Feature Article

Differentiated Science With IVR: Effects on Gifted Students' Engagement, Self-Regulation, and Scientific Creativity

Gifted Child Quarterly
1–25

DOI: 10.1177/00169862251398018
journals.sagepub.com/home/gcq
Sage

Yunus Emre Avcu[1] and Yavuz Yaman[2]

Abstract

This study explored the effects of immersive virtual reality (IVR) supported sustainability-focused differentiated science instruction on gifted students' engagement, self-regulated learning skills, and scientific creativity. A systematically developed instructional design incorporated Sustainable Development Goals (SDGs) related to Clean Water and Sanitation (SDG-6), Accessible and Clean Energy (SDG-7), Climate Action (SDG-13), Life Below Water (SDG-14), and Life on Land (SDG-15). Thirteen 3D scenes, created using Blender, were integrated into the Imedu 3D Metaverse. The embedded mixed-methods design included 40 gifted sixth graders (23 females, 17 males), divided into experimental (IVR-based) and control (non-IVR) groups. The experimental group used Oculus Quest 2 IVR headsets for a 10-week (40-lesson) intervention. Repeated measures ANOVA revealed significant group-by-time interaction effects, indicating that the IVR-supported group showed greater gains than the control group in science engagement, $F(1, 38) = 5.181$, $\eta^2 = 0.12$; self-regulated learning skills, $F(1, 38) = 6.883$, $\eta^2 = 0.153$; and scientific creativity, $F(1, 38) = 68.237$, $\eta^2 = 0.642$. Interviews, self-assessments, and student products confirmed these findings. Future research should explore larger samples and diverse SDG applications.

Plain Language Summary

How Do Immersive Virtual Reality Science Lessons Help Gifted Students Engage, Take Ownership of Their Learning, and Think More Creatively?

This study examined how immersive virtual reality (IVR) science lessons help gifted students in grade six become more engaged, self-directed, and creative learners. The lessons focused on global challenges such as clean energy, climate change, and protecting oceans and forests. Using VR headsets, students explored vivid three-dimensional environments that made these issues easier to understand. Forty gifted students were split into two groups. One group learned with IVR while the other relied on traditional classroom tools such as textbooks and videos. Although both groups covered the same topics, the IVR group showed much higher engagement, they were more curious, interested, and emotionally invested in the lessons. They also displayed stronger self-regulation skills, setting goals, managing their time and attention, and evaluating their own progress. In addition, the IVR group produced more original and practical ideas to solve real-world problems, demonstrating greater scientific creativity. Researchers confirmed these findings through interviews, classroom observations, and student products. Overall, the results suggest that well-designed IVR lessons can motivate gifted students, foster independent learning habits, and nurture creative thinking in science.

Keywords
embedded mixed-methods design, gifted students, student engagement, self-regulated learning skills, scientific creativity

Received: March 26, 2025; revised: August 29, 2025; accepted: September 24, 2025

Children inherit a world challenged by climate change, poverty, and environmental degradation. Sustainable Development (*SD*) balances economic growth, social equity, and environmental preservation to meet present needs without compromising future generations (Dhahri & Omri, 2018). The United Nations (UN) Sustainable Development Goals (SDGs) provide a framework for this effort (UN, 2016). Sustainability

[1]Balıkesir University, Türkiye
[2]İstanbul University-Cerrahpaşa, Türkiye

Corresponding Author:
Yunus Emre Avcu, Necatibey Eğitim Fakültesi, Balıkesir University, Dinkçiler, Soma Cd., Altıeylül, 10100 Balıkesir, Türkiye.
Email: yunusemre.avcu@balikesir.edu.tr

Education (*SE*) promotes active learning, equipping individuals with the skills needed for a sustainable future (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2020). *SE* fosters deep learning and differentiated instruction for gifted students, enhancing their empathy, ethical maturity, and social awareness (Marzetta et al., 2018; Schroth & Helfer, 2017). Their intelligence, creativity, and strong justice orientation position them as future problem solvers (Akhan et al., 2022; Slade, 2021). However, despite their awareness of global issues (Sisk, 2009), they often engage less in environmental action and hold misconceptions (Mutlu & Nacaroglu, 2019; Özarslan, 2022), underscoring the need for targeted *SE* interventions.

SE is best integrated into gifted students' science education, as it already employs inquiry-based, higher-order thinking, and problem-based learning strategies (Akhan et al., 2022). Science education fosters interdisciplinary approaches, expanding learning and innovation (Cotabish et al., 2021; Schroth & Helfer, 2017). It also cultivates scientific literacy, enabling students to understand, apply, and make informed decisions on sustainability issues (Fakhriyah et al., 2017). Science education aligns with gifted students' cognitive and creative traits, fostering inquiry, reasoning, and curiosity (Gallagher, 2021; Smutny & Von Fremd, 2004). Its integration with sustainability can enhance both personal growth and societal impact, emphasizing the need for effective design over mere implementation. Gifted students' science education should be differentiated by adapting content, process, and environment to their needs (Matthews, 2021). It must integrate interdisciplinary themes, inquiry, and real-world applications while fostering creativity, problem-solving, and advanced thinking (Chandler, 2012; Cotabish et al., 2021).

Differentiated science education enhances gifted students' higher-order thinking and scientific creativity (Ayverdi & Öz Aydın, 2022; Washington & Andersen, 2016). Scientific creativity involves problem sensitivity, understanding scientific principles, and generating innovative ideas (Sidek et al., 2020). Its development is crucial for both personal growth and societal progress. Differentiated science instruction should enhance gifted students' self-regulated learning (SRL) skills alongside scientific creativity (Oppong et al., 2019). Strengthening these skills is vital for scientific achievement (Efklides, 2019; Taber, 2007). Differentiated science instruction for gifted students should enhance engagement across cognitive, emotional, behavioral, and social dimensions (M. T. Wang et al., 2016). Given their asynchronous development and diverse profiles, gifted students require tailored strategies to sustain engagement (Ronksley-Pavia & Neumann, 2020). Effective differentiation should address their cognitive and socio-emotional needs (Landis & Reschly, 2013).

Differentiated science instruction for gifted students should be interdisciplinary, in-depth, complex, foster higher-order thinking and scientific creativity, and support SRL skills and engagement (Phelps, 2022). However, sustainability-focused science education faces challenges such as the invisibility of environmental issues, psychological distance, and logistical barriers (Fauville et al., 2020; Markowitz & Bailenson, 2021). IVR technology addresses these challenges by enhancing immersion, fostering presence, and enabling responsive interactions (Makransky & Petersen, 2021; Petersen et al., 2022). It aids decision-making by visualizing long-term consequences and simplifying complex concepts (Scurati et al., 2021). Recognized by UNESCO (2020) and Gorski et al. (2023), IVR is a valuable tool for sustainability-focused differentiated science instruction.

The Cognitive Affective Model of Immersive Learning (CAMIL) explains IVR's impact by analyzing cognitive and emotional processes (Makransky & Petersen, 2021). Key components—immersion, control, and representability—enhance virtual experiences, fostering presence, agency, and embodiment. These factors positively influence motivation, self-efficacy, cognitive load, and self-regulation, facilitating knowledge acquisition and transfer (Makransky & Petersen, 2021). IVR thus enhances learner engagement and SRL skills. IVR and other immersive technologies enhance problem-solving and creativity by enabling experiences impossible in the real world (Reis et al., 2024). While IVR is used in gifted science education (Byeon, 2022; Ucar et al., 2017), no studies focus on its role in sustainability-focused science education. Effective implementation requires careful instructional design and evaluation (Cooper et al., 2024; Matovu et al., 2023). The current study explores IVR-supported sustainability-focused differentiated science instruction's impact on gifted students' engagement, SRL skills, and scientific creativity.

Literature Review

Student Engagement in Gifted Learners

Student engagement is a multidimensional concept crucial for the academic success of all students, particularly those who are gifted (Ronksley-Pavia & Neumann, 2020). It includes behavioral, emotional, cognitive, and social dimensions, each contributing uniquely to learning outcomes (M. T. Wang et al., 2016). Behavioral engagement involves students' efforts, attention, and preparedness, while its absence can lead to inattention, motivation loss, and unpreparedness (Skinner et al., 2009). Emotional engagement reflects enthusiasm, interest, and the value students assign to learning (Fredricks & McColskey, 2012). Cognitive engagement entails goal-setting, deep thinking, and self-regulation, fostering autonomy and deep learning (Gibbs & Poskitt, 2010). Social engagement relates to students' interactions with peers and teachers, encouraging active participation in social relationships (M. T. Wang et al., 2016). These interrelated dimensions collectively support students' full involvement in learning.

Gifted students need specialized educational approaches to sustain engagement, crucial for their academic success and well-being (Landis & Reschly, 2013). Standard curricula often lack sufficient challenge, leading to disengagement (Kanevsky & Keighley, 2003). Delisle (2012) highlights five key engagement factors: control, complexity, common bonds, choice, and caring teachers. Providing autonomy, challenging content, peer connections, and supportive teachers enhances engagement (Delisle, 2012). Formative assessments and authentic learning experiences, such as problem-based learning and real-world applications, further boost motivation and engagement (Eriksson, 2022). Differentiated instruction, through enriched content and flexible learning spaces, fosters engagement, motivation, and academic challenge, helping gifted students reach their potential (Phelps, 2022). IVR enhances gifted students' engagement by fostering deep learning, motivation, and collaboration. It supports critical thinking (S. T. Wang et al., 2018), increases enjoyment and engagement (Ucar et al., 2017), promotes active participation (Byeon, 2022), and strengthens peer interaction (Alali & Wardat, 2024; Byeon, 2022). Overall, IVR enriches engagement for gifted students.

SRL Skills in Gifted Students

SRL is a critical skill that enables students to plan, monitor, and evaluate their learning processes effectively (Zimmerman & Schunk, 2012). Gifted students often demonstrate advanced SRL skills due to their high levels of metacognition and intrinsic motivation (Paz-Baruch & Hazema, 2023). However, their effective utilization of these skills depends on the challenges and supports within their instructional environment (Oppong et al., 2019). SRL consists of cognitive strategies such as goal-setting and task planning, motivational strategies including self-efficacy and maintaining interest, and behavioral strategies like time management and persistence (N. Johnson, 2012; Zimmerman & Schunk, 2012). These components work synergistically to enhance learning outcomes, particularly when instructional design fosters autonomy and reflection (Winne, 2019; Zimlich, 2016). Therefore, gifted students require educational support that nurtures and enhances their SRL skills, ensuring they can fully leverage their potential in diverse learning environments (Housand & Reis, 2008).

Differentiated instruction plays a crucial role in fostering SRL skills by providing personalized tasks that empower students to take ownership of their learning (G. Johnson & Davies, 2014). Through modeling, guided practice, and independent evaluation, students can develop SRL skills, enabling them to manage their own learning processes effectively (Pressley et al., 1992, as cited in Zeidner & Stoeger, 2019). Furthermore, incorporating personal, behavioral, and environmental strategies alongside technology-based learning environments enhances the development of SRL skills (Azevedo, 2008; Reis, 2021). Particularly, IVR has been found to positively impact learners' SRL skills by providing engaging, interactive experiences that support goal-setting, monitoring, and reflection (Jiang et al., 2018; Sakdavong et al., 2019; Wu et al., 2023; Zhao et al., 2024). When combined with differentiated instruction, IVR allows students to adjust cognitive load, personalize their learning pace, and actively regulate their learning strategies, ultimately strengthening both SRL and lifelong learning capacities (Jiang et al., 2018).

Scientific Creativity in Gifted Students

Scientific creativity, characterized by the ability to generate original and valuable ideas within scientific contexts, is a hallmark of gifted learners. It involves cognitive flexibility, divergent thinking, and the capacity to integrate knowledge from various domains to solve complex scientific problems (Washington & Andersen, 2016). Scientific creativity is conceptualized through models such as Hu and Adey's (2002), Son's (2009), and Park's (2010) Scientific Creativity Models. Hu and Adey define it as generating scientific products through thinking and imagination, while Park integrates knowledge, creative thinking, and inquiry skills. Son's model emphasizes competencies, motivation, and career interests (Sidek et al., 2020). This study adopts Hu and Adey's (2002) model, which includes product, trait, and process dimensions, forming a three-dimensional, 24-cell framework to analyze scientific creativity.

Gifted students possess significant potential for scientific creativity, but this capacity needs nurturing through instructional strategies that encourage exploration, experimentation, and interdisciplinary connections (Ayverdi & Öz Aydın, 2022; Root-Bernstein & Root-Bernstein, 2001). Differentiated instruction, particularly in science education, supports creativity by providing open-ended problems, inquiry-based tasks, and opportunities for real-world application (Schroth & Helfer, 2017; Taber, 2007). For instance, sustainability-focused projects challenge students to devise innovative solutions to pressing global issues, fostering both originality and practical problem-solving skills (Akhan et al., 2022). The use of IVR further enhances scientific creativity by creating immersive environments where students can visualize, manipulate, and test scientific concepts. IVR simulations allow learners to explore abstract phenomena, conduct virtual experiments, and engage in scenarios that require creative problem-solving (S. J. Chen et al., 2024; Thornhill-Miller & Dupont, 2016). These environments enable students to interact with high-fidelity models and test hypotheses dynamically, supporting their ability to innovate and think divergently (Bourgeois-Bougrine et al., 2020; Gong & Georgiev, 2020; Gong et al., 2022).

Hu and Adey's (2002) model guides the examination of how IVR supports scientific creativity by enhancing the product (technical product, science knowledge, science phenomena, science problem), trait (fluency, flexibility, originality), and process (thinking, imagination) dimensions through presence, interaction, and sensory feedback. Spatial presence, the perceptual illusion of "being there," contributes significantly to the product component by immersing learners in authentic 3D environments where scientific problems emerge naturally, fostering curiosity and original inquiry (Araiza-Alba et al., 2021; Yu & Wang, 2025). This immersion supports diverse perspective-taking, promoting creative problem identification (Young et al., 2020), while also enhancing focus and motivation in iterative problem-solving tasks within safe, risk-free settings (Elme et al., 2022; Palombi et al., 2023). At the trait level, spatial presence diminishes mental constraints, facilitating a state of flow and enabling fluent, flexible idea generation within vivid, open-ended environments (Ichimura, 2023; Yu & Wang, 2025). It also reinforces the process dimension by transforming abstract phenomena into tangible experiences that scaffold imagination and hypothesis formation (Chang et al., 2023). In inquiry-based learning, such presence supports "what-if" thinking and deeper conceptual understanding through mental simulation (Elme et al., 2022).

Embodied interaction, or learners' physical engagement with virtual environments, strengthens the product dimension by enabling intuitive exploration and real-time manipulation of scientific systems (Bagher et al., 2021). Interacting with virtual tools and receiving immediate feedback supports procedural understanding and creative problem generation (Bagher et al., 2021; Elme et al., 2022). At the trait level, embodied interaction enhances divergent thinking by promoting cognitive flexibility, fluency, and originality (Yang et al., 2018). Gestures, posture changes, and role-play (e.g., becoming a scientist or animal) allow learners to approach problems from multiple perspectives, breaking functional fixedness (Frith et al., 2020; Malinin, 2019). The safe, risk-free nature of IVR encourages creative risk-taking and boosts ideational fluency through a strong sense of agency (Bonnardel & Pichot, 2020). In terms of process, embodied interaction facilitates scientific imagination by enabling learners to enact hypotheses, manipulate variables, and iteratively build mental models. These kinesthetic actions connect bodily experience with abstract thinking, supporting imagination and conceptual exploration (Ceja Salgado, 2022; Frith et al., 2020).

Multisensory feedback deepens scientific creativity by engaging visual, auditory, and tactile channels. In the product dimension, such feedback enhances emotional salience and attention, improving scientific problem detection and solution refinement—for instance, through synchronized sensory input while adjusting a wind turbine (Andonova et al., 2023; Yang et al., 2018; Yu & Wang, 2025). In the trait dimension, multisensory environments stimulate divergent thinking by fostering elaboration, vividness, and originality (H. T. Huang & Chang, 2023). Emotional arousal and associative memory triggered by rich sensory input—like immersive soundscapes or scents—significantly boost creative ideation (Andonova et al., 2023; H. T. Huang & Chang, 2023). Regarding process, multisensory input supports imagination and scientific reasoning by anchoring emotionally rich stimuli in memory. The integration of multiple modalities enables learners to build layered mental models, generate hypotheses, and engage in creative extrapolation (Corral et al., 2023). In conclusion, the combined features of IVR may support all components of scientific creativity in Hu and Adey's (2002) model, fostering innovative and imaginative thinking in gifted learners.

Problem Statement

Despite increasing interest in differentiated science instruction and IVR, their combined impact on engagement, SRL skills, and scientific creativity in gifted students remains underexplored. Prior research has focused on either traditional methods or isolated technologies, leaving a gap in understanding the synergistic effects of IVR-supported sustainability-focused differentiated science education (Byeon, 2022; Kim & Kim, 2022; Tanik Önal & Önal, 2021; Ucar et al., 2017; S. T. Wang et al., 2018). This study aimed to address this gap by examining the following research questions:

1. What are the effects of IVR-supported, sustainability-focused differentiated science instruction on the post-test scores of the Science Engagement Scale (SES), Science Self-Regulation Scale (SSRS), and Scientific Creativity Test (SCT) of gifted students, compared to sustainability-focused differentiated science instruction conducted in the control group?
2. What are the perspectives of the experimental group students regarding the IVR-supported, sustainability-focused differentiated science instruction?
3. What are the engagement levels of the students in the experimental group?
4. To what extent do the students in the experimental group utilize SRL skills?
5. How do learning products from creativity-stimulating activities reflect experimental group students' scientific creativity?

Method

Research Design

This study employs a mixed-methods approach with an embedded design, where the quantitative component is prioritized, and the qualitative data support the findings (Creswell, 2021). Within the quantitative strand, a pre-test–post-test control group quasi-experimental design is utilized to determine the causal effects of the intervention. The qualitative strand, employing phenomenological and case study approaches, investigates students' perceptions, experiences, and learning products to enrich the quantitative data (Creswell, 2021).

Participants

Participants include 40 gifted sixth-grade students (Age M=13.1) from a science and art-focused educational institution called BİLSEM in Türkiye. BİLSEM is an after-school enrichment institution where students identified as gifted receive differentiated education. Türkiye has 393 BİLSEMs serving 83,051 students with 3,178 teachers. This study was conducted with BİLSEM students in Balıkesir, selected as a typical sample among 81 provinces (Büyüköztürk et al., 2022).

Ministry of National Education (MoNE; 2024) defines gifted individuals as those demonstrating advanced cognitive abilities, creativity, leadership, and exceptional performance in academic, artistic, or musical domains. Identification begins in 1st to 3rd grade through teacher nominations in general mental ability, art, and music, followed by pre-assessments and IQ testing for the top 20%. BİLSEMs foster development through programs such as the Compliance Education Program (CEP), Support Education Program (SEP), Recognizing Individual Skills Program (RISP), Developing Special Skills Program (DSSP), and Project Production and Management Program (PPMP). It can be said that BİLSEM is structured similarly to the autonomous learning model, which is one of the educational models for gifted students (Betts & Kercher, 2009). While students identified for general mental ability engage in all programs, those specializing in art and music begin their education with the DSSP.

The CEP supports students' integration and development, followed by the SEP, which enhances key skills like communication, problem-solving, and critical thinking. The RISP fosters creativity and talent exploration, leading to the DSSP, which provides interdisciplinary education in intellectual ability, arts, and music. The PPMP enables students to complete at least one independent or group research project annually under mentor supervision. Evaluation and assessment incorporate formative and summative methods, ensuring systematic progress tracking. Program durations range from 2 months to graduation, promoting continuous academic and personal growth (MoNE, 2024).

These students (in RISP) were identified as gifted in general mental ability through IQ tests and divided equally into an experimental group (n=20) and a control group (n=20). The experimental group received IVR-supported sustainability-focused science instruction, while the control group experienced sustainability-focused differentiated science instruction. A balanced representation in terms of gender and socio-economic background was ensured to maintain diversity and minimize selection bias (Büyüköztürk et al., 2022).

The IVR-Supported Sustainability-Focused Differentiated Science Instructional Design

The design process involved analysis (need, task, and instructional analysis phases), design, development, implementation, and evaluation. The need analysis phase assessed target learners' needs and instructional challenges. The study emphasized the need for differentiated sustainability education for gifted students and its integration into science, exploring IVR-supported approaches as a solution. The study determined learning topics through task analysis, drawing from science curricula, BİLSEM programs, environmental education guidelines, SDG reports, literature, and researcher observations. The identified topics included SDG-13, SDG-14, SDG-15, SDG-6, and SDG-7. The instructional design focused on the theme of "change," highlighting its inevitability, impact, and role in growth. Essential questions covered human-nature interaction, ocean acidification, climate change, future energy sources, and clean water. In the design phase, data from the analysis stage guided the selection of instructional methods, techniques, duration, and assessment approaches to achieve the specified learning outcomes. Instructional methods fostering student engagement, self-regulated learning, and scientific creativity included virtual field trips, personal analogy, brainstorming, inquiry-based learning, experimentation, fishbone, research reporting, self-assessment, invention development, oral presentations, 3-2-1 Bridge, RAFT, See-Think-Wonder, SCAMPER, and gallery walk. Key information on activity plan designs is provided in Table 1. In the development phase, the draft learning materials from the design stage are refined, reviewed, and evaluated based on instructional principles.

To ensure methodological rigor and isolate the specific impact of IVR on students' engagement, scientific creativity, and self-regulated learning skills, both the experimental and control groups were exposed to the same sustainability-focused thematic content, learning objectives, assessment tools, and creative tasks. The only distinction between the two conditions lay in the mode of content delivery: while the experimental group engaged with immersive IVR environments, the control group participated in cognitively and affectively parallel activities utilizing printed visuals, videos, comic books, structured worksheets, gallery walks, and guided discussions. Instructional time was equally allocated in both groups. As presented in Table 1, the detailed week-by-week instructional alignment underscores the instructional equivalence across groups, thereby enabling a more valid attribution of observed differences to the affordances of the IVR-supported learning environment. To control for potential teacher and class effects, a single researcher conducted all instructional sessions for both the experimental and control groups. This approach ensured consistency in teaching style, instructional delivery, and classroom management. Furthermore, all lessons were held in the same classroom and followed an identical weekly schedule to minimize environmental and temporal confounds.

The development process included expert-reviewed activity plans, integrating 3D Metaverse (Imedu) and IVR for the experimental group. The immersive learning design was guided by key instructional principles. CAMIL (Makransky & Petersen, 2021) balanced cognitive load and emotional

Table 1. Key information on Activity Plan Designs in the Experimental and Control Group.

Week	Activity Name and Duration	Experimental Group	Control Group
Week 1	Let's Visit Kaz Mountains National Park! (4x40')	- Exploring the concept of change through interdisciplinary perspectives. - Completing individual drawing and writing tasks on forest ecosystems. - Reading the comic book 'Secrets of the Forests of the Future'. - Introduction to IVR technology using Oculus Quest 2. - IVR Scene 1: Experiencing a healthy Kaz Mountains ecosystem (15 min). - Evidence-based discussion on Scene 1. - IVR Scene 2: Experiencing a degraded ecosystem due to deforestation (15 min). - Evidence-based discussion on Scene 2. - IVR Scene 3: Experiencing a forest fire scenario in Kaz Mountains (15 min). - Evidence-based discussion on Scene 3. - Completing individual analogical reasoning tasks based on the scenes.	- Exploring the concept of change through interdisciplinary perspectives. - Completing individual drawing and writing tasks on forest ecosystems. - Reading the comic book 'Secrets of the Forests of the Future'. - Analyzing photographs, topographical maps, and diagrams of Kaz Mountains. - Visual exploration using printed images, videos, and maps of healthy forest ecosystems (15 min). - Group discussion using printed data, videos, and statistics. - Analyzing case studies on ecosystem degradation with printed texts (15 min). - Guided group discussion on ecological case studies. - Role-play activity simulating forest fire impacts using printed visuals (15 min). - Completing individual analogical reasoning tasks on deforestation impacts.
Week 2	Let's Visit Kaz Mountains National Park! (4x40')	- Linked the activity to SDG-15. - Completed sentence prompts and designed SDG-related inventions. - Researched relevant nonprofit organizations (group task). - Completed evaluation, achievement, and self-assessment forms. - Explored career connections and received extension materials.	- Linked the activity to SDG-15. - Completed sentence prompts and designed SDG-related inventions. - Researched relevant nonprofit organizations (group task). - Completed evaluation, achievement, and self-assessment forms. - Explored career connections and received extension materials.
Week 3	Our Changing Oceans (4x40')	- Exploring marine ecosystems and the importance of healthy oceans. - Reading the comic book 'Annie Sunbeam and Friends' (individual task). - Measuring pH levels and analyzing graphs related to ocean acidification. - Reading and discussing the article 'Analysis of Black Sea Ocean Acidification' (group task). - IVR Scene 1: Experiencing a healthy ocean ecosystem (15 min). - Evidence-based discussion on Scene 1. - IVR Scene 2: Experiencing an acidified ocean environment (15 min). - Evidence-based discussion on Scene 2.	- Exploring marine ecosystems and the importance of healthy oceans. - Reading the comic book 'Annie Sunbeam and Friends' (individual task). - Measuring pH levels and analyzing graphs related to ocean acidification - Reading and discussing the article 'Analysis of Black Sea Ocean Acidification' (group task). -Reviewed posters and handouts on healthy marine ecosystems (15 min). -Discussed key features of healthy oceans using printed evidence (posters, graphs, text excerpts). -Analyzed visuals (photos, videos, explanatory texts) of degraded marine environments (15 min). -Discussed human impacts and proposed evidence-based solutions.
Week 4	Our Changing Oceans (4x40')	- Linked activities to SDG-14. - Developed hypotheses and designed group experiments on ocean acidification. - Presented designs to TÜDAV researchers. - Completed product, achievement, and self-assessment forms. - Designed inventions and researched SDG-14 nonprofits. - Received additional resources and explored career connections.	- Linked activities to SDG-14. - Developed hypotheses and designed group experiments on ocean acidification. - Presented designs to TÜDAV researchers. - Completed product, achievement, and self-assessment forms. - Designed inventions and researched SDG-14 nonprofits. - Received additional resources and explored career connections.
Week 5	Climate Action (4x40')	- Conducted a brainstorming session on unanswered scientific questions about climate change (group task). - Read the comic What is Climate Change? individually, followed by a Q&A session. - Introduced the steps of Problem-Based Learning (PBL). - Explored the open-ended question: "As a climate activist, what can we do in Türkiye to mitigate the effects of climate change?" - IVR Scene 1: Experiencing Agricultural and Livestock Activities and Their Relationship with Climate Change via—IVR (15 min). Conducted an evidence-based discussion on Scene 1. - IVR Scene 2: Experiencing Natural and Anthropogenic Factors Contributing to Climate Change via IVR (15 min). - Conducted an evidence-based discussion on Scene 2. - IVR Scene 3: Experiencing Consequences of Climate Change: Drought, Heavy Rainfall, Floods, Tornadoes, Tropical and Snowstorms via IVR (15 min, individual task). - Conducted an evidence-based discussion on Scene 3.	-Conducted a brainstorming session on unanswered scientific questions about climate change (group task). -Read the comic What is Climate Change? individually, followed by a Q&A session. -Introduced the steps of Problem-Based Learning (PBL). -Explored the open-ended question: "As a climate activist, what can we do in Türkiye to mitigate the effects of climate change?" -Analyzed printed visuals and infographics on agriculture, livestock, and climate change (15 min). -Participated in a whole-class discussion on the impact of agricultural practices using printed evidence. -Examined printed diagrams and texts on natural and human-induced climate factors (15 min). -Took part in small-group discussion interpreting natural vs. anthropogenic causes. -Reviewed printed case studies and photos on climate change consequences (15 min, individual task). -Engaged in a group discussion on how these consequences affect ecosystems and communities.

(continued)

Table 1. (continued)

Week	Activity Name and Duration	Experimental Group	Control Group
Week 6	Climate Action (4x40’)	- Shared evaluation forms for research reports and fishbone posters. - Completed a fishbone diagram on climate change causes and effects (group task). - Filled out the worksheet What Do We Know? What Do We Need to Know? (group task). - Followed Problem-Based Learning (PBL) steps: Define, Gather, Generate, Discuss, Decide, Present, Report. - Presented group solutions via digital presentations. - Linked the activity to SDG-13. - Completed achievement and self-assessment forms (individual tasks). - Received additional resources and explored career connections.	- Shared evaluation forms for research reports and fishbone posters. - Completed a fishbone diagram on climate change causes and effects (group task). - Filled out the worksheet What Do We Know? What Do We Need to Know? (group task). - Followed Problem-Based Learning (PBL) steps: Define, Gather, Generate, Discuss, Decide, Present, Report. - Presented group solutions via digital presentations. - Linked the activity to SDG-13. - Completed achievement and self-assessment forms (individual tasks). - Received additional resources and explored career connections.
Week 7	Accessible and Clean Energy (4x40’)	-Completed the 3-2-1 Bridge worksheet (individual task). -Analyzed the poster Challenges and Solutions in Clean and Renewable Energy and participated in a think-pair-share activity (group task). -IVR Scene 1: Explored renewable and nonrenewable energy sources via IVR; labeled sources during the experience (15 min, group task). -Participated in an evidence-based discussion on Scene 1. -Completed the See-Think-Wonder worksheet. -IVR Scene 2: Experienced wind turbine structure, electricity production, and distribution via IVR; labeled components (15 min, group task). -Participated in an evidence-based discussion on Scene 2.	-Completed the 3-2-1 Bridge worksheet (individual task). -Analyzed the poster Challenges and Solutions in Clean and Renewable Energy and joined a think-pair-share activity (group task). -Reviewed printed infographics comparing renewable and nonrenewable energy sources; completed labeling tasks (15 min, group task). -Participated in a group discussion on the sustainability and environmental impact of different energy sources. -Completed the See-Think-Wonder worksheet. -Examined printed diagrams showing wind turbine structure and energy flow; labeled components (15 min, group task). -Discussed energy generation and distribution based on printed diagrams and explanatory texts.
Week 8	Accessible and Clean Energy (4x40’)	-Revised answers in the 3-2-1 Bridge worksheet (individual task). -Completed a creative writing task using the RAFT framework (group task). -Linked the activity to SDG-7 (Affordable and Clean Energy). -Completed product, achievement, and self-assessment forms (individual tasks). -Explored additional resources and career connections.	-Revised answers in the 3-2-1 Bridge worksheet (individual task). -Completed a creative writing task using the RAFT framework (group task). -Linked the activity to SDG-7 (Affordable and Clean Energy). -Completed product, achievement, and self-assessment forms (individual tasks). -Explored additional resources and career connections.
Week 9	Clean Water and Sanitation (4x40’)	-Reviewed the Sustainability Awareness 3D model by Victoria Jonassen (group task). -Analyzed the poster titled Clean Water and Sanitation (group task). Explained the concept of sanitation. -IVR Scene 1: Experienced a Gallery Walk on Clean Water and Sanitation (15 min). -Participated in an evidence-based discussion on Scene 1. -IVR Scene 2: Experienced activities causing water pollution through -IVR (15 min, individual task). -Participated in an evidence-based discussion on Scene 2. -IVR Scene 3: Explored a Wastewater Treatment Facility, labeling stages after a related video (15 min, individual task). -Participated in an evidence-based discussion on Scene 3.	-Reviewed the Sustainability Awareness 3D model by Victoria Jonassen (group task). -Analyzed the poster titled Clean Water and Sanitation (group task). -Explained the concept of sanitation. -Participated in a gallery walk using printed photos and visual panels on clean water and sanitation (15 min). -Joined a group discussion on water pollution causes and consequences using printed evidence. -Watched a short video showing human activities causing water pollution (e.g., industrial discharge, pesticide use, household waste). -Discussed water pollution based on the video. -Labeled the stages of a wastewater treatment facility using a printed diagram (15 min, individual task). -Discussed how each stage contributes to sanitation using printed explanations.
Week 10	Clean Water and Sanitation (4x40’)	Shared the SCAMPER product evaluation form with students. Explained the SCAMPER technique and completed a sample activity (individual task). Used the SCAMPER method to develop group strategies for reducing plastic usage. Linked the activity to SDG-6 (Clean Water and Sanitation). Completed the achievement assessment and self-assessment forms (individual tasks). Provided supplementary activities, reading materials, and research suggestions. Explored career opportunities and interdisciplinary connections related to SDG-6.	Shared the SCAMPER product evaluation form with students. Explained the SCAMPER technique and completed a sample activity (individual task). Used the SCAMPER method to develop group strategies for reducing plastic usage. Linked the activity to SDG-6 (Clean Water and Sanitation). Completed the achievement assessment and self-assessment forms (individual tasks). Provided supplementary activities, reading materials, and research suggestions. Explored career opportunities and interdisciplinary connections related to SDG-6.

Figure 1. 3D Scenes in Imedu.

engagement, while the Extended Model of Immersive Learning in VR (EMIL VR; Vogt, 2022) optimized user experience. Emotional Design (Plass et al., 2022) and immersion principles emphasized engagement and retention. Additional strategies included Exaggerated Feedback (Stenberdt & Makransky, 2023), Cognitive Load Reduction (Makransky & Petersen, 2021), and Signaling Principle (Mayer, 2014). Thirteen low-poly 3D scenes were created in Blender, integrated into the Imedu Metaverse, and tested with Oculus Quest 2 for IVR-supported learning. Expert reviews refined the final design. Figures 1 and 2 present 3D scenes in Imedu and the immersive virtual environment from students' views.

Data Collection Tools

Quantitative Data Collection Tools. The Science Engagement Scale (SES) in the current study is the Turkish adaptation of Wang et al.'s (2016) Science and Mathematics Engagement Scale, validated by Turan Gürbüz et al. (2020). It assesses cognitive, behavioral, emotional, and social engagement with 33 items. Adaptation involved expert translations and linguistic evaluations. Validity and reliability tests with 519 middle school students confirmed a good model fit ($\chi 2 / df = 1.75$; RMSEA = 0.038; SRMR = 0.049; RMR = 0.072; CFI = 0.98; NFI = 0.96). Reliability analysis showed Cronbach's alpha = 0.90. In the current study, pre-test $\alpha = 0.87$ and post-test $\alpha = 0.89$, demonstrating strong internal consistency (Büyüköztürk, 2014).

The Science Self-Regulation Scale (SSRS) was developed by Nacaroğlu and Bektaş (2023) based on the self-regulation strategies section of the Motivated Strategies for Learning Questionnaire (MSLQ) and adapted for science education. Reviewed by two science education experts, the revised scale was administered to 482 middle school students. Reliability analysis yielded a Cronbach's alpha of 0.90. Exploratory Factor Analysis (EFA) showed a KMO value of 0.88, and after removing overlapping items, the

Figure 2. 3D Scenes in Imedu and Students' Views on IVR.

final 25-item scale was structured into five factors: rehearsal, effort regulation, elaboration, metacognitive self-regulation, and critical thinking. Confirmatory Factor Analysis (CFA) confirmed the model fit, $\chi 2/df = 2.52$, AGFI = 0.91, GFI = 0.92, CFI = 0.94, NFI = 0.91, RMSEA = 0.05. In the current study, pre-test Cronbach's alpha was 0.82 and post-test was 0.89, demonstrating strong reliability (Büyüköztürk, 2014).

The Scientific Creativity Test (SCT) was developed by Hu and Adey (2002) with 160 middle and high school students (ages 12–15). The SCT consists of seven tasks assessing fluency, flexibility, and originality. The first four tasks are evaluated based on fluency, flexibility, and originality, whereas the remaining three tasks are scored only on flexibility and originality. Fluency scores reflect the number of responses provided by students; flexibility scores represent the diversity of categories and approaches utilized; originality scores are derived by analyzing the frequency of unique responses. Tasks include identifying scientific uses for a piece of glass, formulating scientific questions for space exploration, proposing innovative improvements to a bicycle, describing Earth without gravity, dividing a square into four equal parts through multiple methods, comparing the effectiveness of two napkin types using various approaches, and designing an apple-picking machine.

The original scale had a Cronbach's alpha of 0.89. The inter-rater reliability was 0.875. The Turkish adaptation by Ayverdi et al. (2012) was conducted with 58 middle school students, yielding a Cronbach's alpha of 0.861. Three raters assessed the scale, with Pearson correlation coefficients ranging from 0.87 to 0.939. Validity was confirmed by two subject-matter experts, two Turkish language experts, and three foreign language experts, deeming it suitable for Turkish students.

The SCT was scored independently by two raters who were external to the research team to ensure impartiality in the current study. To further mitigate potential scoring biases, raters remained blind to both the condition (experimental or control) and the measurement phase (pre-test or post-test) of the students' responses. This approach strengthened objectivity and enhanced the reliability of the assessment outcomes. The inter-rater reliability for the SCT was established with a correlation coefficient of 0.84. Cronbach's alpha values indicated strong internal consistency, with $\alpha = 0.81$ at pre-test and $\alpha = 0.87$ at post-test, both exceeding the recommended threshold of 0.70 (Büyüköztürk, 2014).

Qualitative Data Collection Tools. The semistructured interview form aimed to explore the impact of this instruction on students' engagement, self-regulated learning skills, and scientific creativity. It included seven main questions with probes for four of them. Experts in gifted education, technology integration, and science education, along with a Turkish language teacher, reviewed the form for content and clarity. After revisions based on their feedback, a pilot evaluation was conducted with a gifted sixth-grade student to ensure the clarity and comprehensibility of the questions. Example questions from the interview form are as follows:

- How do you compare the IVR-supported sustainability-focused science lessons with your previous science lessons? What similarities and differences can you identify?
- What was the most memorable aspect of the IVR-supported sustainability-focused science lessons? Can you share an experience that you will not forget?
- How do you think the IVR-supported sustainability-focused science lessons contributed to your self-regulated learning skills?
- Do you believe that the IVR-supported sustainability-focused science lessons helped develop your scientific creativity?
- Would you like your future science lessons to be IVR-supported? Why or why not?

Classroom sessions and activities were recorded to capture students' behavioral, cognitive, emotional, and social engagement during the learning process (200 min in total, with 160 min utilized). These recordings enabled the researcher to observe and analyze participation patterns and interactions in a naturalistic setting. Students were asked to evaluate their learning processes, strategies, and experiences through self-assessment forms. This tool offered insights into their self-perceived growth in self-regulated learning and their ability to reflect on their achievements and challenges.

Learning outputs developed by students during the instructional process were collected and analyzed. These products served as tangible evidence of students' scientific creativity. The examined learning products include ecosystem-themed drawings and inventions (Let's visit Kaz Dağları Activity), scientific solutions for ocean acidification and pollution (Changing Oceans Activity), and research reports, problem-based solutions, and fishbone analyses (Climate Action Activity). Students also created letters, speeches, and posters using 3-2-1 Bridge and RAFT techniques (Clean and Renewable Energy Activity) and developed SCAMPER-based creative ideas and plastic reduction solutions (Clean Water and Sanitation Activity).

Data Collection and Analysis

This study was approved by the Istanbul University-Cerrahpasa Social and Humanities Research Ethics Committee (approval no: 2023/374). Informed consent was obtained from all student participants and their parents prior to the study. Descriptive statistics provided an overview of the data. Normality was assessed using skewness-kurtosis values, normality tests, and histograms, confirming that each subgroup (pre-test, post-test) followed a normal distribution. Assumptions for Two-Factor ANOVA for Repeated Measures and Independent *t*-test were met. Independent samples *t*-test results showed no significant difference between the experimental and control groups in SES ($t_{38} = -0.517$, $p > .05$), SSRS ($t_{38} = -1.29$, $p > .05$), and SCT ($t_{38} = 1.31$, $p > .05$) pre-test scores. This indicates that both groups were equivalent in terms of these measures before the intervention. Two-Factor ANOVA for Repeated Measures evaluated differences in pre-test and post-test scores for SES, SSRS, and SCT between the experimental and control groups. Effect sizes were calculated using partial eta-squared (η^2) values obtained from the ANOVA tests conducted for SES, SSRS, and SCT to determine the magnitude of the intervention's impact, with thresholds classified as small (0.01), medium (0.06), and large (0.14; Cohen, 1973).

Semistructured interviews were conducted with five students, representing low, medium, and high scores on the SES. Each interview lasted an average of 34.8 min, ranging from 29 to 47 min. The interviews were held in a quiet environment conducive to open responses, and all sessions were audio-recorded with prior consent from both students and their parents. The recordings were transcribed, and student anonymity was maintained by coding participants as Student1, S2, . . ., S5. Inductive content analysis was employed to examine the interviews, self-assessment forms, and video recordings. Initial readings identified recurring themes and patterns, which were coded and categorized into related concepts. To enhance the trustworthiness of the qualitative analysis, the coding process involved two researchers. After an initial phase of independent coding, the researchers engaged in several consensus meetings to review, discuss, and resolve any discrepancies in the codes. The final thematic structure was established only after a full consensus was reached on all data.

A total of 200 min of classroom activities were recorded, edited down to 160 min of analyzable footage. Students' self-reflections on their learning processes were analyzed, with forms coded as F1 to F100. Learning outputs were evaluated according to the activity plans, with descriptive analysis used to interpret the data. The study ensured validity and reliability through expert review, detailed documentation, code validation, and participant verification, with triangulation enhancing credibility.

Findings

Quantitative Findings

The descriptive statistics findings from the groups' pre-test and post-test results are presented in Table 2. Accordingly, in the SES, scores ranged from 127.15 to 137.20 in the experimental group and 128.68 to 130.10 in the control group. In the SSRS, mean scores varied between 84.66 and 102.80 in the experimental group and 88.92 to 91.60 in the control group. The SCT showed mean scores ranging from 67.95 to 87.50 in the experimental group and 59.85 to 69.85 in the control group. Regarding skewness and kurtosis values, all fall within the acceptable range of -1 to +1, confirming that the data distribution is approximately normal (George & Mallery, 2010).

The Repeated Measures Two-Factor ANOVA results are presented in Table 3. Accordingly, inferential analyses revealed significant differences between the groups' post-intervention, with the experimental group showing substantial improvements across all three scales compared to the control group. Repeated Measures Two-Factor ANOVA showed a significant interaction effect between group and test for SES, ($F_{1,38} = 5.181$, $p < .05$, $\eta^2 = 0.12$; SSRS, $F_{1,38} = 6.883$, $p < .05$, $\eta^2 = 0.153$; and SCT, $F_{1,38} = 68.237$, $p < .05$, $\eta^2 = 0.642$). Repeated Measures Two-Factor ANOVA showed a significant interaction effect between group and test for SES, $F_{1,38} = 5.181$, $p < .05$, representing a moderate effect size ($\eta^2 = 0.12$), and for SSRS, $F_{1,38} = 6.883$, $p < .05$, and SCT, $F_{1,38} = 68.237$, $p < .05$), representing large effect sizes ($\eta^2 = 0.153$ and $\eta^2 = 0.642$, respectively).

Qualitative Findings

Students' Perspectives of IVR-Supported Sustainability-Focused Differentiated Science Instruction. Table 4 shows students' perspectives of IVR-supported differentiated science instruction. It highlights cognitive, behavioral, emotional, and social engagement, along with self-regulated learning skills and scientific creativity. Students demonstrated active participation, deep thinking, perseverance, and curiosity but also faced challenges like anxiety and distraction. Their self-regulated learning involved goal setting, planning, and effort regulation, while scientific creativity was reflected in imagination, flexibility, and problem-solving.

S3 emphasized scientific knowledge and scientific problems, finding it intriguing that global warming is influenced not only by human activities but also by natural factors like methane emissions from cows. The student noted that, "everyone thinks of cars, but natural creatures also contribute. Learning new scientific facts is interesting." S1 highlighted enjoyment of learning and the practical value of writing techniques, stating that acquiring these skills was both enjoyable and applicable beyond the course: "Learning writing techniques was enjoyable and useful beyond this course." S4 underscored the importance of collaborative work, emphasizing that teamwork enhances creativity and engagement: "Working with friends is fun and helps generate better ideas." S5 demonstrated metacognitive self-regulation, recognizing the role of self-assessment in deeper learning and reflection: "Self-assessment questions deepened my learning and awareness."

The Engagement Levels of the Students in the Experimental Group According to Video Recordings. Video recordings of classroom sessions revealed a rich and multidimensional profile of student engagement in the experimental group. Across cognitive, behavioral, emotional, and social domains, students actively participated in the learning process throughout the 10-week instructional period.

Cognitive engagement was particularly evident in students' abilities to make informed choices, engage in deep thinking, and demonstrate cognitive effort. Activities such as the scientific creativity tasks, IVR explorations, and the 3-2-1 Bridge and RAFT techniques prompted students to set goals, solve complex problems, and apply strategic thinking. During sessions focused on hypothesis development and experimental designs, students exhibited understanding of complex ideas through analysis and reasoning.

Behavioral engagement was reflected in consistent attention and readiness to learn, timely completion of tasks, and active involvement in classroom activities. Students came prepared to class, followed instructions for both in-person and IVR-supported tasks, and demonstrated sustained focus. Time management and adherence to class norms were observed throughout the implementation, indicating high levels of self-discipline and persistence. Emotional engagement emerged strongly during immersive and creative activities. Students expressed excitement, enjoyment, and curiosity during IVR scenes (e.g., climate change scenarios, underwater ecosystems, and renewable energy simulations). Many showed positive emotions such as happiness, enthusiasm, and interest in learning new content. Some activities also fostered empathy, especially when students explored real-world environmental issues such as deforestation, ocean pollution, and access to clean water.

Social engagement was evident through collaborative work, peer interaction, and respectful communication. Students frequently built upon each other's ideas during group discussions, offered help to peers, and participated enthusiastically in cooperative tasks like problem-based learning and group presentations. Teacher-student interaction remained active and supportive across all weeks, further contributing to a socially rich learning environment. Collectively, these observations suggest that the IVR-supported sustainability-focused differentiated science

Table 2. Descriptive Statistics Findings From the Groups' Pre-Test and Post-Test Results.

Pre-test	Group	M	Median	Mode	*SD*	Skewness	Kurtosis
SES	Experimental	127.15	129.50	126.00	10.72	-.690	-.388
	Control	128.68	128.02	125.00	7.84	.381	.233
SSRS	Experimental	84.66	82.50	82.00	12.47	.054	-.072
	Control	88.92	88.50	82.00	7.86	.233	-.429
SCT	Experimental	67.95	63.50	66.00	25.10	-.596	-.263
	Control	59.85	59.85	58.00	11.37	.355	-.199
Post-test	**Group**	**M**	**Median**	**Mode**	***SD***	**Skewness**	**Kurtosis**
SES	Experimental	137.20	138.00	143.00	9.00	-.771	.223
	Control	130.10	130.00	130.00	8.79	-.299	-.596
SSRS	Experimental	102.80	103.00	103.00	13.64	-.422	-.171
	Control	91.60	87.00	90.50	12.34	-.339	.633
SCT	Experimental	87.50	83.50	83.00	24.35	.532	-.574
	Control	69.85	69.00	68.00	11.33	.343	-.219

Table 3. Repeated Measures Two-Factor ANOVA Results.

	Source of Variance	Sum of Squares	*df*	Mean Square	*F*	*p*	η2
SES	Between Groups	2,553.854	39				
	Group (Experimental /Control)	274.770	1	274.770	4.581	.038	.108
	Error	2,279.084	38	59.976			
	Within Groups	5,469.01	40				
	Test (pre-test and post-test)	886.193	1	886.193	8.350	.006	.180
	Group*Test	549.876	1	549.876	5.181	.028	.12
	Error	4,032.941	38	106.130			
	Total	8,022.864	79				
	Source of Variance	**Sum of Squares**	***df***	**Mean Square**	***F***	***p***	**η2**
SSRS	Between Groups	677,054.287	39	677,054.287			
	Group (Experimental /Control)	240.934	1	240.934	2.309	.137	.057
	Error	3,965.649	38	104.359			
	Within Groups	8,330.886	40				
	Test (pre-test and post-test)	2,166.916	1	2,166.916	12.484	.001	.247
	Group*Test	1,194.800	1	1,194.800	6.883	.012	.153
	Error	6,596.011	38	173.579			
	Total	624,160.398	79				
	Source of Variance	**Sum of Squares**	**df**	**Mean Square**	**F**	**p**	**η2**
SCT	Between Groups	4,075,551.250	39	4,075,551.250			
	Group (Experimental / Control)	3,406.050	1	3,406.050	4.648	.037	.109
	Error	27,847.700	38	732.834			
	Within Groups	5,233.0	40				
	Test (pre-test and post-test)	4,470.050	1	4,470.050	622.433	<.001	.942
	Group*Test	490.050	1	490.050	68.237	<.001	.642
	Error	272.900	38	7.182			
	Total	4,080,784.25	79				

instruction created an engaging and immersive learning experience that activated multiple dimensions of student engagement. The integration of interactive tasks, authentic problems, and collaborative structures appeared to foster students' involvement cognitively, behaviorally, emotionally, and socially.

Self-Regulated Learning Skills Utilization in the Experimental Group Students. Analysis of self-assessment forms revealed that students in the experimental group employed a wide range of SRL strategies during the IVR-supported sustainability-focused science instruction. These strategies were

Table 4. Students' Perspectives of IVR-Supported Differentiated Science Instruction.

Category	Code	Source
Cognitive Engagement	Valuing learning	S4
	Utility value	S1
	Ability to make choices	S4, S5
	Understanding mistakes	S3, S4
	Asking questions	S1, S4, S5
	Contributing to discussions	S1, S2, S3, S5
	Exerting mental effort	S1, S2, S3, S4
	Applying deep thinking processes	S1, S2, S3, S4, S5
Behavioral Engagement	Being ready for learning	S3
	Perseverance	S2, S5
	Effort investment	S1, S3
	Maintaining focus	S1, S2
	Adhering to class and VR usage rules	S1, S2, S5
	Staying engaged in the lesson	S1, S2, S3, S4, S5
	Participating in learning activities	S1, S2, S3, S4, S5
	Completing activities	S1, S2, S3, S4, S5
Emotional Engagement	Empathy	S5
	Losing track of time	S4
	Excitement	S2, S3
	Curiosity	S3, S5
	Enjoying learning new things	S1, S2, S3
	Interest	S2, S3, S5
	Looking forward to lessons	S1, S2, S3
	Feeling good	S1, S3, S4, S5
	Happiness	S1, S2, S3, S4, S5
	Fun experience	S1, S2, S3, S4, S5
Social Engagement	Building on others' ideas	S3
	Enjoying working with peers	S2, S4
	Participating in collaborative learning activities	S1, S2, S3, S4, S5
Negative Emotions and Thoughts	Boredom	S2
	Struggling to generate ideas	S2
	Difficulty in teamwork	S3
	Ineffective time management	S2
	Anxiety	S1
	Distraction	S1, S3
	Headache and nausea	S1, S3
	Disliking self-assessment form completion	S2, S3
	Helplessness	S2, S4, S5
Self-regulated Learning Skills	Goal setting	S4
	Rehearsal	S1
	Environmental structuring	S4
	Resource management	S5
	Metacognitive self-regulation	S5
	Help-seeking	S3
	Note-taking	S1, S3
	Planning	S1, S3, S4
	Organizing	S2, S3, S5
	Time management	S2, S3, S4
	Effort regulation	S1, S2, S5
	Critical thinking	S1, S3, S4, S5
	Elaboration	S1, S3, S4, S5

(continued)

Table 4. (continued)

Category	Code	Source
Scientific Creativity	Scientific phenomenon	S3
	Predicting cause and effect	S3
	Elaboration	S4
	Fluency	S2
	Scientific problems	S3, S4
	Motivation and curiosity	S3, S4
	Imagination	S1, S3
	Flexibility	S4, S5
	Originality	S2, S3
	Inspiration for other subjects	S1, S2
	Technical production	S1, S2, S4
	Scientific knowledge	S1, S3, S4
	Thinking	S1, S2, S3, S4, S5
	Creativity-enhancing techniques	S1, S2, S3, S4, S5

categorized into cognitive, metacognitive, behavioral, and motivational components, reflecting a rich pattern of autonomous learning behaviors. Many students reported applying effort regulation and perseverance, especially in challenging or unfamiliar tasks. They showed a sustained effort to complete activities even when they encountered obstacles, such as generating creative solutions or interpreting 3D models.

Peer learning was one of the most frequently observed strategies. Students emphasized the importance of collaboration and mutual support in group-based activities. For instance, in F43, a student stated, "We completed our project as a group. Every member contributed." This quote highlights how students benefited from sharing responsibilities and building upon each other's ideas, a hallmark of socially mediated self-regulation.

Elaboration and knowledge transfer were also prominent. Students extended their understanding by integrating prior knowledge with new concepts across different environmental themes. In F36, one student reflected on this process: "I already knew the importance of clean and renewable energy sources and their necessity. This activity made everything more tangible for me, and many questions arose in my mind, such as how to prevent changes in bird migration routes." This response demonstrates how the instruction supported deeper thinking and cross-contextual reasoning. In addition, many students engaged in critical thinking, applying analytical reasoning to environmental problems. They also displayed goal setting and planning, outlining the steps needed to complete their tasks effectively. For instance, students reported that they began activities with a clear objective and frequently monitored their progress against that goal.

Note-taking, organization, and visualization strategies were commonly used to process and retain complex information, particularly during IVR-based experiences. As described by the student in F87: "After watching the video about wind turbines in the VR environment and entering the turbine, I took notes, sketched its shape, and identified its components. I also labeled them within the VR." This highlights how immersive learning encouraged multimodal engagement with scientific content. Metacognitive self-regulation was evident in students' ability to reflect on their thinking, monitor comprehension, and adjust learning strategies. Many students practiced help-seeking by reaching out to peers or teachers when they encountered confusion or difficulty.

Students also used rehearsal and resource management techniques, such as reviewing learning materials or organizing their physical and digital tools. Time management was crucial throughout the intervention, as students needed to balance individual and group responsibilities within limited instructional periods. Finally, a strong sense of self-efficacy emerged. Students expressed confidence in their ability to learn complex topics, contribute to group work, and solve real-world problems. This motivational aspect of SRL was reinforced by the differentiated and supportive learning environment.

Reflection of Scientific Creativity in Learning Products of the Experimental Group Students. The IVR-supported differentiated instruction meaningfully enhanced students' scientific creativity by fostering deeper engagement in creative processes. Guided by Hu and Adey's (2002) model—covering traits, processes, and products—these experiences enabled gifted students to move beyond conventional thinking often seen in traditional instruction. The defining features of the IVR environment—spatial presence, embodied interaction, and multisensory feedback—each contributed uniquely to enhancing students' ideation and problem-solving capacity during scientific creativity tasks. Spatial presence allowed students to enter and explore vivid simulations of real-world environmental problems. In the Kaz Mountains activity, for example, students transitioned from experiencing a thriving ecosystem to witnessing the aftermath of deforestation and wildfire. This prompted them to imagine future risks, construct analogies between animal vulnerability and human displacement, and propose early-warning rescue systems, all of which indicate engagement in imaginative simulation and problem sensitivity—key components of the process and product domains.

Embodied interaction, such as walking through wind turbines, operating virtual control panels, or navigating submerged coral reefs, enhanced fluency and flexibility. Students explored scientific content physically and spatially, allowing them to generate multiple, diverse ideas from varying stakeholder perspectives. For instance, in the Clean and Renewable Energy activity, students proposed hybrid systems that combined solar and wind power, designed energy solutions tailored for constrained urban environments, and created persuasive arguments assuming the roles of engineers or community leaders. These behaviors reflected higher-order divergent thinking aligned with the trait dimension of scientific creativity.

Multisensory feedback, including realistic soundscapes, voices, animated visuals, and ambient environmental changes, strengthened emotional engagement and supported originality. In Our Changing Oceans, the experience of swimming through vibrant coral ecosystems followed by degraded, acidified waters inspired students to propose innovations such as autonomous underwater drones equipped with pH sensors for early detection. Similarly, in the Clean Water and Sanitation activity, observing waste discharge and simulated water treatment systems led students to conceptualize sensor-based community filtration technologies that addressed both environmental and human health needs.

When compared with traditional instructional approaches such as printed texts, static diagrams, or photo-based discussions, the IVR environments allowed for richer experiential learning. Students were not limited to abstract representations but instead interacted with complex systems in real time, leading to deeper cognitive and affective engagement. This experiential dimension contributed directly to students' ability to identify nuanced problems, simulate possible futures, and develop interdisciplinary, technically feasible solutions. Moreover, students' use of structured creativity techniques such as SCAMPER, RAFT, Fishbone Diagrams, and 3-2-1 Bridge was transformed by the immersive context. Rather than approaching these tasks as routine exercises, students used them to externalize imaginative ideas rooted in vivid, embodied experiences. Invention tasks became more functionally original, written reflections gained complexity and empathy, and brainstorming generated a wider spectrum of relevant, context-driven alternatives.

In sum, the IVR-supported instructional model enhanced not only the outcomes of students' scientific creativity but the very processes through which ideas emerged, evolved, and were evaluated. Through immersive engagement with environmental challenges, students experienced heightened perspective-taking, emotional resonance, and simulation-based reasoning. These affordances allowed gifted learners to fully activate the trait, process, and product dimensions of scientific creativity as conceptualized by Hu and Adey, demonstrating the potential of IVR to transform creativity-centered science education. Examples of learning products are presented in Figure 3.

Discussion

The current study examined the effects of IVR-supported sustainability-focused differentiated science instruction on gifted students. Ten weeks of differentiated instruction were implemented, and pre-/post-tests measured engagement, self-regulated learning, and scientific creativity. Qualitative data supplemented the findings, which were synthesized and discussed in relation to the literature.

Quantitative analysis showed that IVR-supported sustainability-focused differentiated science instruction was associated with greater gains in gifted students' engagement more than the control group. The intervention had a moderate effect size based on pre-/post-test measures. While the control group's post-test scores were higher than pre-test scores, this difference was not statistically significant. However, engagement still improved. Qualitative findings showed that IVR-supported sustainability-focused differentiated science instruction was linked to higher levels of gifted students' engagement more than traditional methods. Students reported cognitive, behavioral, affective, and social engagement, citing deep thinking, task completion, enjoyment, and collaboration. Some faced challenges with self-assessment, teamwork, and repetition. A few experienced mild discomfort during IVR use, indicating mixed perceptions. Analyzing students' behaviors, expressions, discussions, and interactions provided evidence of their cognitive, behavioral, affective, and social engagement. In the IVR-supported sustainability-focused differentiated science instruction, cognitive engagement was reflected in deep thinking, decision-making, and mental effort. Behavioral engagement emerged through rule adherence and active participation. Affective engagement was evident in enthusiasm, enjoyment, and anticipation of lessons. Social engagement was demonstrated through peer interactions, collaboration, and group activities.

Analysis of quantitative and qualitative data indicated that IVR-supported sustainability-focused differentiated science instruction was associated with more favorable outcomes for gifted students' engagement than traditional differentiated instruction. No prior studies were found specifically examining its impact on gifted students. However, the findings align with research on VR/IVR, AR, and XR as Metaverse technologies, which have been linked to engagement-related variables in gifted students (Byeon, 2022; Kim & Kim, 2022; Laurens-Arredondo, 2021; Shim et al., 2000; Tanik Önal & Önal, 2021; Ucar et al., 2017; S. T. Wang et al., 2018). For instance, Ucar et al. (2017) found that gifted middle school students learning chemical bonds through IVR

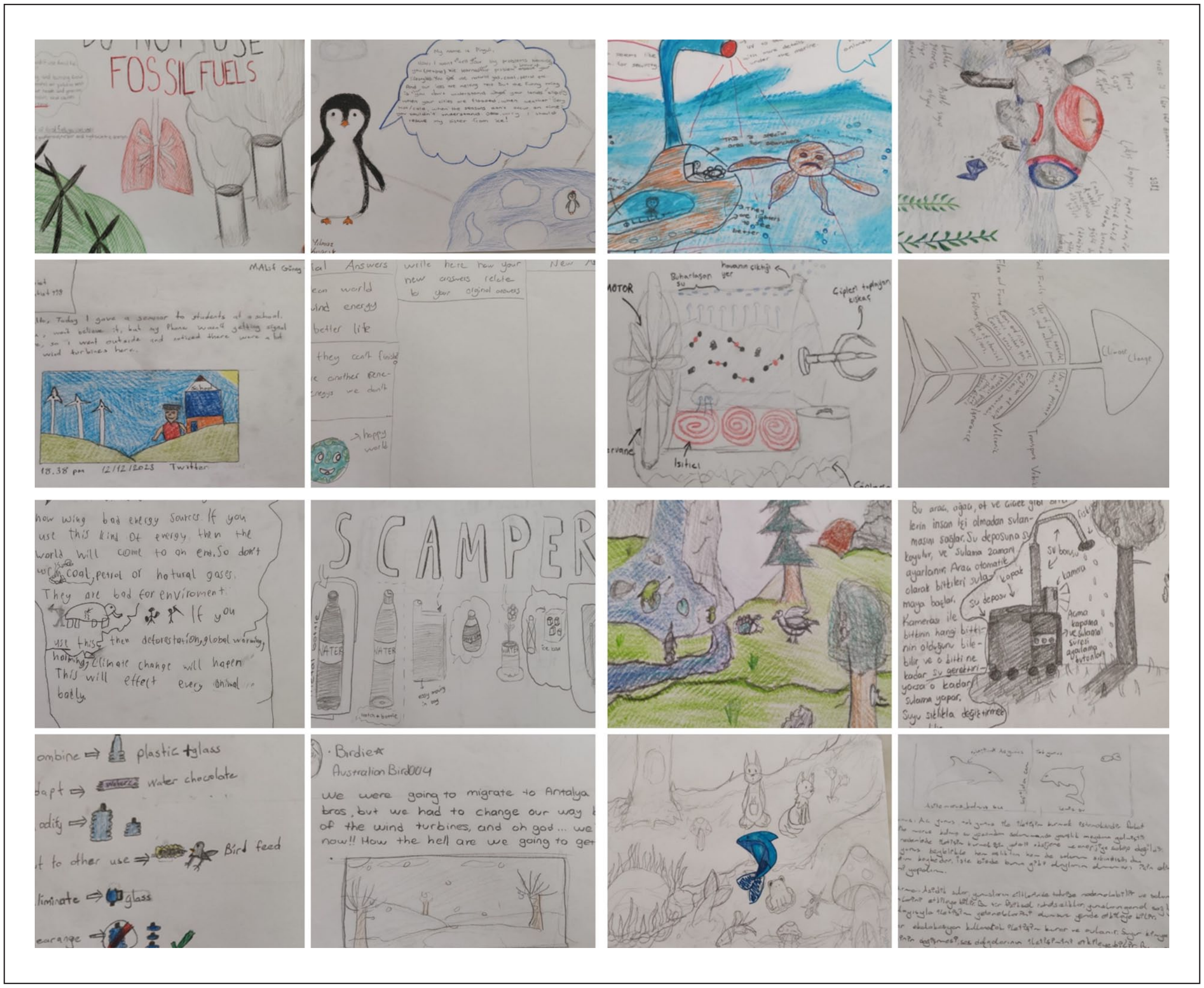

Figure 3. Learning Products.

reported greater interest and positive perceptions, indicating higher affective engagement.

S. T. Wang et al. (2018) found that IVR-based learning enhanced gifted students' motivation, interest, and deep thinking, supporting its impact on cognitive and affective engagement. Similarly, Byeon (2022) reported that a Metaverse-based biology program improved motivation, task commitment, and social interaction of gifted students, aligning with behavioral, affective, and social engagement. Alali and Wardat (2024) highlighted that Metaverse-supported mathematics education with VR and 3D environments fostered interactive and immersive learning, enhancing active participation. These studies reinforce IVR and VR's engagement-enhancing potential. The finding that VR technologies may enhance gifted middle school students' engagement aligns with studies on its effects in typical students across different educational levels (Al-Kfairy et al., 2024; X. Huang et al., 2023; Luo et al., 2024; Makransky & Mayer, 2022; Stenberdt & Makransky, 2023; Villegas-Ch et al., 2024). Papanastasiou et al. (2019) found that VR enhances cognitive engagement, enabling deeper knowledge acquisition. Similarly, Makransky and Lilleholt (2018) reported that IVR improves learning by increasing cognitive effort and task value. These studies highlight VR technologies' positive impact on cognitive engagement.

Y. Chen et al. (2022) and Makransky and Mayer (2022) found that Metaverse and VR enhance learning motivation, enjoyment, and cognitive engagement, aligning with this study's findings. Research also highlights their role in social interaction and collaboration (Grover et al., 2023). Most studies focus on behavioral engagement, underscoring the need for further research on cognitive, affective, and social engagement (Ak et al., 2024; Jalhotra et al., 2024; López-Belmonte et al., 2023; Shi & Park, 2024). Integrating IVR into science education may enhance engagement, academic success, and conceptual understanding, though further research is needed (Saphira et al., 2024). This study contributes by examining IVR-supported sustainability-focused differentiated science instruction's impact on student engagement. Studies show that IVR-based instruction enhances student engagement, aligning with this study's findings. However, Zhang et al. (2023) reported that while VR technologies improved affective engagement, it had no significant effect on cognitive or behavioral engagement, possibly due to differences in pedagogical approaches and implementation (López-Belmonte et al., 2023). Effective use also depends on technological infrastructure and teacher competence (Jalhotra et al., 2024). In addition, two gifted students in this study reported headaches and nausea after IVR use, consistent with Tekel and Yaman (2023), who noted potential health risks alongside Metaverse's educational benefits. Gifted students' hypersensitivity in psychomotor and sensory domains may contribute to these effects, as some experience discomfort due to visual, auditory, or tactile sensitivity. Hein et al. (2023) linked motion sickness susceptibility to dizziness, nausea, and eye strain in IVR. Despite being an advanced technology, Oculus Quest 2, used in this study, may still pose health challenges for some students.

Gifted students in the experimental group experienced 3D scenes on the Imedu Metaverse platform using Oculus Quest 2 IVR headsets. Their greater engagement increase compared to the control group suggests IVR's effectiveness. As the most used Metaverse technology (Lin et al., 2024), IVR differs from VR through immersion, which occurs when users actively engage in tasks (agency), focus on meaning and narrative (cognition), and feel physically or socially present (system; Pedrosa et al., 2023). Well-designed immersive learning environments can enhance cognitive, behavioral, affective, and social engagement (Çiğdem & Öncü, 2023). The current study suggests that the IVR-based 3D scenes on the Imedu platform provided an immersive learning experience, enhancing student engagement. The effectiveness of IVR-supported sustainability-focused differentiated science instruction can be explained through the CAMIL, which highlights the role of immersion, control, and representational fidelity in learning (Petersen et al., 2022). Immersion deepens learning by intensifying responses to stimuli, control factors enhance motivation by allowing interaction, and representational fidelity strengthens presence through realism. These factors influence motivation, self-efficacy, cognitive load, and self-regulated learning, impacting learning outcomes (Makransky & Petersen, 2021). In the current study, IVR experiences included real-world representations (Kaz Mountains, ocean, city, farm), where students could interact, teleport, and navigate scenes using custom avatars. Oculus Quest 2 provided a high-resolution, fast 3D experience. Since the design considered CAMIL's key elements, it likely contributed to enhanced student engagement.

The sense of presence and agency in IVR experiences directly influences student motivation, as greater control and immersion enhance engagement (Makransky & Petersen, 2021). Motivation is a prerequisite for effective engagement (Saeed & Zyngier, 2012), and gifted students require stimulating learning environments to maintain active engagement (Phelps, 2022). Such environments help prevent boredom, disengagement, and underachievement (Kanevsky & Keighley, 2003; Ronksley-Pavia & Neumann, 2020). Providing autonomy and authenticity in instruction enhances gifted students' motivation. Autonomy allows students to control what and how they learn, including topic selection, depth, pace, and intensity (Zimlich, 2016). This fosters higher engagement and achievement (Fakolade & Adeniyi, 2010). Authenticity involves working on real-world projects, creating meaningful products, and presenting them to authentic audiences (Eriksson, 2022). In addition, self-efficacy, challenging tasks, real-life connections, teacher support, and diverse learning options further enhance motivation (Delisle, 2012; Fredricks & McColskey, 2012). Value beliefs also shape motivation (Wigfield & Eccles, 2002). These factors likely influenced gifted students' engagement in the current study.

The differentiated science instruction provided gifted students with autonomy, authenticity, depth, and challenge, fostering peer-teacher interaction and real-world engagement with sustainability and SDGs. Its interdisciplinary nature supports inquiry-driven and creative thinking, enhancing motivation and engagement (Slade, 2021). Both groups received differentiated instruction, as gifted students need tailored approaches (VanTassel-Baska & Wood, 2023). Technology played a key role, with the experimental group's greater improvement attributed to their IVR experience in the Metaverse (J. Chen et al., 2013; Zimlich, 2016).

The current study also examined SRL skills alongside student engagement. Findings revealed that IVR-supported sustainability-focused differentiated science was associated with a significant improvement in gifted students' SRL skills compared to traditional differentiated instruction. While the control group showed improvement, the increase was not statistically significant. Qualitative data from semistructured interviews and self-assessment forms supported these results. Gifted students reported using goal-setting, planning, note-taking, metacognitive regulation, time management, and effort regulation strategies. Self-assessment forms confirmed that experimental group students actively applied SRL strategies, demonstrating persistence, knowledge transfer, visualization, and self-efficacy.

Quantitative and qualitative findings indicate that IVR-supported sustainability-focused differentiated science instruction appeared to effectively support the development of gifted students' SRL skills. No prior studies have specifically examined its impact on gifted students, highlighting this study's unique contribution. However, findings align with research on IVR's and other immersive technologies' role in promoting SRL in typical students (Al-Duhani et al., 2024; Arici, 2024; Y. L. Chen & Hsu, 2020; Jiang et al., 2018; Liu et al., 2023 T. Wang et al., 2024). For instance, Jiang et al. (2018) found that IVR interactions in science education improved SRL skills in middle school students. The current study demonstrated that IVR technologies support SRL skills by promoting deep cognitive processing, effective learning strategies (e.g., note-taking, self-monitoring, resource management), and monitoring of learning processes. Similarly, Y. L. Chen and Hsu (2020) found that VR-based applications enhanced self-efficacy and SRL skills through flow and presence. Al-Duhani et al. (2024) reported that a web-based virtual laboratory was more effective than a physical lab in developing cognitive awareness, effort regulation, peer learning, and time management in eighth-grade students. While Ateş (2024) and Nacaroğlu and Bektaş (2023) showed the impact of flipped learning on SRL skills in both students with typical development and gifted students, these studies, though not directly examining 3D immersive environments, support the effectiveness of technology-based learning in enhancing SRL skills.

Flipped learning typically uses web-based platforms and videos, while Metaverse technologies, including IVR and AR, offer immersive, self-directed, and multi-sensory learning environments that can enhance SRL skills (Arici, 2024; Makransky & Petersen, 2021). Applying SRL strategies in these environments improves learning efficiency, independence, and academic performance (Çiğdem & Öncü, 2023). The current study suggests that IVR technologies effectively support SRL skill development. As research on IVR and SRL is still emerging, further studies are needed to explore their potential in fostering independent learning.

Findings indicate that IVR-supported sustainability-focused differentiated science instruction was associated with a significant enhancement of gifted students' SRL skills, aligning with research on technology-supported learning (Al-Duhani et al., 2024; Y. Chen et al., 2022). However, factors such as cognitive load and individual differences may influence SRL development (T. Wang & Lajoie, 2023). To address these challenges, the learning environment was designed using research-based design principles, reducing distractions and supporting SRL growth (Mayer, 2021). In addition, gifted students' cognitive strengths may have further facilitated their SRL improvements (Lawson & Mayer, 2024). Both groups showed SRL improvement, but IVR's immersive nature likely provided additional benefits. CAMIL suggests that presence and agency in IVR learning enhance motivation, self-efficacy, and SRL (Makransky & Petersen, 2021).

Students completed self-assessment forms after sessions, reflecting on learning, challenges, collaboration, and strategy use, supporting SRL development (Harris & Brown, 2018; He et al., 2024). The differentiated instruction included inquiry-based learning, problem-solving, virtual field trips, and creative thinking, fostering SRL skills (Biswas et al., 2009; Reis, 2021). Constructivist, student-centered approaches further supported autonomous and collaborative learning (W. S. Wang et al., 2024). Explicit SRL strategy instruction and a supportive learning environment helped students set goals, manage resources, reflect, and apply critical thinking, contributing to SRL development across both groups.

The experimental group's gifted students showed greater improvement in scientific creativity, engagement, and SRL skills than the control group, as well as a significant association between the intervention and gains in scientific creativity over time. While the control group also showed notable gains, the IVR-supported instruction was associated with more positive outcomes, supported by qualitative findings. Students reported using scientific creativity dimensions such as process (thinking, imagination), traits (fluency, flexibility, originality), and products (technical production, scientific knowledge, problem-solving). They also noted increased motivation, curiosity, and benefits from creative thinking techniques, enhancing their cause–effect reasoning skills. The analysis revealed that differentiated instruction activities effectively fostered gifted students' scientific creativity across traits (fluency, flexibility, originality), processes (analysis, synthesis, imagination), and products (innovation, problem-solving), as demonstrated by their creative solutions to environmental issues, interdisciplinary projects, and sustainable innovation proposals using techniques like 3-2-1 Bridge, RAFT, SCAMPER, and problem-based learning.

Findings indicate that IVR-supported sustainability-focused differentiated science instruction was associated with significant gains in gifted students' scientific creativity, aligning with research on immersive technologies and creativity (Barabanschikov & Selivanov, 2022; S. J. Chen et al., 2024). While no prior studies specifically examined its impact on gifted students, results are consistent with research on Metaverse technologies improving fluency, originality, and problem-solving (Bourgeois-Bougrine et al., 2020; Nanjappan et al., 2023). Studies suggest that IVR can enhance creativity through immersion, interactivity, and presence, which may foster motivation, collaboration, and problem-solving (Gong & Georgiev, 2020; Thornhill-Miller & Dupont, 2016). In the current study, exploratory, task-based, and inquiry-driven approaches likely contributed to scientific creativity development (W. S. Wang et al., 2024). Both experimental and control groups showed significant creativity gains, emphasizing the importance of tailored instructional strategies for gifted students (Mukhopadhyay & Sen, 2013). The integration of inquiry-based learning, SCAMPER, RAFT, and problem-based approaches provided opportunities for scientific exploration and innovation (Akhan et al., 2022; Washington & Andersen, 2016). In addition, working on sustainability-related topics may have increased motivation, further enhancing creativity (Schroth & Helfer, 2017).

The immersive nature of IVR appeared to uniquely contribute to the development of scientific creativity. Spatial presence helped students engage with environmental problems, supporting problem identification and imagination (Araiza-Alba et al., 2021; Yu & Wang, 2025). Embodied interaction fostered fluency and flexibility through kinesthetic exploration (Bagher et al., 2021; Frith et al., 2020). Multisensory feedback boosted originality and emotional engagement, enabling meaningful and creative connections (Andonova et al., 2023; H. T. Huang & Chang, 2023). These features collectively supported innovative, grounded, and personally relevant solutions in sustainability education.

In interpreting the study findings, it is essential to acknowledge the potential influence of novelty effects associated with IVR technologies. Although the instructional design ensured equivalency between the experimental and control groups in terms of content, duration, and assessment tools, the novelty of the IVR modality might have contributed to heightened engagement and creative performance. Previous research has shown that users tend to focus more on the technology itself during initial encounters, which can limit its educational value unless familiarization is provided beforehand (Miguel-Alonso et al., 2024). In our study, a structured pre-training session on using the Oculus Quest 2 headset was included in Week 1, as shown in Table 1. This familiarization phase aimed to reduce potential novelty effects by ensuring students became comfortable with the IVR equipment before engaging with content-related activities. Nevertheless, as the intervention lacked a crossover or delayed-treatment phase, distinguishing the specific contribution of IVR from residual novelty or expectancy effects remains a limitation. Consequently, the results should be framed as preliminary and exploratory, offering foundational insights for more rigorously controlled future studies.

This study presents several limitations. First, the lack of a crossover or delayed-treatment design constrains the ability to isolate the specific effects of IVR from novelty or expectancy-related influences. Second, the study did not include direct measures of academic achievement such as curriculum-aligned science concept tests, limiting conclusions about instructional effectiveness. Third, the qualitative strand was limited to five students from the experimental group. These students were purposefully selected to represent a range of engagement levels—low, medium, and high scores on the SES. However, the absence of systematically collected qualitative data from the control group restricted deeper process-based comparisons between groups. To mitigate this limitation, both groups followed the same thematic content, learning objectives, assessment tools, and creative tasks, which helps support the validity of observed differences. Nonetheless, the lack of control group perspectives, combined with the exclusion of teacher interviews, restricted the breadth and balance of qualitative insights.

Future research should adopt more rigorous experimental designs, such as crossover or within-subject frameworks, to differentiate the effects of IVR from novelty-induced gains. Including curriculum-based science achievement tests or embedding performance assessments within IVR environments would enhance the alignment between instruction and measured learning outcomes. Expanding the qualitative strand to incorporate control group students, individuals with neutral or negative IVR experiences, and teacher perspectives will provide a more holistic understanding of instructional impact. In addition, longitudinal research should explore the persistence of IVR's effects beyond initial exposure, and comparative studies should evaluate IVR against other interactive technologies such as 360° video or other technology-enhanced methods.

Conclusion

This study offers an innovative contribution to gifted education by integrating IVR with sustainability-focused, differentiated science instruction. It highlights the potential of IVR environments to foster engagement, enhance self-regulated learning, and stimulate scientific creativity in gifted learners. The promising outcomes suggest that IVR can act as both an engaging instructional medium and a catalyst for deeper cognitive and affective development. However, the absence of academic outcome measures and a crossover design limits causal claims. Thus, the findings should be viewed as exploratory yet encouraging, warranting future research with stronger experimental controls.

Authors' Note

This research was produced from the doctoral dissertation of the first author.

Acknowledgments

We thank the gifted students and BİLSEM administrators.

ORCID iDs

Yunus Emre Avcu https://orcid.org/0000-0001-8286-0837
Yavuz Yaman https://orcid.org/0000-0002-4837-9959

Ethical Considerations

Ethical approval for this study was obtained from the Istanbul University-Cerrahpasa Social and Humanities Research Ethics Committee (approval no. 2023/374) on November 23, 2023.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Open Science Disclosure Statement

The data analyzed in this study are available upon request for purposes of reproducing the results. The code or protocol used to generate the findings reported in the article is available upon request for purposes of reproducing the results or replicating the study. The following newly created, unique materials used to conduct the research are available upon request for purposes of replicating the procedure: The IVR-Supported Sustainability-Focused Differentiated Science Instructional Design.

Artificial Intelligence Use

The authors confirm that no generative AI tools were used in the development of this article.

References

Ak, O., Şen Akbulut, M., Soydan, S., & Yildirim, E. (2024). Designing educational metaverses: A literature review to determine guidelines. *Interactive Learning Environments*. Advance online publication. https://doi.org/10.1080/10494820.2024.2365956

Akhan, N. E., Çiçek, S., & Kocaağa, G. (2022). Critical and creative perspectives of gifted students on global problems: Global climate change. *Thinking Skills and Creativity*, *46*, Article 101131. https://doi.org/10.1016/j.tsc.2022.101131

Alali, R., & Wardat, Y. (2024). Assessing the utilization level of Metaverse: Teaching mathematics at the primary level. *International Journal of Distance Education Technologies*, *22*(1), 1–19. https://doi.org/10.4018/IJDET.346988

Al-Duhani, F., Saat, R. M., & Abdullah, M. N. S. (2024). Effectiveness of web-based virtual laboratory on grade eight students' self-regulated learning. *Eurasia Journal of Mathematics, Science and Technology Education*, *20*(3), Article em2410. https://doi.org/10.29333/ejmste/14282

Al-Kfairy, M., Alzaabi, M., Snoh, B., Almarzooqi, H., & Alnaqbi, W. (2024, May). Metaverse-based classroom: The good and the bad. In *2024 IEEE Global Engineering Education Conference (EDUCON)* (pp. 1–7). IEEE.

Andonova, V., Reinoso-Carvalho, F., Jimenez Ramirez, M. A., & Carrasquilla, D. (2023). Does multisensory stimulation with virtual reality (VR) and smell improve learning? An educational experience in recall and creativity. *Frontiers in Psychology*, *14*, Article 1176697. https://doi.org/10.3389/fpsyg.2023.1176697

Araiza-Alba, P., Keane, T., Chen, W. S., & Kaufman, J. (2021). Immersive virtual reality as a tool to learn problem-solving skills. *Computers & Education*, *164*, Article 104121. https://doi.org/10.1016/j.compedu.2020.104121

Arici, F. (2024). Investigating the effectiveness of augmented reality technology in science education in terms of environmental literacy, self-regulation, and motivation to learn science. *International Journal of Human–Computer Interaction*. Advance online publication. https://doi.org/10.1080/10447318.2024.2310921

Ateş, H. (2024). Designing a self-regulated flipped learning approach to promote students' science learning performance. *Educational Technology & Society*, *27*(1), 65–83. https://www.jstor.org/stable/48754842

Ayverdi, L., Asker, E., Aydın, S. Ö., & Sarıtaş, T. (2012). Determination of the relationship between elementary students' scientific creativity and academic achievement in science and technology courses. *Elementary Education Online*, *11*(3), 646–659.

Ayverdi, L., & Öz Aydın, S. (2022). The effects of instructional design based on the STEM approach on the teaching process of training of gifted secondary school students. *Hacettepe University Journal of Education*, *37*(1), 254–273. https://doi.org/10.16986/HUJE.2020062717

Azevedo, R. (2008). The role of self-regulation in learning about science with hypermedia. In D. Robinson & G. Schraw (Eds.), *Recent innovations in educational technology that facilitate student learning* (pp. 127–156). Information Age.

Bagher, M. M., Sajjadi, P., Wallgrün, J. O., La Femina, P. C., & Klippel, A. (2021). Move the object or move the user: The role of interaction techniques on embodied learning in VR. *Frontiers in Virtual Reality*, *2*, Article 695312. https://doi.org/10.3389/frvir.2021.695312

Barabanschikov, V. A., & Selivanov, V. V. (2022). In a didactic VR environment of various immersiveness. *Experimental Psychology (Russia)*, *15*(2), 4–19. https://doi.org/10.17759/exppsy.2022150201

Betts, G., & Kercher, J. (2009). Autonomous learner. *Encyclopedia of Giftedness, Creativity, and Talent*, *1*, 83–84.

Biswas, G., Roscoe, R., Jeong, H., & Sulcer, B. (2009, December). Promoting self-regulated learning skills in agent-based learning environments. In *Proceedings of the 17th international conference on computers in education* (pp. 67–74). Asia-Pacific Society for Computers in Education.

Bonnardel, N., & Pichot, N. (2020). Enhancing collaborative creativity with virtual dynamic personas. *Applied Ergonomics*, *82*, Article 102949. https://doi.org/10.1016/j.apergo.2019.102949

Bourgeois-Bougrine, S., Richard, P., Burkhardt, J. M., Frantz, B., & Lubart, T. (2020). The expression of users' creative potential in virtual and real environments: An exploratory study. In *Creative learning in digital and virtual environments* (pp. 96–117). Routledge.

Büyüköztürk, Ş. (2014). *Sosyal bilimler için veri analizi el kitabı istatistik, araştırma deseni, SPSS uygulamaları ve yorum* [Data analysis handbook for social sciences—Statistics, research design, SPSS applications and interpretation]. Pegem Akademi.

Büyüköztürk, Ş., Akgün, Ö. E., Demirel, F., Karadeniz, Ş., & Çakmak, E. K. (2022). *Bilimsel araştırma yöntemleri* [Scientific research methods]. Pegem Akademi.

Byeon, J. (2022). The effect of biology inquiry program using metaverse platform on the affective field of elementary science gifted student. *Korean Association for Learner-Centered Curriculum and Instruction*, *22*(13), 641–657. https://doi.org/10.22251/jlcci.2022.22.13.641

Ceja Salgado, O. (2022). *Embodied learning in immersive virtual reality: The role of sensory-motor affordances in shaping conceptual and procedural understandings* [Doctoral dissertation, University College London]. UCL Discovery. https://discovery.ucl.ac.uk/id/eprint/10157845/

Chandler, K. L. (2012). Science curriculum for the gifted: Innovations for meeting student needs. *Journal of Science Education in Japan*, *36*(2), 113–121. https://doi.org/10.14935/jssej.36.113

Chang, Y. S., Chou, C. H., Chuang, M. J., Li, W. H., & Tsai, I. F. (2023). Effects of virtual reality on creative design performance and creative experiential learning. *Interactive Learning Environments*, *31*(2), 1142–1157. https://doi.org/10.1080/10494820.2020.1821717

Chen, J., Yun Dai, D., & Zhou, Y. (2013). Enable, enhance, and transform: How technology use can improve gifted education. *Roeper Review*, *35*(3), 166–176. https://doi.org/10.1080/02783193.2013.794892

Chen, S. J., Chen, C. Q., & Shan, X. F. (2024). The effects of an immersive virtual-reality-based 3D modeling approach on the creativity and problem-solving tendency of elementary school students. *Sustainability*, *16*(10), Article 4092. https://doi.org/10.3390/su16104092

Chen, Y., Lin, W., Zheng, Y., Xue, T., Chen, C., & Chen, G. (2022). Application of active learning strategies in metaverse to improve student engagement: An immersive blended pedagogy bridging patient care and scientific inquiry in pandemic. *SSRN Electronic Journal*. Advance online publication. https://doi.org/10.2139/ssrn.4098179

Chen, Y. L., & Hsu, C. C. (2020). Self-regulated mobile game-based English learning in a virtual reality environment. *Computers & Education*, *154*, Article 103910. https://doi.org/10.1016/j.compedu.2020.103910

Çiğdem, H., & Öncü, S. (2023). Learner engagement in the metaverse: A community of inquiry for self-regulated learners. In G. Durak & S. Cankaya (Eds.), *Shaping the future of online learning: Education in the Metaverse* (pp. 17–36). IGI Global.

Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and Psychological Measurement*, *33*(1), 107–112. https://doi.org/10.1177/001316447303300111

Cooper, G., Thong, L. P., & Tang, K. S. (2024). Transforming science education with virtual reality: An immersive representations model. *Educational Media International*, *61*(3), 229–251. https://doi.org/10.1080/09523987.2024.2389348

Corral, C. S., Maier, M. I., & Argus-Calvo, B. (2023). Developing imagination and creativity in a music and arts-based program. *Journal of Management, Spirituality & Religion*, *20*(2), 143–162. https://doi.org/10.51327/mqpr5605

Cotabish, A., Dailey, D., Miller, R., Coxon, S. V., & Adams, C. M. (2021). The next generation science standards and high-ability learners. In J. Danielian, C. M. Fugate, & E. Fogarty (Eds.), *Teaching gifted children* (pp. 275–282). Routledge.

Creswell, J. W. (2021). *A concise introduction to mixed methods research*. Sage.

Delisle, J. R. (2012). Reaching those we teach: The five Cs of student engagement. *Gifted Child Today*, *35*(1), 62–67. https://doi.org/10.1177/1076217511427513

Dhahri, S., & Omri, A. (2018). Entrepreneurship contribution to the three pillars of sustainable development: What does the evidence really say? *World Development*, *106*, 64–77. https://doi.org/10.1016/j.worlddev.2018.01.008

Efklides, A. (2019). Gifted students and self-regulated learning: The MASRL model and its implications for SRL. *High Ability Studies*, *30*(1–2), 79–102. https://doi.org/10.1080/13598139.2018.1556069

Elme, L., Jørgensen, M. L., Dandanell, G., Mottelson, A., & Makransky, G. (2022). Immersive virtual reality in STEM: Is IVR an effective learning medium and does adding self-explanation after a lesson improve learning outcomes? *Educational Technology Research and Development*, *70*(5), 1601–1626. https://10.1007/s11423-022-10139-3

Eriksson, G. (2022). Pretense or belief: Creating meaningful scenarios and simulations for authentic learning about diverse underserved gifted students. *Education Sciences*, *12*(8), Article 532. https://doi.org/10.3390/educsci12080532

Fakhriyah, F., Masfuah, S., Roysa, M., Rusilowati, A., & Rahayu, E. S. (2017). Student's science literacy in the aspect of content science? *Journal Pendidikan IPA Indonesia*, *6*(1), 81–87. https://doi.org/10.15294/jpii.v6i1.7245

Fakolade, O. A., & Adeniyi, S. O. (2010). Efficacy of enrichment triad and self-direct models on academic achievement of gifted students in selected secondary schools in Nigeria. *International Journal of Special Education*, *25*(1), 10–16.

Fauville, G., Queiroz, A. C. M., & Bailenson, J. N. (2020). Virtual reality as a promising tool to promote climate change awareness. *Technology and Health*, *2020*, 91–108. https://doi.org/10.1016/B978-0-12-816958-2.00005-8

Fredricks, J. A., & McColskey, W. (2012). The measurement of student engagement: A comparative analysis of various methods and student self-report instruments. In S. L. Christenson, A. L. Reschly, & C. Wylie (Eds.), *Handbook of research on student engagement* (pp. 763–782). Springer US.

Frith, E., Miller, S., & Loprinzi, P. D. (2020). A review of experimental research on embodied creativity: Revisiting the mind–body connection. *The Journal of Creative Behavior*, *54*(4), 767–798. https://doi.org/10.1002/jocb.406

Gallagher, S. (2021). Guiding gifted students toward science expertise. In F. Dixon & T. Kettler (Eds.), *The handbook of secondary gifted education* (2nd ed., pp. 333–366). Routledge.

George, D., & Mallery, M. (2010). *SPSS for Windows step by step: A simple guide and reference, version 17.0 update* (10th ed.). Pearson.

Gibbs, R., & Poskitt, J. (2010). *Student engagement in the middle years of schooling (years 7–10): A report to the Ministry of Education*. Ministry of Education.

Gong, Z., & Georgiev, G. V. (2020). Literature review: Existing methods using VR to enhance creativity. In J.-F. Boujut, G. Cascini, S. Ahmed-Kristensen, G. V. Georgiev, & N. Iivari (Eds.), *Proceedings of the sixth international conference on design creativity (ICDC 2020)* (pp. 117–124). The Design Society. https://doi.org/10.35199/ICDC.2020.15

Gong, Z., Lee, L. H., Soomro, S. A., Nanjappan, V., & Georgiev, G. V. (2022). A systematic review of virtual brainstorming from the perspective of creativity: Affordances, framework, and outlook. *Digital Creativity*, *33*(2), 96–127. https://doi.org/10.1080/14626268.2022.2064879

Gorski, A. T., Ranf, E. D., Badea, D., Halmaghi, E. E., & Gorski, H. (2023). Education for sustainability—Some bibliometric insights. *Sustainability*, *15*(20), Article 14916. https://doi.org/10.3390/su152014916

Grover, P., Phutela, N., & Guess, W. (2023). Metaverse and students engagement—Instructors' perspective. In *2023 IEEE Pune Section International Conference (PuneCon)* (pp. 1–6). IEEE. https://doi.org/10.1109/PuneCon58714.2023.10450138

Harris, L. R., & Brown, G. T. (2018). *Using self-assessment to improve student learning*. Routledge.

He, S., Epp, C. D., Chen, F., & Cui, Y. (2024). Examining change in students' self-regulated learning patterns after a formative assessment using process mining techniques. *Computers in Human Behavior*, *152*, Article 108061. https://doi.org/10.1016/j.chb.2023.108061

Hein, O., Rauschnabel, P., Hassib, M., & Alt, F. (2023, August). Sick in the car, sick in VR? Understanding how real-world susceptibility to dizziness, nausea, and eye strain influences VR motion sickness. In J. Abdelnour Nocera, M. K. Lárusdóttir, H. Petrie, A. Piccinno, & M. Winckler (Eds.), *Human—computer interaction—INTERACT 2023* (Lecture Notes in Computer Science, Vol. 14143, pp. 552–573). Springer. https://doi.org/10.1007/978-3-031-42283-6_30

Housand, A., & Reis, S. M. (2008). Self-regulated learning in reading: Gifted pedagogy and instructional settings. *Journal of Advanced Academics*, *20*(1), 108–136. https://doi.org/10.4219/jaa-2008-865

Hu, W., & Adey, P. (2002). A scientific creativity test for secondary school students. *International Journal of Science Education*, *24*(4), 389–403. https://doi.org/10.1080/09500690110098912

Huang, H. T., & Chang, Y. S. (2023). Effects of virtual reality on creative performance and emotions: A study of brainwaves. *Computers in Human Behavior*, *146*, Article 107815. https://doi.org/10.1016/j.chb.2023.107815

Huang, X., Huss, J., North, L., Williams, K., & Boyd-Devine, A. (2023). Cognitive and motivational benefits of a theory-based immersive virtual reality design in science learning. *Computers and Education Open*, *4*, Article 100124. https://doi.org/10.1016/j.caeo.2023.100124

Ichimura, K. (2023). Effects of virtual reality's viewing medium and the environment's spatial openness on divergent thinking. *PLOS ONE*, *18*(3), Article e0283632. https://doi.org/10.1371/journal.pone.0283632

Jalhotra, A., Sharma, S., Dev Sharma, S., Pathak, A., & Lande, A. (2024). Application of metaverse in education. In *2024 IEEE 1st Karachi Section Humanitarian Technology Conference (Khi-HTC)* (pp. 1–6). IEEE. https://doi.org/10.1109/KHI-HTC60760.2024.10482118

Jiang, Y., Clarke-Midura, J., Baker, R. S., Paquette, L., & Keller, B. (2018). How immersive virtual environments foster self-regulated learning. In R. Zheng (Ed.), *Digital technologies and instructional design for personalized learning* (pp. 28–54). IGI Global.

Johnson, G., & Davies, S. (2014). Self-regulated learning in digital environments: Theory, research, praxis. *British Journal of Research*, *1*(2), 1–14.

Johnson, N. (2012). Examining self regulated learning in relation to certain selected variables. *Acta Didactica Napocensia*, *5*(3), 1–12.

Kanevsky, L., & Keighley, T. (2003). To produce or not to produce? Understanding boredom and the honor in underachievement. *Roeper Review*, *26*(1), 20–28. https://doi.org/10.1080/02783190309554235

Kim, E. J., & Kim, H. K. (2022). The effect of science class using smart devices on the perceptions and scientific attitude of middle school gifted students. *Journal of the Korean Chemical Society*, *66*(4), 323–332. https://doi.org/10.5012/jkcs.2022.66.4.323

Landis, R. N., & Reschly, A. L. (2013). Reexamining gifted underachievement and dropout through the lens of student engagement. *Journal for the Education of the Gifted*, *36*(2), 220–249. https://doi.org/10.1177/0162353213480864

Laurens-Arredondo, L. (2021, November). Mobile augmented reality adapted to the Gentry-Gable motivation model: An experience of gifted students. In *2021 40th International Conference of the Chilean Computer Science Society (SCCC)* (pp. 1–8). IEEE. https://doi.org/10.1109/SCCC54552.2021.9650370

Lawson, A. P., & Mayer, R. E. (2024). Individual differences in executive function affect learning with immersive virtual reality. *Journal of Computer Assisted Learning*, *40*(3), 1068–1082. https://doi.org/10.1111/jcal.12925

Lin, X. P., Li, B. B., Yao, Z. N., Yang, Z., & Zhang, M. (2024). The impact of virtual reality on student engagement in the classroom—A critical review of the literature. *Frontiers in Psychology*, *15*, Article 1360574. https://doi.org/10.3389/fpsyg.2024.1360574

Liu, Z., Yu, P., Liu, J., Pi, Z., & Cui, W. (2023). How do students' self-regulation skills affect learning satisfaction and continuous intention within desktop-based virtual reality? A structural equation modelling approach. *British Journal of Educational Technology*, *54*(3), 667–685. https://doi.org/10.1111/bjet.13278

López-Belmonte, J., Pozo-Sánchez, S., Moreno-Guerrero, A. J., & Lampropoulos, G. (2023). Metaverse in education: A systematic review. *Revista de Educación a Distancia*, *23*(73), 1–25. https://doi.org/10.6018/red.511421

Luo, H., Li, X., Zhang, J., Zhang, F., Liang, J., & Yin, X. (2024). July). Metaverse improves the learning experiences rather than learning outcomes: Evidence from an experimental study in higher education. In *2024 International Symposium on Educational Technology (ISET)* (pp. 217–222). IEEE. https://doi.org/10.1109/ISET61814.2024.00050

Makransky, G., & Lilleholt, L. (2018). A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development*, *66*(5), 1141–1164.

Makransky, G., & Mayer, R. E. (2022). Benefits of taking a virtual field trip in immersive virtual reality: Evidence for the immersion principle in multimedia learning. *Educational Psychology Review*, *34*(3), 1771–1798. https://doi.org/10.1007/s10648-022-09675-4

Makransky, G., & Petersen, G. B. (2021). The cognitive affective model of immersive learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review*, *33*(3), 937–958. https://doi.org/10.1007/s10648-020-09586-2

Malinin, L. H. (2019). How radical is embodied creativity? Implications of 4E approaches for creativity research and teaching. *Frontiers in Psychology*, *10*, Article 2372. https://doi.org/10.3389/fpsyg.2019.02372

Markowitz, D. M., & Bailenson, J. N. (2021). Virtual reality and the psychology of climate change. *Current Opinion in Psychology*, *42*, 60–65. https://doi.org/10.1016/j.copsyc.2021.03.009

Marzetta, K., Mason, H., & Wee, B. (2018). 'Sometimes they are fun and sometimes they are not': Concept mapping with English Language Acquisition (ELA) and Gifted/Talented (GT) elementary students learning science and sustainability. *Education Sciences*, *8*(1), Article 13. https://doi.org/10.3390/educsci8010013

Matovu, H., Ungu, D. A. K., Won, M., Tsai, C. C., Treagust, D. F., Mocerino, M., & Tasker, R. (2023). Immersive virtual reality for science learning: Design, implementation, and evaluation. *Studies in Science Education*, *59*(2), 205–244. https://doi.org/10.1080/03057267.2022.2082680

Matthews, M. S. (2021). Science curriculum for gifted learners. In K. R. Stephens & F. A. Karnes (Eds.), *Introduction to curriculum design in gifted education* (pp. 175–193). Routledge.

Mayer, R. E. (2014). Cognitive theory of multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 43–71). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.005

Mayer, R. E. (2021). Cognitive theory of multimedia learning. In R. E. Mayer & L. Fiorella (Eds.), *The Cambridge handbook of multimedia learning* (pp. 57–72). Cambridge University Press.

Miguel-Alonso, I., Checa, D., Guillen-Sanz, H., & Bustillo, A. (2024). Evaluation of the novelty effect in immersive virtual reality learning experiences. *Virtual Reality*, *28*(1), Article 27. https://doi.org/10.1007/s10055-023-00926-5

Ministry of National Education. (2024). *BILSEM guideline* (Guideline No. 64832509). https://umraniyebilimvesanatmerkezi.meb.k12.tr/meb_iys_dosyalar/34/21/765047/dosyalar/2024_02/02140122_bilsemyonergesi.pdf?CHK=112ddab0c70ca7d3675cfeb13f54fea

Mukhopadhyay, R., & Sen, M. K. (2013). Scientific creativity: A new emerging field of research: Some considerations. *International Journal of Education and Psychological Research*, *2*(1), 1–9.

Mutlu, F., & Nacaroglu, O. (2019). Examination of perceptions of gifted students about climate change and global warming. *Journal of Baltic Science Education*, *18*(5), 780–192.

Nacaroğlu, O., & Bektaş, O. (2023). The effect of the flipped classroom model on gifted students' self-regulation skills and academic achievement. *Thinking Skills and Creativity*, *47*, Article 101244. https://doi.org/10.1016/j.tsc.2023.101244

Nanjappan, V., Uunila, A., Vaulanen, J., Välimaa, J., & Georgiev, G. V. (2023). Effects of immersive virtual reality in enhancing creativity. *Proceedings of the Design Society*, *3*, 1585–1594. https://doi.org/10.1017/pds.2023.159

Oppong, E., Shore, B. M., & Muis, K. R. (2019). Clarifying the connections among giftedness, metacognition, self-regulation, and self-regulated learning: Implications for theory and practice. *Gifted Child Quarterly*, *63*(2), 102–119. https://doi.org/10.1177/0016986218814008

Özarslan, M. (2022). Environmental problems according to the gifted and talented students and their solution proposals: A qualitative research. *International Journal of New Trends in Arts, Sports & Science Education (IJTASE)*, *11*(4), 201–216.

Palombi, T., Galli, F., Giancamilli, F., D'Amico, M., Alivernini, F., Gallo, L., Neroni, P., Predazzi, M., De Pietro, G., Lucidi, F., Giordano, A., & Chirico, A. (2023). The role of sense of presence in expressing cognitive abilities in a virtual reality task: An initial validation study. *Scientific Reports*, *13*(1), Article 13396. https://doi.org/10.1038/s41598-023-40510-0

Papanastasiou, G., Drigas, A., Skianis, C., Lytras, M., & Papanastasiou, E. (2019). Virtual and augmented reality effects on K-12, higher and tertiary education students' twenty-first century skills. *Virtual Reality*, *23*(4), 425–436. https://doi.org/10.1007/s10055-018-0363-2

Park, J. (2010, June). Practical ways for teaching and evaluating scientific creativity. In *Proceedings of the XIV IOSTE Symposium: Socio-Cultural and Human Values in Science and Technology Education* (pp. 1–16). International Organization for Science and Technology Education.

Paz-Baruch, N., & Hazema, H. (2023). Self-regulated learning and motivation among gifted and high-achieving students in science, technology, engineering, and mathematics disciplines: Examining differences between students from diverse socioeconomic levels. *Journal for the Education of the Gifted*, *46*(1), 34–76. https://doi.org/10.1177/01623532221143825

Pedrosa, D., Morgado, L., & Beck, D. (2023). June). Immersive learning environments for self-regulation of learning: A literature review. In *International Conference on Immersive Learning* (pp. 497–511). Springer Nature.

Petersen, G. B., Petkakis, G., & Makransky, G. (2022). A study of how immersion and interactivity drive VR learning. *Computers & Education*, *179*, Article 104429. https://doi.org/10.1016/j.compedu.2021.104429

Phelps, V. (2022). *Successful online learning with gifted students: Designing online and blended lessons for gifted and advanced learners in grades 5–8*. Routledge.

Plass, J. L., Hovey, C., Saurina Maso, A., Fröhlich, F., Ghosh, S., Olsen, A., & Perlin, K. (2022). Designing effective immersive VR learning experiences. In *Proceedings of the 8th International Conference of the Immersive Learning Research Network (iLRN2022) Practitioner Proceedings*. Immersive Learning Research Network. https://doi.org/10.56198/A6PFY1CBT

Reis, I. W., Romeiro, A. E., Berg, C. H., & Ulbricht, V. R. (2024). Sociodigital experiences and creativity in the metaverse: An integrative review. *Heliyon*, *10*(7), Article e29047. https://doi.org/10.1016/j.heliyon.2024.e29047

Reis, S. M. (2021). Self-regulated learning and academically talented students. In J. L. Jolly, D. J. Treffinger, T. F. Inman, & J. F. Smutny (Eds.), *Parenting gifted children* (pp. 42–52). Routledge.

Ronksley-Pavia, M., & Neumann, M. M. (2020). Conceptualising gifted student (dis) engagement through the lens of learner (re) engagement. *Education Sciences*, *10*(10), Article 274. https://doi.org/10.3390/educsci10100274

Root-Bernstein, R. S., & Root-Bernstein, M. (2001). *Sparks of genius: The thirteen thinking tools of the world's most creative people*. Houghton Mifflin Harcourt.

Saeed, S., & Zyngier, D. (2012). How motivation influences student engagement: A qualitative case study. *Journal of Education and Learning*, *1*(2), 252–267. https://doi.org/10.5539/jel.v1n2p252

Sakdavong, J. C., Burgues, M., & Huet, N. (2019). May). Virtual reality in self-regulated learning: Example in art domain. In H. C. Lane, S. Zvacek, & J. Uhomoibhi (Eds.), *Proceedings of the 11th International Conference on Computer Supported Education (CSEDU 2019)* (Vol. 2, pp. 79–87). SciTePress. https://doi.org/10.5220/0007718500790087

Saphira, H. V., Prahani, B. K., Hariyono, E., & Marianus. (2024). Metaverse: A paradigm shift in STEM education for science learning beyond the review. *E3S Web of Conferences*, *482*, Article 04004. https://doi.org/10.1051/e3sconf/202448204004

Schroth, S. T., & Helfer, J. A. (2017). Gifted & green: Sustainability/environmental science investigations that promote gifted children's learning. *Gifted Child Today*, *40*(1), 14–28. https://doi.org/10.1177/1076217516675903

Scurati, G. W., Bertoni, M., Graziosi, S., & Ferrise, F. (2021). Exploring the use of virtual reality to support environmentally sustainable behavior: A framework to design experiences.

Sustainability, *13*(2), Article 943. https://doi.org/10.3390/su13020943
Shi, C., & Park, J. Y. (2024). A systematic review of the metaverse in formal education. *Journal of Applied Research in Higher Education*, *16*(5), 1–19. https://doi.org/10.1108/JARHE-04-2024-0162
Shim, K. C., Kim, H. S., & Park, Y. C. (2000). Science education and virtual reality. In *Application of multi-media in biology education, summer program of Korean Society of Biology Education* (pp. 25–37). Korean Society of Biology Education.
Sidek, R., Halim, L., Buang, N. A., & Arsad, N. M. (2020). Fostering scientific creativity in teaching and learning science in schools: A systematic review. *Jurnal Penelitian dan Pembelajaran IPA*, *6*(1), 13–35.
Sisk, D. A. (2009). *Making great kids greater: Easing the burden of being gifted*. Corwin Press.
Skinner, E. A., Kindermann, T. A., & Furrer, C. J. (2009). A motivational perspective on engagement and disaffection: Conceptualization and assessment of children's behavioral and emotional participation in academic activities in the classroom. *Educational and Psychological Measurement*, *69*(3), 493–525. https://doi.org/10.1177/0013164408323233
Slade, M. L. (2021). Global citizenship as a means for teaching environmental education to gifted learners. In S. T. Schroth & J. Daniels (Eds.), *Building STEM skills through environmental education* (pp. 1–13). IGI Global.
Smutny, J. F., & Von Fremd, S. E. (2004). *Differentiating for the young child: Teaching strategies across the content areas (K–3)*. Corwin Press.
Son, M. J. (2009). *A study of Korean students' creativity in science using structural equation modeling* [Doctoral dissertation, University of Arizona]. ProQuest Dissertations Publishing.
Stenberdt, V. A., & Makransky, G. (2023). Mastery experiences in immersive virtual reality promote pro-environmental waste-sorting behavior. *Computers & Education*, *198*, Article 104760. https://doi.org/10.1016/j.compedu.2023.104760
Taber, K. S. (2007). *Enriching school science for the gifted learner*. Gatsby Science Enhancement Programme.
Tanik Önal, N., & Önal, N. (2021). The effect of augmented reality on the astronomy achievement and interest level of gifted students. *Education and Information Technologies*, *26*(4), 4573–4599. https://doi.org/10.1007/s10639-021-10474-7
Tekel, K. Y., & Yaman, Y. (2023). Metaverse Risk Perceptions of Gifted Students. *International Journal of Contemporary Educational Research*, *10*(4), 1035–1049. https://doi.org/10.52380/ijcer.2023.10.4.355
Thornhill-Miller, B., & Dupont, J. M. (2016). Virtual reality and the enhancement of creativity and innovation: Under recognized potential among converging technologies? *Journal of Cognitive Education & Psychology*, *15*(1), 102–121. https://doi.org/10.1891/1945-8959.15.1.102
Turan Gürbüz, G., Açıkgül Fırat, E., & Aydın, M. (2020). The adaptation of math and science engagement scales in the context of science course: A validation and reliability study. *Adiyaman University Journal of Educational Sciences*, *10*(2), 122–131. https://doi.org/10.17984/adyuebd.670173
Ucar, E., Ustunel, H., Civelek, T., & Umut, I. (2017). Effects of using a force feedback haptic augmented simulation on the attitudes of the gifted students towards studying chemical bonds in virtual reality environment. *Behaviour & Information Technology*, *36*(5), 540–547. https://doi.org/10.1080/0144929X.2016.1264483
UNESCO. (2020). *Education for sustainable development: A roadmap*. https://unesdoc.unesco.org/ark:/48223/pf0000374802
United Nations. (2016). *Sustainable development goals: 17 goals to transform our world*. https://sdgs.un.org/goals
VanTassel-Baska, J., & Wood, S. M. (2023). The integrated curriculum model. In J. S. Renzulli, E. J. Gubbins, K. S. McMillen, R. D. Eckert, & C. A. Little (Eds.), *Systems and models for developing programs for the gifted and talented* (pp. 655–691). Routledge.
Villegas-Ch, W., García-Ortiz, J., & Sánchez-Viteri, S., Jr. (2024). Educational advances in the metaverse: Boosting learning through virtual and augmented reality and artificial intelligence. *IEEE Access*, *12*, 59093–59109. https://doi.org/10.1109/ACCESS.2024.3393776
Vogt, A. G. (2022). *Fostering deep learning in immersive virtual reality: Interplay of learner's characteristics with internal and external support* [Doctoral dissertation, Universität Ulm]. OPARU—Ulm University Publication System. https://oparu.uni-ulm.de/xmlui/handle/123456789/46161
Wang, M. T., Fredricks, J. A., Ye, F., Hofkens, T. L., & Linn, J. S. (2016). The math and science engagement scales: Scale development, validation, and psychometric properties. *Learning and Instruction*, *43*, 16–26. https://doi.org/10.1016/j.learninstruc.2016.01.008
Wang, S. T., Liu, L. M., & Wang, S. M. (2018, June). The design and evaluate of virtual reality immersive learning: The case of serious game "calcium looping for carbon capture." In *2018 International Conference on System Science and Engineering (ICSSE)* (Article 8520002). IEEE. https://doi.org/10.1109/ICSSE.2018.8520002
Wang, T., & Lajoie, S. P. (2023). How does cognitive load interact with self-regulated learning? A dynamic and integrative model. *Educational Psychology Review*, *35*(3), Article 69. https://doi.org/10.1007/s10648-023-09794-6
Wang, W. S., Pedaste, M., Lin, C. J., Lee, H. Y., Huang, Y. M., & Wu, T. T. (2024). Signaling feedback mechanisms to promoting self-regulated learning and motivation in virtual reality transferred to real-world hands-on tasks. *Interactive Learning Environments*, *32*(10), 7661–7676. https://doi.org/10.1080/10494820.2024.2331151
Washington, A. M., & Andersen, L. (2016). Efficacy of creative training for gifted science students. In M. K. Demetrikopoulos & J. L. Pecore (Eds.), *Interplay of creativity and giftedness in science* (pp. 71–85). Brill.
Wigfield, A., & Eccles, J. S. (2002). The development of competence beliefs, expectancies for success, and achievement values from childhood through adolescence. In A. Wigfield & J. S. Eccles (Eds.), *Development of achievement motivation* (pp. 91–120). Academic Press. https://doi.org/10.1016/B978-012750053-9/50006-1
Winne, P. H. (2019). Self-regulated learning in research with gifted learners. *High Ability Studies*, *30*(1–2), 277–287. https://doi.org/10.1080/13598139.2019.1622224
Wu, W. L., Hsu, Y., Yang, Q. F., Chen, J. J., & Jong, M. S. Y. (2023). Effects of the self-regulated strategy within the context of spherical video-based virtual reality on students' learning performances in an art history class. *Interactive Learning Environments*, *31*(4), 2244–2267. https://doi.org/10.1080/10494820.2021.1878231

Yang, X., Lin, L., Cheng, P. Y., Yang, X., Ren, Y., & Huang, Y. M. (2018). Examining creativity through a virtual reality support system. *Educational Technology Research and Development*, *66*, 1231–1254. https://doi.org/10.1007/s11423-018-9604-z

Young, G. W., Stehle, S., Walsh, B. Y., & Tiri, E. (2020). Exploring virtual reality in the higher education classroom: Using VR to build knowledge and understanding. *Journal of Universal Computer Science*, *26*(8), 904–928. https://doi.org/10.3897/jucs.2020.049

Yu, H., & Wang, J. (2025). Enhancing college students' creativity through virtual reality technology: A systematic literature review. *Humanities and Social Sciences Communications*, *12*(1), 1–14. https://doi.org/10.1057/s41599-025-05044-y

Zeidner, M., & Stoeger, H. (2019). Self-regulated learning (SRL): A guide for the perplexed. *High Ability Studies*, *30*(1–2), 9–51. https://doi.org/10.1080/13598139.2019.1589369

Zhang, F., Zhang, Y., Li, G., & Luo, H. (2023). Using virtual reality interventions to promote social and emotional learning for children and adolescents: A systematic review and meta-analysis. *Children*, *11*(1), Article 41. https://doi.org/10.3390/children11010041

Zhao, J. H., Panjaburee, P., Hwang, G. J., & Wongkia, W. (2024). Effects of a self-regulated-based gamified virtual reality system on students' English learning performance and affection. *Interactive Learning Environments*, *32*(9), 5509–5536. https://doi.org/10.1080/10494820.2023.2219702

Zimlich, S. L. (2016). Motivating gifted students: Technology as a tool for authenticity and autonomy. *International Journal of Learning, Teaching and Educational Research*, *15*(13), 1–11.

Zimmerman, B. J., & Schunk, D. H. (2012). Motivation: An essential dimension of self-regulated learning. In Zimmerman, B. J., & Schunk, D. H. (Eds.), *Motivation and self-regulated learning* (pp. 1–30). Routledge.

Author Biographies

Yunus Emre Avcu is Assistant Professor of Gifted Education at Necatibey Faculty of Education in Balıkesir University. He has been working with gifted students for more than 10 years. He received his BA in Computer Education & Instructional Technology and MS in Curriculum and Instruction at Çanakkale Onsekiz Mart University. He gained a Ph.D. in Curriculum and Instruction at Balıkesir University in November 2019. He has a Ph.D. in Gifted Education at İstanbul University-Cerrahpaşa. His interest areas are gifted education, science education for gifted, differentiation, creativity, design thinking, computational thinking, instructional design, programming education for gifted students, and using technology in gifted education.

Yavuz Yaman is Assistant Professor of Special Education at İstanbul University-Cerrahpaşa. Dr. Yaman received his BA in Biology Education at Dokuz Eylül University and his MS in Elementary Education/Science Education at University of Colorado at Boulder in the United States. He gained his Ph.D. in Special Education at Istanbul University-Cerrahpaşa in 2014. His interest areas are special education, educational technology, teaching methods, gifted education, robotics, and science education.