggesting that interaction within the VR environment required less cognitive investment from learners. This advantage is plausibly attributable to VR's immersive and highly interactive context, which mitigates task switching and operational distraction and thereby permits greater allocation of cognitive resources to the comprehension of instructional content. On the mental-load dimension, the VR group likewise outperformed the PC group, $t = 3.67$, $p < 0.01$, implying that VR imposed a lighter affective and stress burden during learning. The strong sense of presence and intuitive interactions afforded by VR likely facilitate the conversion of abstract information into concrete experiences, thus reducing overall mental load throughout the learning process.

4.5 Interview on students' environmental literacy and cognitive load in VR group

This study conducted semi-structured interviews with the experimental (VR) group to explore how VR-based digital games influence students' environmental literacy and cognitive load. Interview questions revolved around environmental issues presented in the learning content, such as pesticide use and land development. All interview excerpts were coded as follows: T = researcher, A = male student, B = female student, followed by a numeric identifier (e.g., A01 = Male Student 01).

4.5.1 Enhancement of environmental attitudes through VR DGBL

T: Regarding the pesticide issue: What are your thoughts on the game characters' use of pesticides?



FIGURE 1
VR DGBL learning activity.



FIGURE 2
Web learning activity.

VR -A06: Everyone has their own standpoint. Older farmers can use pesticides, but they should avoid overuse, because excessive spraying may poison plants, humans, and animals, creating a vicious cycle.

VR -B17: I agree with the young farmer's view. We should avoid using pesticides to prevent environmental damage. Residues left in plants can be ingested by animals; if the dose keeps

TABLE 2 Environmental knowledge pre-test and post-test scores.

Group	Pre-test		Post-test	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
VR (<i>n</i> = 17)	12.53	1.77	13.82	1.01
Web (<i>n</i> = 17)	12.94	2.11	13.21	2.11

Environmental knowledge (max = 15).

TABLE 3 Summary of ANCOVA (with pre-test as covariate).

Source of variation	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p</i>
Group (post-test)	58.80	1	58.80	12.64	0.001**
Error	146.48	32	4.58		

p* < 0.05, *p* < 0.01.

TABLE 4 Environmental sensitivity pre-test and post-test scores.

Group	Pre-test		Post-test	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
VR (<i>n</i> = 17)	3.73	0.66	4.40	0.51
Web (<i>n</i> = 17)	3.60	0.83	4.25	0.64

TABLE 5 Summary of ANCOVA (with pre-test as covariate).

Source of variation	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p</i>
Group (post-test)	0.073	1	0.073	0.521	0.476
Error	4.486	32	0.140		

p* < 0.05, *p* < 0.01.

TABLE 6 Environmental attitudes pre-test and post-test scores.

Group	Pre-test		Post-test	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
VR (<i>n</i> = 17)	3.50	0.21	3.72	0.20
Web (<i>n</i> = 17)	3.60	0.29	3.63	0.21

TABLE 7 Summary of ANCOVA (with pre-test as covariate).

Source of variation	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>p</i>
Group (post-test)	0.352	1	0.352	25.75	0.000**
Error	0.407	30	0.014		

p* < 0.05, *p* < 0.01.

TABLE 8 Cognitive load analysis results.

Cognitive load dimension	VR (<i>n</i> = 17)		Web (<i>n</i> = 17)		<i>t</i>	<i>p</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
Mental effort	4.21	0.18	3.91	0.18	2.82	<0.05*
Mental load	4.10	0.14	3.48	0.38	3.67	<0.01**

accumulating, it could cause deaths and set off a negative chain reaction.

VR -A07: I support the young farmer's eco-friendly approach—such as adopting the rice-duck symbiosis method instead of pesticides. Pesticide residues degrade soil quality and could eventually render the land useless.

Student A06 tried to understand the economic pressure behind the NPC's pesticide use but simultaneously stressed that over-application can poison plants, humans, and animals, initiating harmful cycles. This shows a shift beyond mere yield concerns toward long-term ecological health. Student A07 went a step further by offering a feasible alternative (rice-duck symbiosis), revealing an emerging awareness of sustainability. Taken together, the three students not only recognized the hazards of pesticide use but also began exploring substitutes and the importance of ecological conservation, demonstrating a deeper commitment to sustainable values.

T: From the standpoint of economic growth and human survival, what are your views on land development?

VR -A08: I think it's a recurring cycle.

VR -A01: We could look for alternative energy sources—wind power, solar power, and so on.

VR -A03: While developing land, we should keep creating things that can be reused. Some resources are simply discarded after use, so we need either to find new ones or redesign them so they can be continually redeveloped.

Across the interviews, students generally needed time to reflect and often felt caught in a dilemma when responding to questions about “pesticide use” and “land development versus environmental protection.” This reflective struggle is precisely what the study set out to examine: when students simultaneously encounter opposing perspectives—such as “pro-pesticide” versus “anti-pesticide,” or “pursue economic benefits” versus “preserve ecological balance”—how do they repeatedly gather information, analyze it, and weigh the pros and cons within the VR game scenario? These exchanges reveal the value conflicts intentionally embedded in the VR digital game. Faced with multiple viewpoints, students increasingly realize that the relationship between human interests and the environment is not a black-and-white issue, but rather demands thoughtful, integrative value judgments.

4.5.2 Students' perceptions of cognitive load when using the VR DGBL

To gain deeper insight into the cognitive load students experienced while engaging with the VR game-based learning environment, the researchers included follow-up questions in the semi-structured interviews. These questions probed the perceived difficulty of comprehension, information-processing demands, and attention-maintenance during the learning tasks.

T: When you were in the VR learning environment, did you find it difficult to understand the content?

VR -A04: It was a bit hard at first because there was a lot of information. Sometimes I forgot what I had just seen.

VR -B11: *I found the clue-searching part the most time-consuming. You have to keep scanning everything in the scene, and that's a little tiring.*

VR -A10: *I was okay. Each task explained what to do, so I could just follow the steps one by one. It wasn't too hard.*

T: Did playing this game make you feel tired or require a lot of mental effort?

VR -A04: *Yes, somewhat. I had to stay very focused or I'd miss important hints.*

VR -B11: *For me, constantly remembering things was tiring. Sometimes I mixed up which character said what.*

The interviews reveal differing experiences of cognitive load. Students A04 and B11 reported increased mental effort while receiving and processing information, especially when they had to pay attention to scene details and recall earlier clues. This placed a burden on short-term memory and divided their attention. By contrast, A10 felt little overload because the task instructions were explicit and could be completed step by step. These differences underscore the strong link between VR learning effectiveness and design quality. When task structure is clear and guidance cues are easy to follow, students can engage effectively and keep intrinsic and extraneous load to a minimum. Although some learners still needed intense concentration to keep track of narrative information suggesting that the pacing of information delivery may need refinement the immersive environment combined with clear task scaffolding generally helped reduce overall cognitive load. This finding aligns with Mayer (2014), which highlights the importance of managing integrative processing demands and balancing interactivity with cognitive pacing to optimize learning in immersive contexts.

4.5.3 Interview on students' environmental literacy and cognitive load in web group

Consistent with the experimental group, semi-structured interviews were also conducted with the Web group to examine how web-based learning impacts students' environmental literacy and cognitive load. All interview excerpts were coded as follows: Web group; T = researcher, A = male student, B = female student, followed by a numeric identifier (e.g., A01 = Male Student 01).

4.5.4 Enhancement of environmental attitudes through web-based learning

T: The web-based videos and news articles you viewed highlighted the pesticide issue. What are your thoughts on the use of pesticides as presented in those materials?

Web-A08: *"I think the government should set an upper limit; otherwise everyone will spray pesticides indiscriminately, and in the end, everyone will suffer."*

Web-B20: *"If pesticides flow into the water, the fish will die, right? The video mentioned that the pond used to have many frogs, but later there were none."*

Web-B02: *"I do not think there's a clear right or wrong—farmers are making a living, but we still need to protect public health."*

Overall, students in the Web group tended to engage in rational deliberation from policy-level and pluralistic perspectives. For instance, Web-A08 called for governmental regulation of pesticide use; Web-B02 demonstrated an attempt to balance the interests of farmers with those of the broader public; and Web-B20 expressed an initial awareness of ecological change. However, these perspectives remained partly at the level of abstract, institutional discussion, with comparatively limited situational empathy and connection to concrete action. Accordingly, the research team proceeded with a follow-up question.

T: From the standpoint of economic growth and human survival, what are your views on land development?

Web-A10: *"We should listen to residents' opinions so that everyone can reach a compromise."*

Web-B15: *"If relocation is necessary, the government should be responsible for arranging housing."*

Web-A08: *"From my personal standpoint, I think it would be undesirable to expropriate that area. Otherwise, the government might engage in land speculation, and the public would resist."*

These responses indicate that students in the Web group were able to incorporate elements of social institutions and civic participation when reasoning about environmental issues, reflecting a certain degree of cognitive sophistication. However, compared with the VR group—who, through embodied participation in virtual scenarios, directly perceived environmental change and developed concrete affective reactions—the Web group's learning was more analytic and observational, lacking the emotional resonance and intention to act typically fostered by immersive experiences. In sum, although the Web group showed less pronounced gains in quantitative learning outcomes than the VR group, the qualitative data nonetheless suggest that students possessed a meaningful understanding of environmental issues and engaged in reasoned deliberation. This implies that web-based learning retains potential value in environmental education, particularly in cultivating institutional and civic lenses. Even so, relative to the VR condition—which leverages role interactions, task choices, and real-time feedback to elicit affective engagement and value conflict—the Web group's experience appeared more constrained in deep motivation and the translation from intention to action. To further investigate how medium characteristics shape students' learning trajectories, the next section analyzes the cognitive load experienced by Web-group students, thereby illuminating potential differences in cognitive engagement and learning efficiency across media.

4.5.5 Students' perceptions of cognitive load when using the web-based learning

T: When using the web-based learning platform, did you find the content difficult to understand?

Web-A06: *At first, the information load felt heavy; there was a lot of text. Even after watching the videos, I still had to read a large amount of explanatory material.*

Web-B20: Finding the relevant news clips was the most time-consuming part. I kept clicking back and forth among different reports, which was a bit exhausting.

Web-A10: I thought it was fine. Each task specified which video or article to consult, so I just followed the instructions.

T: Did using this platform make you feel fatigued or require considerable effort to process the information?

Web-A08: For me, the videos played too slowly, so I set the playback to $2 \times$ speed.

Web-A04: To some extent. I had to concentrate intensely on each video to avoid missing key points, and I usually increased the speed to $1.5 \times$ or $2 \times$; otherwise, the pace was too slow.

Web-B11: Retaining all the content was tiring. Sometimes I mixed up which news segment said what. I also used accelerated playback.

From the interviews above, students Web-A08, Web-A04, and Web-B11 reported using accelerated playback to access required information more quickly. Follow-up interviews further indicated that this practice was not an isolated case but reflects a broader trend among contemporary learners using digital tools: students increasingly rely on speed-up functions to save time and to rapidly absorb and filter information. In summary, while students commonly employ accelerated playback to enhance perceived learning efficiency, this behavior also constitutes a response to platform-level information overload and instructional pacing. From a cognitive-load perspective, the strategy may reduce perceived extraneous interference in the short term, yet it can heighten demands on sustained attention and working memory and compress opportunities for deeper processing—effects that may, in turn, be reflected in students' environmental literacy outcomes.

5 Conclusion, limitations, and suggestions for future work

This study simultaneously evaluates the effectiveness of VR and Web platforms in elementary school environmental education and examines their impacts on learners' environmental literacy, specifically knowledge, attitudes, and sensitivity, along with cognitive load. The findings indicate that VR-integrated DGBL markedly enhances learners' environmental knowledge and value-oriented attitudes. Within an immersive VR experience, students intuitively grasp environmental issues; the high level of interactivity and realistic scenes convert abstract concepts into concrete sensory experiences while overcoming the logistical constraints of outdoor instruction (Zhang et al., 2024). For instance, in our VR environment learners can observe a polluted river in real time and understand how changes in water quality affect ecosystem processes. By assuming multiple non-player-character roles, they examine the causes and scope of environmental problems from varied perspectives. This situated approach not only

strengthens cognitive understanding but also enables hands-on decision making, allowing students to perceive the consequences of their actions and deepening their sense of environmental responsibility. Compared with conventional digital classroom instruction, VR DGBL offers experiential interaction that builds more tangible environmental awareness, which is internalized as long-term environmental literacy, as evidenced by significant post-test gains in both environmental knowledge and pro-environmental attitudes.

In addition, the VR learning environment produced a significant positive effect on environmental attitudes. Interview data showed that, after encountering diverse non-player-character perspectives during play, learners increasingly adopted pro-environmental positions, recognized that pesticide use can harm ecosystems, and emphasized the importance of alternative practices. These findings suggest that digital games can steer students' value judgments toward sustainable development goals. Although gains in environmental sensitivity did not reach statistical significance, the study identifies scope for further enhancement and discussion. Qualitative analysis revealed that learners demonstrated reflective thinking and exploratory interest in the VR topics: they drew on personal experience to explain the causes of environmental problems and assessed how such issues influence their daily lives. Their discourse not only signaled concern for environmental challenges but also initiated deliberation on coping strategies. For instance, when environmental protection conflicts with commercial development, learners acknowledged the complexity of the trade-off and advocated for win-win solutions that balance ecological preservation with economic growth and social needs. Therefore, while the VR environment did not significantly raise environmental sensitivity, it prompted initial reflection, multiperspectival exploration, and attempts to outline concrete actions in response to real-world challenges. Future optimization of VR design may heighten sensitivity, enabling learners to detect subtle environmental impacts on ecosystems and society and to develop clearer intentions for environmental action. Previous research indicates that environmental education programs more readily improve knowledge than sensitivity, attitudes, or actual behavioral capability (Herlanti et al., 2024; Srbiniowski et al., 2010).

The study's second digital learning platform, the Web condition, engaged students with environmental news articles, videos, and comparative viewpoints delivered through multimedia resources. Pre- and post-test results revealed a modest gain in environmental knowledge. Although the combination of multimedia narrative and forum discussion did not markedly enhance pro-environmental attitudes, it exhibited a positive trend for environmental sensitivity. Several factors may explain this outcome. Despite using the same instructional content as the VR condition, the Web platform relied primarily on text, static images, and point-and-click navigation, creating a learning context with lower immersion and interactivity. This format supported basic knowledge construction but lacked the mission-oriented tasks and real-time feedback loops present in the VR game (for example, immediate deterioration of rivers and forests). Without instant visual consequences linked to their actions, learners could not readily perceive the environmental impact of their decisions, thereby limiting deeper attitude transformation. While the Web condition's discussion forum provided community participation, its feedback was delayed and offered no vivid sensory cues, making it difficult to foster swift emotional connections between actions

and outcomes and thus impeding significant change in environmental attitudes.

Finally, both quantitative and qualitative evidence on cognitive load showed that the VR group significantly outperformed the Web group on mental effort and perceived task load. The advantage appears to stem from mission-focused DGBL in the VR setting, where contextual cues are concentrated and task goals are explicit, enabling learners to allocate their limited cognitive resources more efficiently. Specifically, students in the VR condition had to explore the virtual environment, identify task-relevant cues, and retrieve information or solve problems through direct interaction with characters or objects. Because these cues were concrete and manipulable, they created a clear learning pathway that lowered extraneous load. By contrast, although the Web platform was structurally organized so that learners could sequentially view news videos and mixed media content, its operations were more constrained. Rewatching a video segment or revisiting a specific article required dragging a timeline slider or re-searching for the relevant passage, a process that consumed time and disrupted the learning flow, thereby increasing cognitive burden. The Web condition therefore lacked the immediacy and smooth interaction of the VR experience and could not offload cognitive demand to the same extent. Overall, integrating DGBL with immersive virtual reality offers an innovative avenue for fostering environmental literacy. Compared with traditional classroom instruction, the immersive environment adopted in this study promoted active participation and rich interaction, situating environmental knowledge in realistic contexts and thus supporting deeper development of environmental literacy.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Human Research Ethics Committee of National Cheng Kung University (HREC). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

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Conflict of interest

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