EFFICACY OF AUGMENTED REALITY (AR) AND VIRTUAL REALITY (VR) TECHNOLOGIES ON SECONDARY SCHOOL STUDENTS' ENGAGEMENT IN SCIENCE EDUCATION

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ABSTRACT

This study investigated the efficacy of augmented reality (AR) and virtual reality (VR) technologies on secondary school students' engagement in science education, with focus on Biology. The study further examined the influence of gender and the interaction effect between instructional strategies and gender on students' engagement. A quasi experimental design involving 243 senior secondary school Biology students was adopted, with participants randomly assigned to either AR or VR instructional groups. Student Engagement Questionnaire (SEQ) was used to collect data on behavioral, emotional, and cognitive engagement. The reliability of the instrument was established using Cronbach Alpha method, and reliability coefficient of .93 was obtained. Mean and standard deviation was used to answer all the research questions while Analysis of Covariance (ANCOVA) was used to test the formulated hypotheses at 0.05 level of significance. The findings revealed no significant difference in the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies; no significant influence of gender on senior secondary school students' engagement in Biology, and the interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology is not significant. These results suggest that both AR and VR are equally effective in fostering student engagement in Biology, and that engagement levels are consistent across gender. The study recommends the adoption of immersive technologies in science classrooms, teacher training on AR/VR integration, and the design of inclusive, student-centered instructional strategies.

Keywords: Augmented Reality (AR), Virtual Reality (VR), Interactive Learning in STEM, Student Engagement, Science Education and Biology Education

Introduction

The 21st century has witnessed unprecedented growth in digital technology and innovation, leading to a fundamental transformation in the educational landscape across the globe. Among the emerging technologies reshaping instructional delivery are Augmented Reality (AR) and Virtual Reality (VR), two immersive technologies with immense potential to enhance teaching and learning processes. These technologies integrate real and virtual environments to provide interactive, experiential, and student-

centered learning experiences that promote engagement, understanding, and motivation (Radianti, Majchrzak, Fromm, & Wohlgenannt, 2020). In science education, where abstract concepts, complex processes, and experimental constraints often limit learners' participation, AR and VR provide unique opportunities to visualize, manipulate, and interact with scientific phenomena that may otherwise be too dangerous, expensive, or inaccessible in real-world classroom settings.

These immersive technologies offer capabilities that traditional pedagogies cannot easily match. They enable students to interact with three-dimensional models of abstract scientific phenomena, explore complex biological structures, and simulate environments that would otherwise be inaccessible (Makransky & Petersen, 2021). This potential is especially pertinent to Biology instruction at the secondary school level, where students frequently grapple with abstract and spatially challenging concepts such as cellular organelles, ecological systems, and molecular interactions. However, science, especially Biology, being an inquiry-based discipline, demands learners' active participation, curiosity, and critical thinking. However, in many secondary schools in Ebonyi state, Nigeria, traditional teaching methods dominated by rote memorization and teacher-centered instruction have been reported to impede students' engagement and understanding of scientific concepts (Achor, Njoku, & Iji, 2022). These instructional approaches tend to portray Biology as abstract and difficult, leading to low motivation, poor achievement, and declining interest among students. This poor achievement of students in Biology in the state was evidence in West African Examination Council (WAEC) Chief examiners report 2020-2024; where students' achievement were below average. In this regard, the integration of immersive digital technologies such as AR and VR presents a viable alternative to conventional teaching by enabling interactive visualization, simulation, and hands-on vistual experimentation that align with the constructivist paradigm of learning.

Augmented Reality (AR) involves the overlaying of digital information; such as images, sounds, or 3D models onto the physical environment, enhancing learners' perception and interaction with real-world objects (Azuma, 2015). In contrast, Visual Reality (VR) immerses students completely within a simulated environment that replaces the real world, enabling them to explore, manipulate, and engage with virtual objects in real-time through headsets or mobile applications (Bailenson, 2018). Both AR and VR provide rich, multisensory experiences that can improve learners' understanding of abstract scientific phenomena, promote problem-solving, and sustain attention. For instance, AR can allow students to examine the human circulatory system in 3D within the classroom, while VR can transport them into a virtual laboratory to conduct chemical experiments safely. These strategies (AR and VR) are believed to enhance students' engagement in Biology when adopted in teaching and learning.

Student engagement is a multidimensional construct encompassing behavioral, emotional, and cognitive dimensions that reflect students' active participation, interest, and investment in learning activities (Fredricks, Blumenfeld, & Paris, 2004). It is a critical predictor of students' academic achievement and long-term success in science education. Engaged students are more likely to exhibit curiosity, persistence, and enthusiasm for learning, whereas disengaged students often display apathy, absenteeism, and poor performance (Henrie, Halverson, & Graham, 2015). However, studies have shown that many secondary school students in Nigeria and other developing nations are disengaged from science learning due to inadequate laboratory facilities, overcrowded classrooms, lack of instructional resources, and limited exposure to digital learning experiences (Nwoye & Ezeudu, 2021). Hence, the use of AR and VR technologies has the potential to address these limitations by providing vitual laboratories, interactive simulations, and immersive visualizations that enhance students' engagement and participation.

Empirical research across different contexts supports the efficacy of AR and VR technologies in promoting student engagement and achievement. Akçayır and Akçayır (2017) found that AR

applications improve learners' motivation and attention by offering real-time feedback and interactive experiences. Similarly, Makransky and Petersen (2021) observed that VR fosters emotional engagement and cognitive involvement by providing realistic, immersive environments that allow students to visualize and experience complex concepts. In addition, immersive learning environments encourage collaborative learning, creativity, and exploration, which are essential skills for the modern knowledge economy (Parong & Mayer, 2018). These studies affirm that AR and VR not only make science learning enjoyable but also promote deeper understanding through active participation and visualization.

The theoretical foundation of this study is rooted in constructivist learning theories, which posit that learners actively construct knowledge through interaction with their environment (Piaget, 1973; Vygotsky, 1978). AR and VR technologies provide the interactive and contextual learning experiences that constructivists advocate, allowing students to learn by doing, reflecting, and collaborating. Furthermore, Dale's Cone of Experience (Dale, 1969) suggests that learners retain more knowledge when they engage in direct, purposeful experiences compared to passive learning modes such as reading or listening. Thus, the immersive and interactive nature of AR and VR aligns with the upper levels of the Cone of Experience, enhancing retention and understanding.

Despite these pedagogical advantages, the adoption of AR and VR technologies in Nigerian secondary schools, especially in Ebobyi State remains minimal due to challenges such as high costs, inadequate infrastructure, limited teacher training, and lack of locally developed AR/VR content aligned with the national curriculum (Okoye, Uzoegwu, & Nwosu, 2023). Nonetheless, with the increasing availability of smartphones, affordable headsets, and open-source AR/VR applications, there is growing potential for integrating these technologies into classroom practice. Therefore, the efficacy of AR and VR technologies on secondary school students' engagement in science education (Biology) warrants systematic investigation. Understanding how these tools effect students' behavioral, cognitive, and emotional engagement can provide empirical evidence for curriculum specialists, educational evaluators, and policymakers seeking to transform science education. By promoting interactive, learner-centered experiences, AR and VR can bridge the gap between theoretical knowledge and practical application, preparing students for future scientific inquiry and innovation.

Purpose of the Study

The general purpose of this study was to determine the efficacy of augmented reality (AR) and virtual reality (VR) technologies on secondary school students' engagement in science education, with focus on Biology. Specifically, the study determined the;

1. mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies.
2. influence of gender on senior secondary school students' engagement in Biology.
3. interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology.

Research Questions

To guide the study, the following research questions were posed;

1. What are the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies?
2. What is the influence of gender on senior secondary school students' engagement in Biology?

3. What is the interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology?

Hypotheses

The following hypotheses were formulated and tested at 0.05 level of significance;

1. There is no significant difference in the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies.
2. There is no significant influence of gender on senior secondary school students' engagement in Biology.
3. There is no significant interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology.

Materials and Methods

This study adopted a quasi-experimental, pretest–posttest non-equivalent group design. A sample size of 243 Senior Secondary School Two (SSS II) Biology students in Ebonyi State was used for the study. Data were collected using a researchers'-developed instrument titled Students' Engagement Questionnaire (SEQ). The instrument consisted of 20 items designed to measure students' engagement in Biology. The face validity of the instrument was established by three experts from Department of Science Education (two from Biology Education unit and one from Measurement and Evaluation unit), Alex Ekwueme Federal University, Ndufu-Alike, Ikwo, Ebonyi State. Their corrections and suggestions were incorporated to improve the clarity, relevance, and alignment of items with research objectives. The reliability of the SEQ was established through a pilot test involving 30 SS II Biology students in Enugu state, which is outside the study area but with similar characteristics with those in the study area. The responses were analyzed using Cronbach Alpha method, which yielded a reliability coefficient of 0.93, indicating that the instrument was internally consistent and reliable for data collection for the study.

Experimental Procedure

The experiment was conducted over a six-week period and organized into three stages: pre-treatment, treatment, and post-treatment. Prior to the implementation of the intervention, the researchers provided training to the Biology teachers who participated in the study and served as research assistants.

Phase I: Pre-treatment (Week 1)

Prior to the commencement of the intervention, both Experimental Group I and Experimental Group II were given the pretest form of the Students' Engagement Questionnaire (SEQ) to assess their initial levels of engagement in Biology. The pretest outcomes were then analyzed to verify that the groups were comparable before the treatment phase began.

Phase II: Treatment Stage (Week 2-5)

Both experimental groups were taught selected Biology topics over a four-week period, following the approved Senior Secondary School Biology curriculum using AR for experimental group one and VR for experimental group two.

Phase III: Post-treatment (Week 6)

After the intervention, the posttest version of the instrument was administered to all groups to assess any changes in students' interest. The scores collected at different stages of the study were analyzed to evaluate the effects of the two metacognitive strategies and to examine whether gender had any moderating influence.

Method of Data Analysis

The data obtained were analyzed using a combination of descriptive and inferential statistical methods. Means and standard deviations were computed to address the research questions, while Analysis of Covariance (ANCOVA) was employed to test the null hypotheses at the 0.05 significance level, using the pretest scores as covariates to account for any initial differences between the groups.

Experimental Control Measures

To maintain the integrity and validity of the experiment, the following control measures were implemented:

1. **Teacher Training:** The researchers provided a one-week training session for the Biology teachers participating in the study on how to use the augmented reality (AR) and virtual reality (VR) technologies.

2. **Time Control:** All groups received the same number of lessons and duration.

3. **Testing Effect*:*** The same instrument (SEQ) was used for pre-test and post-test to ensure comparability.

4. **Observer Monitoring:** *The researcher monitored each class a minimum of twice per week to maintain fidelity in the implementation.*

Results

Research Question One

What are the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies?

Table 1: Mean and standard deviation of mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies

Groups		Pre-test		Post-test		Mean Gain Scores	Mean Gain Difference
	n	Mean	SD	Mean	SD		
AR	124	20.40	3.75	37.97	4.24	17.57	.79
VR	119	20.18	4.34	36.96	4.02	16.78	

Result in Table 1 shows that Biology students exposed to augmented reality technology had pre-test mean engagement score of 20.40 with standard deviation of 3.75 and post-test mean engagement score of 37.97 with standard deviation of 4.24, while those exposed to virtual reality (VR) technology had pre-test mean engagement score of 20.18 with a standard deviation of 4.34 and post-test mean engagement score of 36.96 with standard deviation of 4.02. Mean gain scores of 17.57 and 16.78 were obtained for students exposed to AR and VR respectively with mean gain difference of .79 in favour of students exposed to augmented reality (AR) technology. The obtained post-test standard deviations of 4.24 and 4.02 for the two groups of students respectively indicate that the variation from the mean was small.

Research Question Two

What is the influence of gender on senior secondary school students' engagement in Biology?

Table 2: Mean and standard deviation of male and female students' engagement in Biology

Gender		Pre-test		Post-test		Mean Gain Scores	Mean Gain Difference
	N	Mean	SD	Mean	SD		
Male	113	20.27	3.58	37.17	3.99	16.9	0.52
Female	130	20.32	4.42	37.74	4.29	17.42	

Result in Table 2 revealed that at the pre-test, male students had mean engagement score of 20.27 with a standard deviation of 3.58 while their female counterpart had mean engagement score of 20.32 with standard deviation of 4.42. At the post-test, male students had mean engagement score of 37.17 and standard deviation of 3.99 while female students had mean engagement score of 37.74 with standard deviation of 4.29. The mean gain score of the males was 16.9 while that of their female counterpart was 17.42. The results therefore, show that female students had a slight higher mean engagement score compared to their male counterpart. This can be seen from a very slight mean gain score difference of .52 in favour of the female students.

Research Question Three

What is the interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology?

Table 3: Mean and standard deviation of interaction effect of teaching strategy and gender on students' engagement in Biology

Groups	Gender	N	Mean	Std. Dev.
Augmented Reality (AR) Technology	Male	58	37.74	4.12
	Female	66	38.17	4.36
Virtual Reality (VR) Technology	Male	55	36.56	3.79
	Female	64	37.30	4.20

Result of the analysis in Table 3 revealed that male students exposed to Augmented Reality (AR) Technology had a higher mean engagement score of 37.74 and standard deviation of 4.12 as against their male counterparts exposed to Virtual Reality (VR) Technology had a mean engagement score of 36.56 with standard deviation of 3.79. On the other hand, female students exposed to Augmented Reality (AR) Technology had a higher mean engagement score of 38.17 and a standard deviation of 4.36 while their female counterparts in the Virtual Reality (VR) Technology had a mean engagement score of 37.30 with

standard deviation of 4.20. The results do not suggest ordinal interaction effect between instructional strategies and gender on students' engagement in Biology. This was because at all the levels of gender, the mean engagement scores were higher for students in the Augmented Reality (AR) Technology than those in the Virtual Reality (VR) Technology.

Hypothesis One

There is no significant difference in the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies.

Table 4: Summary of Analysis of covariance (ANCOVA) of significant difference in the mean engagement scores of students taught engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	154.542[a]	4	38.635	2.286	.061	.037
Intercept	11064.721	1	11064.721	654.744	.000	.733
PreEngagement	71.139	1	71.139	4.210	.041	.017
Treatment	59.105	1	59.105	3.497	.063	.014
Gender	19.622	1	19.622	1.161	.282	.005
Treatment * Gender	.438	1	.438	.026	.872	.000
Error	4022.035	238	16.899			
Total	345408.000	243				
Corrected Total	4176.576	242				

Result of the analysis in Table 4 shows that teaching strategy is not a significant factor on students' engagement in Biology; F (1, 238) = 3.497, P = .063. Thus, the null hypothesis of no significant difference in the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies was accepted. This is because the exact probability value of .063 is greater than the level of significance set at 0.05. Therefore, the researchers conclude that there is no significant difference in the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies. However, the Partial Eta Square (effect size) value of .014 shows that learning strategies had 14% effect on students' engagement in Biology.

Hypothesis Two

There is no significant influence of gender on senior secondary school students' engagement in Biology.

Result of the analysis in Table 4 was also used to test hypothesis two. The Table shows that gender is not a significant factor on students' engagement in Biology; F (1, 238) = 1.161, P = .282. Therefore, the null hypothesis of no significant influence of gender on senior secondary school students' engagement in Biology was accepted because the exact probability level of .282 is greater than level of significance set at 0.05. The researchers therefore, conclude that there is no significant influence of gender on senior secondary school students' engagement in Biology. The result indicated that gender is not a significant factor in the mean engagement scores of male and female students in Biology.

Hypothesis Three

There is no significant interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology.

The result of the analysis in Table 4 was also used to test hypothesis three. The Table shows that the exact probability value of .872 associated with instructional strategies and gender is greater than 0.05 level of significance; (F (1, 238) = .026, P = .872). Thus, the null hypothesis of no significant interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology was upheld. The researchers therefore, conclude that the interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology is not significant. The result of interaction effect was also interpreted using screen plot as shown in figure 1 below.

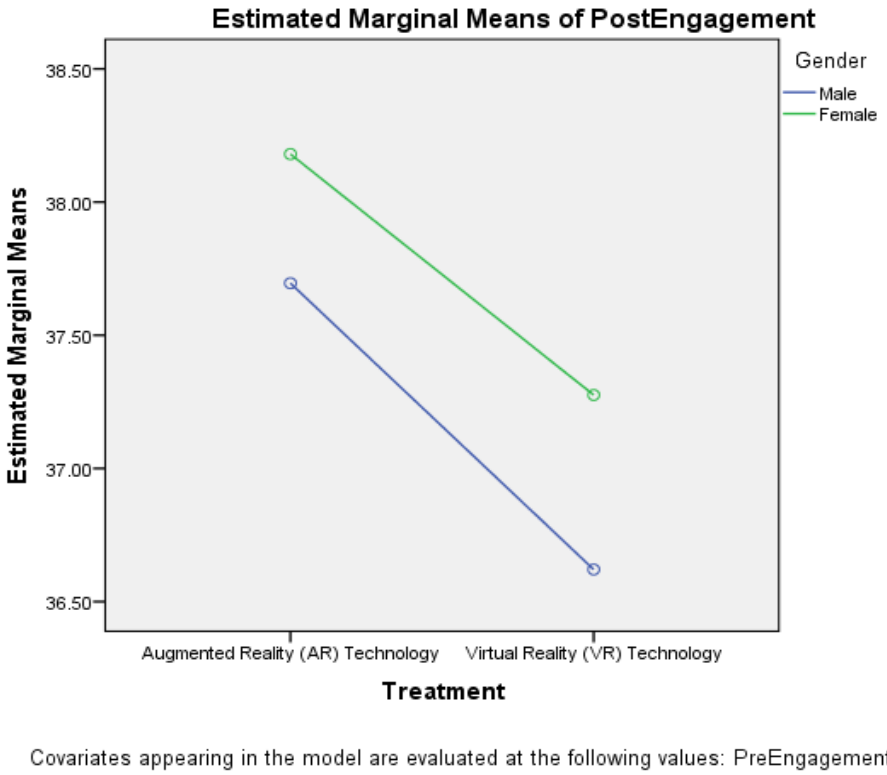

Figure 1: Graph of the interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology.

The screen plot in figure 1 shows that there is no interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology. This is indicated by the separate lines for the male and female students' engagement in Biology in the respective two instructional strategies (that is, the connecting cells in the diagram are parallel).

Discussion of Findings

Mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies

The findings of the study revealed no significant difference in the mean engagement scores of students taught Biology using augmented reality (AR) and those taught with virtual reality (VR) technologies. The finding indicates that both immersive technologies are equally effective in promoting students'

engagement in science classroom. One possible explanation for this outcome is that AR and VR share pedagogical affordances that are foundational for engagement. Both modalities support visualization of abstract scientific phenomena, real-time interaction with 3D models, and multisensory learning experiences that stimulate curiosity and sustained attention. Consequently, students in both treatment groups may have experienced similar levels of cognitive stimulation and emotional involvement, resulting in non-differential engagement scores. Similar findings have been reported by Makransky and Mayer (2022), who observed that although VR provides higher immersion, AR offers stronger contextual embedding, and these affordances often balance out in terms of overall engagement.

Another interpretation is that students' engagement may be affected more by the novelty and interactivity of immersive technologies generally, rather than by the specific type of immersion offered. For many secondary school students, both AR and VR represent innovative departures from traditional textbook-based teaching, thus generating high baseline excitement and participation. Studies by Zhao et al. (2022) and Akçayır & Akçayır (2017) support this argument, noting that students often report similarly high engagement when exposed to either technology due to the shared novelty effect. This aligns with contemporary research indicating that immersive learning environments whether augmented or fully virtual tend to produce comparable cognitive and affective learning outcomes when instructional content, duration, and teacher mediation are held constant (Ibáñez & Delgado-Kloos, 2018; Radianti et al., 2020). Additionally, the similarity in engagement outcomes might reflect successful instructional design, meaning that lesson plans, scaffolding, teacher guidance, and learning objectives were carefully aligned across both groups. When pedagogical frameworks are standardized, technology type becomes a secondary factor in determining students' engagement (Wu et al., 2020). Thus, the non-significant difference may indicate that both AR- and VR-mediated lessons were equally well implemented by the instructors.

However, the finding also contrasts with some studies that have reported higher engagement with VR due to its more immersive and presence-inducing nature (Parong & Mayer, 2018). The divergence may be due to contextual variables such as students' prior experience with technology, classroom environment, the nature of Biology content taught, or the duration of exposure (eight weeks). If students faced issues such as motion sickness, device unfamiliarity, or technical interruptions—commonly associated with VR—these may have reduced VR's potential engagement advantage (Radianti et al., 2020).

Influence of gender on senior secondary school students' engagement in Biology

The findings of the study revealed no significant influence of gender on senior secondary school students' engagement in Biology. The result indicated that gender is not a significant factor in the mean engagement scores of male and female students in Biology. This finding suggests that male and female learners participated, interacted, and emotionally invested in Biology learning activities at relatively similar levels. This result aligns with a growing body of contemporary research indicating that when instructional environments are well-structured, interactive, and supportive, gender differences in engagement tend to diminish (Adeniyi & Ibrahim, 2021; Areepattamannil & Khine, 2017).

One key explanation to the outcome of the study is that engagement in modern science classroom is shapped more by instructional quality than gender. When teaching strategies incorporate hands-on tasks, digital tools, collaborative learning, and inquiry-based activities, both male and female students are equally motivated to participate (King & Ritchie, 2022). Thus, if the Biology lessons used in the study were engaging and inclusive, gender would not be expected to create significant variation in learner engagement. Another possible explanation is that engagement is multidimensional, encompassing behavioral, emotional, and cognitive components. Research has shown that while boys may sometimes

demonstrate higher behavioral engagement, girls often exhibit stronger cognitive and emotional engagement, resulting in overall balanced engagement levels (Fredricks, Blumenfeld, & Paris, 2004). Therefore, aggregated engagement scores may show no significant gender-based variation, as observed in this study.

The finding is in agreement with previous studies that have specifically reported no significant gender difference in students' engagement and achievement in Biology, especially when learner-centered instructional techniques are used (Okoli & Akuma, 2020; Obasoro & Ayoola, 2022). This suggests that cultural stereotypes that previously portrayed Biology as more suitable for one gender may be weakening as teachers adopt more inclusive pedagogies. However, this result contrasts with some earlier studies that found boys more engaged in science due to higher perceived relevance or girls more engaged due to stronger study discipline (Simpkins et al., 2015). The disparity may be due to contextual variables such as classroom environment, teacher attitude, availability of instructional materials, and the nature of the topics taught. When these variables are controlled or optimized, as in this study, gender differences tend to diminish.

Interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology

The findings of the study revealed that the interaction effect of instructional strategies and gender on senior secondary school students' engagement in Biology was not significant. The finding indicates that the effect of the instructional strategies used in the study did not vary according to whether the students were male or female. In other words, the effectiveness of the instructional strategies on students' engagement was consistent across genders. This suggests that both male and female students responded similarly to the strategies employed, and neither group benefited disproportionately from the instructional approaches implemented.

One possible explanation for the non-significant interaction is that instructional strategies in modern classrooms increasingly emphasize multimodality, incorporating visual, auditory, and kinesthetic elements. These features tend to meet the learning needs of a broad range of students regardless of gender. Research indicates that both boys and girls engage more effectively with lessons that provide autonomy, real-world relevance, and technological integration, which reduce gender-based variations in engagement (Areepattamannil & Khine, 2017; Makransky & Mayer, 2022). Therefore, if the instructional strategies in the study were robust and universally appealing, they would naturally minimize gender-driven differences in engagement. This result aligns with contemporary literature which argues that when instructional strategies are well-designed, learner-centered, and inclusive, gender differences tend to diminish or disappear (King & Ritchie, 2022; UNESCO, 2021). Strategies such as collaborative learning, digital-enhanced instruction, inquiry-based learning, and immersive technologies have been found to engage students of both genders in similar ways because they emphasize active participation, hands-on exploration, and personalized learning experiences (Fredricks, Blumenfeld, & Paris, 2004; Radianti et al., 2020).

The finding is also consistent with studies that have reported limited or no interaction effects between gender and instructional methods on engagement or achievement in science subjects (Okoli & Akuma, 2020; Obasoro & Ayoola, 2022). These studies note that when teachers provide equal opportunities for participation, equitable access to learning resources, and consistent feedback, gender-based discrepancies become minimal. However, the finding contrasts with earlier research suggesting that some instructional strategies may favor one gender more than the other; for example, competitive or spatially demanding tasks that may engage male students more strongly, or collaborative and language-rich tasks that may enhance engagement among female students (Simpkins et al., 2015). The absence of

such differences in this study may indicate that the strategies used were balanced, supportive, and adaptable to diverse learners.

Conclusions

This study demonstrates that immersive instructional technologies can be effectively integrated into senior secondary school Biology classrooms to promote meaningful student engagement. The results highlight that well-designed instructional strategies, rather than learner characteristics such as gender, play a central role in shaping how students participate and interact with learning experiences. The study reinforces the value of adopting innovative, student-centered, and inclusive pedagogical approaches that provide equal learning opportunities for all students. The study's findings therefore, underscore the importance of prioritizing sound instructional design when implementing emerging technologies to enhance engagement and support quality science education.

Recommendations

Based on the outcomes of this study and the insights gained regarding the use of immersive technologies in Biology instruction, several practical recommendations are proposed to guide educators, school administrators, and policymakers in enhancing student engagement and improving the quality of science education.

1. Schools and educators should incorporate immersive technologies such as Augmented Reality and Virtual Reality into Biology lessons to enhance students' engagement and make abstract concepts more accessible.
2. Professional development workshops should be organized to equip teachers with the skills needed to effectively design, implement, and manage AR and VR enhanced lessons.
3. Teachers should continue using instructional approaches that promote equal participation for both male and female students, ensuring that all learners have access to supportive and engaging learning environments.
4. School administrators should invest in adequate AR/VR devices and ensure fair access for all students to maximize the benefits of immersive learning tools.
5. When integrating innovative technologies, educators should focus on sound pedagogy, clear learning objectives, and meaningful activities, as engagement depends more on instructional design than on the specific technology used.
6. Educational policymakers and curriculum developers should collaborate with technology experts to produce context-appropriate AR and VR learning materials aligned with the Biology curriculum.

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