Fostering Sustainable Living Awareness in Gifted Students with Immersive Virtual Reality

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Abstract: Gifted students possess the potential to make innovative contributions to the Sustainable Development Goals (SDGs) due to their ethical sensitivity, advanced problem-solving skills, creative thinking capacity, and heightened awareness of global issues. However, despite their high sensitivity to these topics, they must first develop a personal awareness of sustainable living to fully realize this potential. Immersive Virtual Reality (IVR) can support this process by fostering a deeper understanding of environmental challenges and encouraging active engagement in generating effective and innovative solutions, ultimately contributing to a more sustainable and equitable society. We aimed to enhance gifted students' sustainable living awareness using IVR. Thirteen 3D scenes were implemented to explore students' learning experiences and IVR's impact on their awareness. Seventeen gifted students participated (average age 12.4), utilizing a mixed-methods approach combining a case study for qualitative insights and a single-group pre-test-post-test design for quantitative analysis. Data collection tools included the Sustainable Living Awareness Scale (SLAS), the Word Association Test (WAT), and reflective letters. Quantitative data were analyzed using the Wilcoxon Signed-Rank Test, showing a significant post-test improvement in SLAS scores ($p<0.05$, Cohen's $d=2.003$). Qualitative findings revealed IVR's role in deepening engagement with environmental issues, reducing psychological distance, and promoting concrete understanding. Despite these benefits, some students experienced challenges such as focus loss and physical discomfort. The study highlights the potential of IVR in sustainability education for gifted students, recommending strategies to mitigate its challenges for broader application.

Keyword: Immersive virtual reality, IVR

Introduction

Gifted education not only nurtures advanced abilities but also fosters societal contributions. Sternberg et al. (2020) introduced the concept of transformational giftedness, emphasizing both personal development and the ability to inspire societal change. Rooted in a desire to contribute to the greater good (Napier & Halsey, 2022), this framework highlights education's dual role in fostering both personal potential and collective impact (Sternberg, 2020; Subotnik & Jarvin, 2005).

Sustainability education provides an ideal platform for developing transformational giftedness, as its open-ended and complex nature fosters critical and creative thinking (Akhan et al., 2022; Schroth et al., 2017; Renzulli & Reis, 2014). Gifted students often exhibit a heightened sensitivity to global challenges and social justice issues, making them well-suited to engage with sustainability topics (Schroth et al., 2017). Their advanced problem-solving abilities position them as future leaders in addressing environmental issues (Gibson et al., 2008; Kaplan Sayı, 2022). Early exposure to global inequalities further nurtures empathy, ethical maturity, and a commitment to ecological and societal well-being (Renzulli & Reis, 2014; Silverman, 1994). In this regard, gifted students have the potential to significantly contribute to the Sustainable Development Goals (SDGs) by offering innovative solutions to pressing global challenges (Watters & Diezmann, 2003).

The SDGs address economic, social, and environmental priorities, including poverty eradication, climate action, and biodiversity protection (Carlsen & Bruggemann, 2021). Sustainability education supports these goals by integrating these dimensions into curricula, fostering critical thinking, problem-solving, and sustainable behaviors (Ayaydın et al., 2023a; Hsiao & Su, 2021; Lewis et al., 2019). However, challenges such as the invisibility of environmental issues, psychological distance, and experimental complexity hinder its effectiveness (Fauville et al., 2020; Markowitz & Bailenson, 2021). IVR can address these barriers by creating immersive, interactive environments that enhance learning and promote eco-friendly behaviors (Hajj-Hassan et al., 2024; Makransky & Mayer, 2022). Through realistic simulations, IVR makes environmental changes tangible, helping students engage with complex ecological processes (Coban et al., 2022; Hsu & Wang, 2021).

In sustainability education, IVR has the potential to demonstrate climate change impacts through exaggerated feedback, helping students visualize long-term consequences and better understand environmental challenges (Hsu & Wang, 2021; Stenberdt & Makransky, 2023). However, its effectiveness largely depends on students' interest and engagement (Kleinlogel et al., 2023). Given their intrinsic motivation and deep curiosity, gifted students are particularly well-positioned to benefit from IVR-based sustainability education, enabling them to develop a profound understanding of sustainability issues and actively contribute to environmental solutions.

Gifted Students and Sustainability Education

Gifted students possess strong moral sensitivity and ethical reasoning, fostering social consciousness and a commitment to justice (Lovecky, 1997; Schroth et al., 2017; Sisk, 1982). Research indicates their heightened climate competence, environmental awareness, and climate literacy, surpassing that of their peers (Nacaroğlu & Karaaslan, 2020; Saricam & Sahin, 2015). They excel in generating creative, realistic solutions to environmental challenges and display deep emotional sensitivity to ecological issues (Akhan et al., 2022; Lovecky, 1992).

Despite their high environmental awareness, gifted students often struggle to apply their knowledge to address solutions. In Türkiye, they show strong recycling metacognition but less willingness to sacrifice the environment and focus more on local issues (Bakar et al., 2018; Mutlu & Nacaroğlu, 2019). Climate education raises awareness, but rarely leads to behavioral changes, with reluctance to address future challenges (Özarslan, 2022; Sanad et al., 2021). Sustainability education benefits gifted students by enhancing their environmental awareness and attitudes through field trips, hands-on activities, and discussions (Ayaydın et al., 2018; Tortop, 2007). STEAM and differentiated curricula can improve climate literacy and global responsibility (Choi et al., 2021). Enrichment programs and summer courses focusing on ecology and waste management foster critical thinking and an understanding of global warming (Balaban, 2023; Ceylan, 2022). Engaging in sustainability topics enhances creativity, scientific perception, and emotional and behavioral engagement in environmental issues (Ayaydın et al., 2023a; Park & Chung, 2014). Interdisciplinary and out-of-school education further boosts awareness (Suna & Köse, 2023).

IVR in Sustainability Education

IVR enhances learning through cognitive and affective engagement, leveraging presence, agency, and embodiment (Petersen et al., 2022). It effectively supports sustainability education, reduces paper consumption (Ahn et al., 2014), improves science learning and self-efficacy (Huang et al., 2023), and fosters eco-friendly attitudes, such as energy saving and water conservation (Kleinlogel et al., 2023; Hsu et al., 2018). While IVR promotes nature connections, its impact on eco-friendly behaviors is similar to that of video watching (Spangenberger et al., 2022). IVR enhances knowledge, environmental intentions, and self-efficacy in waste management and eco-friendly behaviors (Stenberdt & Makransky, 2023), and increases awareness of food impacts (Plechata et al., 2022a). Although both traditional and VR methods promote sustainability (Ronaghi, 2023), IVR excels in raising climate change awareness, particularly glacier melting (Thoma et al., 2023), although its impact on self-efficacy varies (Plechata et al., 2022b).

IVR effectively promotes eco-friendly behaviors, enhancing students' knowledge, environmental awareness, intentions, and self-efficacy (Stenberdt & Makransky, 2023; Plechata et al., 2022a). It reduces psychological distance and increases climate change awareness, particularly regarding glacier melting, outperforming traditional methods (Thoma et al., 2023; Meijers et al., 2023). While both traditional and VR-based methods support sustainable behaviors, IVR also impacts carbon footprint reduction, although its effect on self-efficacy varies (Plechata et al., 2022b; 2022c; Ronaghi, 2023). Compared with real experiences, IVR has significant potential for promoting conservation behaviors and climate-friendly actions (Hofman et al., 2021; Queiroz et al., 2023; Yu & Lin, 2020). Additionally, IVR has been effectively utilized to enhance nature relatedness and environmental attitudes among gifted students (Avcu & Yaman, 2025).

To enhance gifted students' sustainability awareness, this study utilized IVR-based 3D scenes focused on SDGs 6, 7, 13, 14, and 15, emphasizing environmental, social, and economic interconnections. Developed as part of the first author's doctoral dissertation (Avcu, 2025), these 13 scenes fostered transformational giftedness and leadership in sustainability (Slade, 2021; Stenberdt & Makransky, 2023; Walshe, 2008). The current study investigated both students' learning experiences with IVR and the impact of IVR-based learning on their awareness of sustainable living. The research seeks to answer the following questions:

- Is there a significant difference between the pre-test and post-test scores of the Sustainable Living Awareness Scale (SLAS) among gifted students?
- What are the perceptions of gifted students regarding the concept of sustainable living before and after learning with IVR?
- What are the opinions of gifted students about learning with IVR?

Method

Research design

This study used both quantitative and qualitative methodologies. This study implemented a case study approach with a single-group pre- and post-test weak experimental design for data collection (Büyüköztürk et al., 2022). Yıldırım and Şimsek (2013) defined a case study as an in-depth analysis of events, environments, social groups, or systems. Case studies aim to elucidate the complexities of an event, assess its significance, and offer explanatory perspectives (Flyvbjerg, 2011). This study selected a case study method to comprehensively analyze gifted students’ perceptions of sustainable living before and post-IVR. Furthermore, this method was deemed suitable for capturing nuanced student reflections through letters regarding their IVR experience.

The study involved 17 gifted students from the Science and Art Center (BİLSEM), a model and after school enrichment program, providing supplementary education for gifted learners. The 17 students involved in the current study were different from those who participated in the main study. Selection was based on nominations, group screening, and individual evaluations (IQ and talent tests) (Bildiren & Çitil, 2022). Participants completed pre- and post-tests, including the SLAS and a Word Association Test (WAT), along with reflective writing.

The study involved five, sixth, and seventh-grade gifted students (average age 12.4) from a BİLSEM in the southern Marmara Region in Türkiye, who participated in the study. Students were selected using criterion sampling (giftedness and relevance to the research) and convenience sampling (accessibility) methods (Yıldırım & Şimşek, 2013). All 17 students (10 boys and 7 girls) volunteered and provided their parental consent. Informed consent was obtained from all participants and parents after providing detailed information about the study. Consent was written and documented.

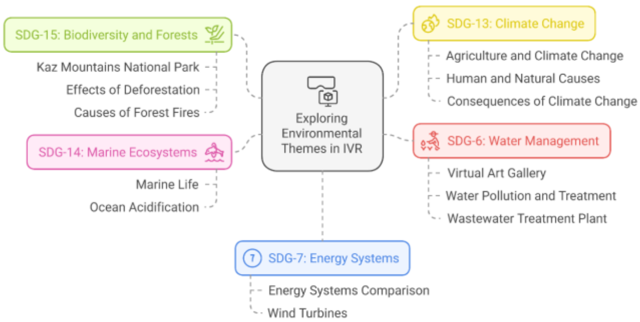
Procedure

Over six weeks, students engaged with 13 3D scenes in IVR-based sustainability education, totaling 12 lesson hours. The study applies the Cognitive Affective Model of Immersive Learning (CAMIL) to examine IVR's impact on cognitive and emotional processes (Makransky & Petersen, 2021). CAMIL's key elements—immersion, control, and representability—enhance presence, agency, and embodiment, influencing motivation, self-efficacy, cognitive load, and self-regulation for effective learning (Makransky & Petersen, 2021). The 3D scene design follows Mayer's Cognitive Theory of Multimedia Learning (CTML), incorporating dual-channel processing, limited capacity, and active learning principles (Mayer, 2014). CTML strategies such as pre-training, signaling, discovery, personalization, and segmenting were applied alongside Exaggerated Feedback (Stenberdt & Makransky, 2023).

Students used Oculus Quest 2 VR headsets, accessing IVR both in classrooms and designated open areas at BİLSEM for an immersive experience. Each IVR session lasted approximately 15 minutes per scene, followed by discussions on sustainability's environmental, social, and economic dimensions. The study aligns with SDG-4 on quality education. In the first week, students received an introduction to sustainable living. The experimental process was facilitated by the researcher and a BİLSEM IT teacher. Figure 1 presents the 13 3D scenes used in the study.

The students experienced 13 3D scenes in IVR, each designed to explore critical environmental and ecological themes. In the first scene (SDG-15), they explored the Kaz Mountains National Park, observing its biodiversity, and examining the natural balance of the ecosystem. The second scene (SDG-15), focused on the effects of deforestation, in which students analyzed issues such as reduced carbon absorption, biodiversity loss, and disruptions to the water cycle. In the third scene (SDG-15), the students investigated the causes and environmental consequences of forest fires, including habitat destruction and carbon emissions. In subsequent scenes, the students shifted their focus to marine ecosystems. In the fourth scene (SDG-14), they observe marine life, including corals and sea butterflies, exploring symbiotic relationships and the food chain.

Figure 1.
3D scenes used with Oculus Quest 2 VR headsets



The fifth scene (SDG-14) addressed ocean acidification and examined its impact on pH levels and marine life, particularly on shellfish. The sixth scene (SDG-13) explores the contributions of agriculture and livestock to climate change, emphasizing greenhouse gas emissions and global warming. The seventh scene (SDG-13) broadened the scope to include human and natural causes of climate change such as fossil fuel use and volcanic activity. In the eighth scene (SDG-13), students examined the consequences of climate change, including glacier melting and extreme weather events, and their effects on polar bears, humans, and the broader environment.

The ninth and tenth scenes (SDG-7) were shifted to energy systems. Students compared renewable and non-renewable energy sources and analyzed their environmental impacts and links to climate change. They also studied wind turbines and explored their structure, energy production processes, and their associated advantages and disadvantages. In the eleventh scene (SDG-6), the students visited a virtual art gallery, worked collaboratively to analyze paintings, and fostered higher-order thinking and teamwork. The twelfth scene (SDG-6) focused on water pollution and treatment. Students examined the causes and consequences of water pollution with an emphasis on plastic decomposition and its environmental impact. In the thirteenth scene (SDG-6), they visited a wastewater treatment plant to learn about the stages of the treatment process and the potential uses of the treated water.

Data Collection Instruments

The SLAS is a 3-point Likert scale developed by Akgül and Aydoğdu (2020) to assess middle school students' awareness of sustainable living. The scale comprises 20 items distributed across three dimensions: environmental (7 items), economic (5 items), and social (8 items). The validity and reliability of the scale were established through descriptive, item, exploratory factor analysis (EFA), and confirmatory factor analyses (CFA). Cronbach's Alpha coefficient was calculated as 0,77 for the overall scale, as 0,76, 0,73, and 0,69 for the respective sub-dimensions, demonstrating the scale's reliability. In this study, the Cronbach's alpha coefficients for the pre-test and post-test were found to be 0,86 and 0,89, respectively, further confirming the scale's reliability (Büyüköztürk et al., 2022).

The Word Association Test (WAT) on Sustainable Living aims to investigate the perceptions of gifted students regarding sustainable living and virtual reality concepts. A WAT was administered both before and after the experimental intervention. WAT is a tool that elucidates individuals' mental processes and cognitive structures by analyzing their associations with specific words (Kostova & Radoynovska, 2008; Nakiboglu, 2024). Students were instructed to write 10 words related to each concept, with a time limit of 60 s per word.

Reflective Letters from Students were used to gain insights into the thoughts and experiences of gifted students concerning learning with IVR, and students were asked to compose reflective letters addressed to their teachers. In these letters, students were encouraged to discuss the positive and negative aspects of their educational experience, their personal reflections on the experimental process, and the emotions they encountered.

Data Analysis

During the data analysis phase, the pre- and post-test data from the SLAS were checked and transferred to SPSS 27. The Shapiro-Wilk test results showed that the pre-test ($p = .001$) and post-test ($p = .043$) scores did not follow a normal distribution. The Levene's test indicated homogeneity of variances for both the pre-test (p = .097) and post-test (p = .283). Kurtosis and skewness values suggest deviations from normality in both tests (George & Mallery, 2019). The Shapiro-Wilk test, commonly used for small samples, was employed to assess the normal distribution of the data (Khatun, 2021). Due to the small sample size, non-parametric analysis methods were deemed appropriate for testing the impact of the experimental intervention on students' awareness of sustainable living. The Wilcoxon Signed-Rank Test was used to analyze the pre-test and post-test results, and effect sizes were calculated using the z-value and total number of participants (Fritz et al., 2012). Cohen's d was calculated according to Lenhard and Lenhard's (2016) formula, with effect sizes categorized as small (.10), medium (.30), or large (.50) (Cohen, 1998).

The Cut-Off Point (COP) technique was used to analyze the WATs (Bahar et al., 1999). This technique is frequently applied to analyze data from WATs (Bostan Sarıoğlan & Deveci, 2021; Polat, 2013). In this study, a table was created to show the frequency of concept repetition, and a concept network was developed by determining the COP (Işıklı et al., 2011). Responses below a certain threshold were used as the COP, whereas responses above that threshold formed the first part of the concept network. The analysis continued by lowering the COP in intervals until all the keywords were included in the concept network. For the concept of sustainable living, the COP was set at three, and new concept networks were created within this range. Content analysis was used to examine student letters, code, and categorize recurring themes. Two researchers reached a consensus on the codes, enhancing internal reliability, as recommended in qualitative research (Yıldırım & Şimşek, 2013). An inter-coder reliability coefficient was not provided, following qualitative research practices.

Results

Results from Pre-Test and Post-Test Scores of SLAS

Table 1 presents the Wilcoxon Signed-Rank Test results, which evaluate the significance of differences between pre-test and post-test SLAS scores for gifted students engaged in IVR-supported sustainability education. Table 1 shows a significant difference between the pre-test (M = 48.17) and post-test (M = 53.41) SLAS scores, with post-test scores showing higher value (z = -2.928, p < .05). The effect size, as measured by Cohen's d, was 2.003, indicating a large effect (Cohen, 1988).

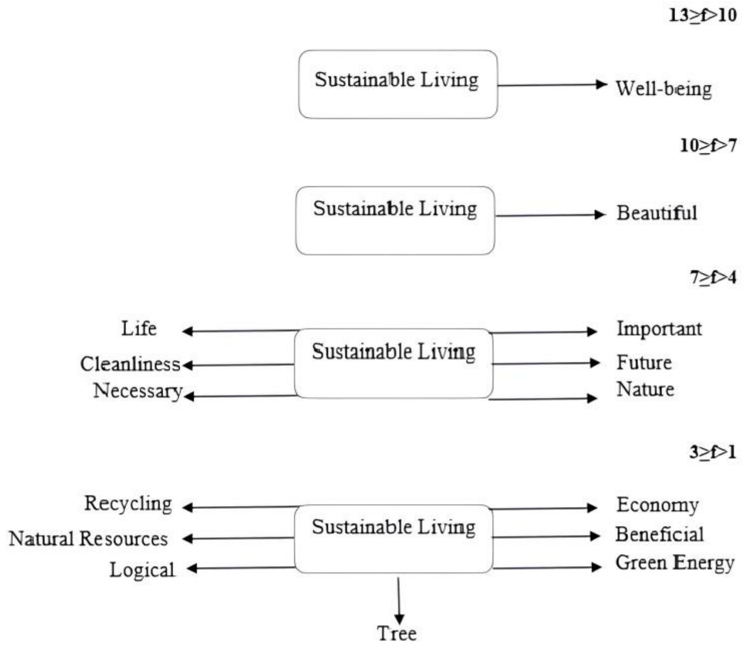
Table 1.
Results from Pre-Test and Post-Test Scores of SLAS

Measurement tools	Ranks	N	Mean rank	Sum of rank	z	p
SLAS Pre-test/Post-test	Negative Ranks	1d	8.50	8.50	-2.928b	.003
	Positive Ranks	14e	7.96	111.50		
	Ties	2f				
	Total	17				

Gifted Students' Perceptions of Sustainable Living

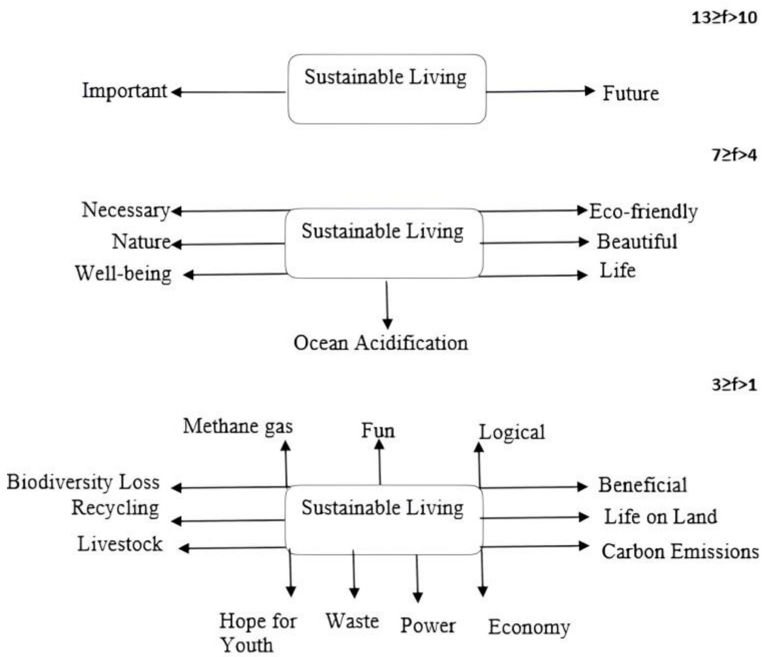
Figure 2 presents the concept map derived from WAT analysis conducted before learning with IVR. Gifted students associated the concept of sustainable living with various terms across different frequency ranges: well-being (13≥f>10), beauty (10≥f>7), importance, future, nature, life, cleanliness, and necessity (7≥f>4). In the lower frequency range (4≥f>1), the associations included economy, benefits, green energy, recycling, natural resources, logical resources, and trees. Figure 3 presents the concept map derived from the analysis of the word association test conducted after learning through IVR.

Figure 2.
Concept Map of Sustainable Living Before Learning with IVR



The gifted students' responses indicated that the concept map began to form in the frequency range of 13≥f>10, extending to 3≥f>1, with no connections made in the 10≥f>7 range. Students associated the concept of sustainable living with well-being and importance in the 13≥f>10 range, and with ocean acidification, life, beauty, well-being, nature, necessity, and eco-friendliness in the 7≥f>4 range. In the 4≥f>1 range, they linked it to beneficial terrestrial life, carbon emissions, biodiversity loss, recycling, livestock, hope for youth, waste, economy, power, methane gas, fun, and logical.

Figure 3.
Concept Map of Sustainable Living After Learning with IVR



Results on Students' Opinions

After learning with IVR, the students expressed their feelings, thoughts, and experiences about the learning process by writing a reflective letter to their teacher. The codes and categories derived from content analysis of the 17 letters are presented in Table 2 reveals that students felt that learning became easier and more lasting, experienced something different, and successfully transferred their learning.

They noted a change in their perspective of IVR, overcame prejudices, and felt happy. Students also highlighted the quality of the instructor and their understanding of sustainability topics and found that the education was enjoyable. However, some students reported difficulties in understanding the content, adjusting VR glasses, concerns about technological advancements, and physical discomfort such as eye strain and focus issues. They also mentioned technical problems, limited 3D scenes, need for an adjustment period, insufficient time, nausea, and dizziness.

Table 2.
Student Opinions Regarding Learning with IVR

Category	Code	Participants
Positive Aspects	Facilitates learning	S2
	Permanent learning	S13
	Experiencing something different	S1, S4
	Transfer of learning	S2, S4
	Change in perspective on VR	S9, S16, S17
	Breaking prejudices	S1, S2, S3, S15
	Feeling happy	S1, S2, S6, S12, S15, S16
	Instructor quality	S1, S2, S4, S9, S10, S12, S13, S14, S16
	Understanding sustainability topics	S2, S4, S5, S6, S8, S10, S12, S13, S14, S15, S17
	Being fun	S1, S2, S3, S4, S6, S7, S9, S10, S11, S12, S13, S14, S16, S17
Negative Aspects	Difficulty understanding content	S3
	Difficulty adjusting VR glasses	S4
	Concern about technological advancement	S4
	Eye strain	S5
	Focus issues	S7
	Technical problems	S9
	Limited 3D scenes	S5, S7
	Need for adjustment period	S9, S13
	Insufficient time	S3, S13
	Nausea	S2, S6, S13, S15, S16
	Dizziness	S2, S5, S11, S14, S15, S16

S2 stated that realistic modeling in education made it easier to understand, highlighting how IVR-supported sustainability education facilitated learning. S9 expressed a change in perspective on VR after the education, saying, *"I thought VR was just for games, but now I see it as a powerful tool for learning real-world problems. It made learning about climate change much more interesting and realistic*." S15 noted understanding sustainability topics, saying, "*These five days taught me how to tackle environmental and climate issues that should be central to my life*." Similarly, S15 mentioned gaining awareness and knowledge about biodiversity and human-caused threats through VR experience.

S4 expressed concern about rapid technological advancements after the education, saying, "*Even as I write this letter, many new VR applications have emerged. The rapid development, especially with Apple Vision and Quest 3, worries me.*" S16 mentioned that "*using VR was great, but it caused dizziness and nausea after a while*." S7 reported focus issues, stating, "*When I put on the VR glasses, I occasionally lost focus in the lesson and couldn't concentrate fully.*" S13 indicated the need for an adjustment period, saying, *“The only downside was the difficulty in adapting to VR. It took until the end of the second day to get used to the controls and glasses. It needs some time to adjust*."

Discussion, Conclusion, and Recommendations

A key finding of this study was IVR’s effectiveness of IVR in enhancing sustainability awareness among gifted students. IVR provides a concrete experience of environmental challenges, improving the understanding of abstract concepts, such as climate change and biodiversity. Gifted students showed significant improvements in SLAS post-test scores. This is consistent with the findings of Hsu and Wang (2021) and Makransky and Mayer (2022), which emphasize IVR’s role of IVR in bridging theoretical knowledge and practical applications. Ayaydın et al. (2023b) found similar improvements with a 6-weeks program focused on sustainability. These results indicate that sustainability education programs positively impact awareness among both gifted and typical students (Lewis et al., 2019; Suna & Köse, 2023; Yüzbaşıoğlu, 2023).

Many studies have shown that environmental education and sustainability programs positively impact gifted students’ environmental awareness and attitudes (Ayaydın et al., 2018), attitudes (Ceylan, 2022; Tortop, 2007), climate literacy (Choi et al., 2021; Sanad et al., 2021), emotional and behavioral tendencies (Ayaydın et al., 2023a), and views of climate change (Bodur et al., 2023). Our study differs in that it incorporates IVR technology into sustainability education.

A study with gifted students showed IVR enhanced nature relatedness and environmental attitudes but addressed only one SDG (Avcu & Yaman, 2025). In contrast, this study takes a more comprehensive approach. While limited research explores IVR in sustainability education for gifted students (Avcu, 2025), IVR has been linked to increased sustainability awareness in typical students.

Experiences such as virtual tree cutting, water conservation, and ocean acidification supported by IVR allow participants to concretely experience environmental issues, positively impacting their awareness of and attitudes toward these issues (Ahn et al., 2014; Hsu et al., 2018; Markowitz et al., 2018). For example, a 20% reduction in paper consumption after a virtual tree-cutting experience suggests that IVR can promote sustainable behavioral changes (Ahn et al., 2014). IVR also positively affects energy savings and environmental attitudes, indicating its potential to enhance sustainability awareness and encourage eco-friendly behaviors (Kleinlogel et al., 2023). Virtual trips to Greenland and other IVR experiences that connect with nature improve participants' knowledge and self-efficacy, boost sustainable living awareness, and promote climate-friendly behaviors (Makransky & Mayer, 2022; Petersen et al., 2020; Queiroz et al., 2023). These findings highlight IVR's potential of IVR as a versatile tool in sustainability education for deepening sustainability awareness.

Analysis of students' reflective letters and word association tests revealed that IVR enhanced gifted students' awareness of sustainable living and emotional connection to environmental issues. They frequently associated sustainability with "future," "important," "eco-friendly," and "nature," later expanding to global issues like ocean acidification and biodiversity loss. This aligns with Sternberg’s (2020) concept of transformative giftedness, highlighting IVR’s role in fostering both individual growth and societal contribution through improved retention and understanding of sustainability topics.

Another key finding is that despite addressing the environmental, social (e.g., well-being, hope for youth), and economic (e.g., energy, economy) dimensions of sustainability before and after the training, gifted students focused predominantly on the environmental aspect. This aligns with Ayaydın et al. (2023b), who found similar focus among gifted students. Studies with typical students have also shown a similar emphasis on the environmental dimension post-training (Demir & Atasoy, 2021; Fiedler et al., 2023; Kagawa, 2007; Walshe, 2008). This focus may highlight a limitation of the learning content for IVR, suggesting that sustainability education should integrate environmental, social, and economic dimensions, and explore their interrelationships and interactions over time and space (Boeve-de Pauw et al., 2015).

The qualitative results of this study highlight IVR's role of IVR in bridging the psychological distance related to environmental issues. Before IVR-supported lessons, students associated sustainability with general and distant concepts like "future" and "well-being." After the IVR experiences, their associations became more specific and action-oriented, focusing on terms such as "carbon emissions," "biodiversity loss," "logical," "hope for youth," and "renewable energy." renewable energy. This shift indicates that IVR helps students internalize environmental challenges, bringing distant global issues closer to their immediate concerns. IVR appears to be effective in reducing psychological distance and enhancing awareness (Fauville et al., 2020; Markowitz & Bailenson, 2021; Meijers et al., 2023). Similarly, this study suggests that IVR reduces psychological distance, thereby aiding in raising awareness.

Gifted students using IVR interact with simulated environments that reflect ecosystems, environmental processes, and their impacts on individuals, the economy, and society, which is particularly valuable for those with advanced analytical, critical, and creative thinking skills (Akhan et al., 2022; Avcu & Yaman, 2024; Scroth et al., 2017; Worrell et al., 2019). While research shows promise for IVR in sustainability education, some studies suggest that IVR may not effectively foster a connection with nature (Spangenberger et al., 2022), self-efficacy, or pro-environmental behaviors (Plechatá et al., 2022b, 2022c; Soliman et al., 2017). Makransky et al. (2019) also found that IVR increases cognitive load compared with traditional media, which could hinder information retention. Enjoying technology does not necessarily enhance learning (Makransky et al., 2019). Currently, students report on content comprehension issues, focus problems, time constraints, and the need to adapt to IVR. Therefore, IVR may not always be the most effective tool for cognitive and affective gains in sustainability education, indicating the need for further research to fully understand its potential. Some students experienced physical discomfort such as nausea and eye strain with VR, while others faced technical issues such as poor graphics and equipment malfunctions, disrupting learning. These findings highlight the need for proper equipment assessment, technical support, and addressing health risks, consistent with the studies by Tekel and Yaman (2023), Özden Çınar et al. (2022), and Kim and Kim (2022).

Incorporating IVR technology into gifted education programs can enhance awareness of sustainable living and provide pedagogical advantages. However, physical discomfort such as dizziness and nausea must be addressed. Limiting IVR experience to 15 minutes per session with breaks in between is advisable. An interdisciplinary approach covering the environmental, economic, and social dimensions of sustainability in terms of the content and application of education is essential. Overall, the findings of this study indicate that IVR has a significant potential to improve students' awareness of sustainable living and make learning more engaging and meaningful. Nonetheless, to fully realize these benefits, the challenges of IVR technology must be carefully managed to optimize its potential as an effective educational tool.

The current study has notable limitations, including the implementation of IVR over six weeks with a single group of gifted students. Future research could explore IVR's effects of IVR in more detail using experimental and control groups and conducting long-term studies. The generalizability of the results is limited by the small number of participants and their gifted status. Comparative studies involving a larger sample, including both gifted and typically developing students, are recommended. Data were collected through the SLAS, WAT, and students' reflective letters. Using diverse data sources, such as video recordings, student interviews, and learning products, could enrich data variety. The cost of IVR technology, such as high-priced Oculus Quest 2, is another significant limitation. To mitigate this, project grants for device access could be sought and alternative, more affordable VR devices could be used. A strength of this study is the design of 3D scenes by researchers, who were well received by students. These designs can be shared with other researchers and teachers and used in studies with different groups of gifted students. In addition, online applications of these designs and the development of IVR-supported education on various sustainability topics are suggested.

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