TYPE Original Research
PUBLISHED 12 September 2025
DOI 10.3389/feduc.2025.1626181

OPEN ACCESS

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RECEIVED 15 May 2025
ACCEPTED 18 August 2025
PUBLISHED 12 September 2025

CITATION
Neiroukh NMI and Ayyoub A (2025) Beyond traditional biology instruction: a mixed-methods comparative study on virtual reality's impact on high school students' habits of mind. *Front. Educ.* 10:1626181.
doi: 10.3389/feduc.2025.1626181

Beyond traditional biology instruction: a mixed-methods comparative study on virtual reality's impact on high school students' habits of mind

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This mixed-method quasi-experimental study investigated the effects of virtual reality immersion (VRI) in biology classes on East Jerusalem high school students' scientific habits of mind, specifically self-regulation, critical thinking, and creative thinking. The study was grounded in the Cognitive Affective Model of Immersive Learning (CAMIL), which emphasizes how immersive environments enhance cognitive and affective engagement. A random cluster sample of 207 male and female students from three East Jerusalem high schools (two male and one female) participated in the study. Over a four-month period, participants were exposed to VRI-based biology content designed according to CAMIL principles. Data were collected using pre- and post-tests to measure changes in students' self-regulation, critical thinking, and creative thinking. A mixed-method design was employed to capture both measurable outcomes and students' lived experiences, integrating quantitative results with qualitative insights to ensure methodological triangulation. Quantitative analysis using the non-parametric Wilcoxon Signed-Rank Test revealed statistically significant and substantial improvements in students' self-regulation, critical thinking, and creative thinking following the integration of VRI. Qualitative findings supported these outcomes, highlighting students' positive perceptions and experiences with immersive biology learning. The findings demonstrate that incorporating VRI into biology instruction can meaningfully enhance students' higher-order thinking skills and scientific habits of mind. These results suggest the potential of VRI to encourage greater student interest and enrollment in scientific tracks. However, further research is recommended across other science subjects (e.g., physics, chemistry, and mathematics) to validate the broader applicability of these results. Educators and researchers are encouraged to explore VRI integration to foster students' cognitive growth and promote pursuit of higher education in scientific domains.

KEYWORDS
virtual reality immersion, flow experience, motivation, self-regulation, critical thinking, creative thinking

1 Introduction

Virtual reality immersion (VRI) has emerged as a transformative technology in education, offering learners interactive, immersive, and engaging learning environments. Research has increasingly focused on its cognitive and behavioral effects, particularly on students' Habits of Mind (HoM), which encompass Self-Regulation (SR), Critical Thinking (CRIT), and Creative Thinking (CRET) (Guerra-Tamez, 2023; Marzano et al., 1993). The Cognitive Affective Model of Immersive Learning (CAMIL) provides a theoretical foundation for explaining how immersion influences cognitive outcomes through interaction, engagement, and exploration. The model describes how these affordances influence six affective and cognitive factors that play a role in immersive learning, including interest, intrinsic motivation, self-efficacy, embodiment, cognitive load, and self-regulation.

There is evidence that HoM and cognitive learning outcomes in biology are affected by learning processes (Ariyati et al., 2024). Therefore, a focus on the components of SR, CRIT, and CRET is required by educators and teachers to get insights into the cognitive and metacognitive skills of students' HoM. Educational applications of VR in science subjects such as biology have been noted for their potential to support HoM development by simulating complex, often abstract, phenomena (Solmaz et al., 2024). VR-based biology classes are thought to be autotelic for the fun they provide. It is a hope for out-of-school experiences within the school where students can discover and contribute within a safe and convenient environment. VR outperforms interactive screens and computers by giving each student a sufficient opportunity to engage, explore and discover freely while fully immersed.

Kamińska et al. (2019) highlighted the necessity of abstract thinking for learners, especially in science where concepts are not entirely tangible and might cause deficiencies in understanding fundamentals which consequently hinders further development and exploration of the learner. Rakhmawati et al. (2020) indicated that Indonesian biology school textbooks are full of writings with little pictures that make them incomprehensible. This reduces students' interest in learning and results in a distorted conception of biology concepts.

Constructivism believes that learning is an active process (Bharathi and Pande, 2024; Fadli et al., 2024; Kurt and Sezek, 2021) that enhances thinking skills (Angraini et al., 2024; Bharathi and Pande, 2024) and that knowledge is a quality that is built around discovery and is constructed best when the learner is free to discover and solve problems (Kurt and Sezek, 2021; Mvududu and Thiel-Burgess, 2012; Sengul, 2024; Stigall and Sharma, 2017) rather than acquired by oral transmission of information and can be implemented at any grade level (Zhao et al., 2023) either within a group or individually (Marougkas et al., 2023). It affects critical thinking (CRIT) and creativity (CRET) in problem-solving and therefore, improves academic achievement (Almulla, 2023).

As a result, modern technologies such as VR became of great importance in the educational field in a way that they affected every aspect of the teaching learning process as tools used to enhance learning motivation and student outcomes (Cevikbas et al., 2023). Hence, it became critically important for educators to understand VRI's impact on group dynamics and cognitive performance in professional settings (Macchi and De Pisapia, 2024).

However, this positive view of VRI is not without limitations or contradictory findings. Learning might be impeded by the cognitive load in some cases especially when learners lack sufficient scaffolding. Several studies report that the cognitive load induced by immersive technologies can, in some cases, impede learning, particularly when learners lack sufficient scaffolding (Makransky et al., 2021). Although VR environments enhanced perceived understanding, they did not lead to measurable improvements in learning outcomes (Clegg et al., 2024). This implies a risk of an illusion of learning, where technological complexity is mistaken for instructional effectiveness.

Parong and Mayer (2021) media-comparison study showed that participants who studied in immersive VR performed more poorly on transfer tests, reported higher extraneous cognitive load and emotional arousal, and evidenced lower cognitive engagement, compared to those using a well-designed desktop slideshow. Mediation analyses indicated that these negative effects stemmed indirectly from distraction and overload. Therefore, multimedia principles such as coherence, contiguity, and reduced redundancy, are essential rather than mere immersion.

Educational VR is the construction of the desired learning environment through the simulation of computer equipment and adding real or virtual pictures in the simulated situations to live and realize that situation (Hu et al., 2016). It is visiting the subject matter virtually through technology while keeping safe, staying in place, and having the freedom to explore here and there. It provides with highly authentic interaction, allowing the users to operate and interact with the objects through the man-machine interface. Liu et al. (2013) proposed three elements to construct a VR situation which he called (3Is): Immersion, Interaction, and Imagination.

Therefore, VRI has emerged as a potentially effective method for teaching science by increasing students' engagement, and enhancing student's SR, CRIT, and CRET.

1.1 Theoretical framework

Recent studies about engagement support the idea that interactive teaching methods generate higher levels of students' engagement (Kurt and Sezek, 2021). In a study about the use of VR in educational environments (Scavarelli et al., 2021) were optimistic about VR as an educational tool. The study concluded that VR-based instruction is effective for enhancing learning outcomes. Students can engage with diverse perspectives, solve problems, and participate in analytical tasks which contribute to the development of CRIT when they work together.

A learner-centered environment where knowledge can be constructed through actual experiences can be easily applied by the help of VR technology (Serna-Mendiburu and Guerra-Tamez, 2024; Zhao et al., 2023). Meaningful learning according to constructivism happens when learners interact with the surrounding environment, engage in exploration, experimentation, and reflection (Pande and Bharathi, 2020). Attempts to enhance the quality of science teaching and learning process and enhancing

HoM usually engage learners in scientific practices to encourage the "how" and "why" of the learners CRIT (Wang et al., 2024).

Richardson (2023) considers any interactive content as always preferred to a static one in terms of retention, cognition, and increased levels of engagement. Educators nowadays can integrate a combination of media in the classrooms to increase students' interaction (Chang et al., 2011), therefore, an increased engagement or immersion, leading to better outcomes (Behmanesh et al., 2022; Haleem et al., 2022). VR in education has a great potential in providing students with immersive and interactive experiences. VRI technologies and learning experiences have been increasingly used in education settings to support a variety of instructional methods and outcomes by providing experiential and authentic learning experiences (Lowell and Yan, 2024; Marougkas et al., 2023).

Habits of Mind (HoM) is a mixture of skills, attitudes, and experiences of the past and are very supportive of students' performance in everyday life (Idris and Hidayati, 2017). They can be developed by applying specific learning models and techniques based on student-centered environments where students can freely explore their knowledge and share ideas.

Based on the above, this study aims to investigate the effects of VRI method of teaching biology on high school students' HoM based on Marzano et al. (1993)'s habits of minds, namely: *SR, CRIT* and *CRET*. This awareness will enable curriculum designers, school principals and educators to effectively plan for the best strategies to be applied for a smooth and successful achievement of the goals wished for.

1.1.1 Virtual reality immersion

Virtual reality immersion (VRI) refers to the degree to which senses are absorbed in the virtual simulation with enjoyment, energy, and involvement (Berkman and Akan, 2019). Implementing VR in education provides more immersive and engaging learning experiences. VR takes the learners to difficult-to-access places, such as historical monuments, outer space or even within the human body. Students can better understand the subject and engage with the learning material (Marougkas et al., 2023). According to Di Mitri et al. (2024), immersive learning highlights the idea of enhancing the quality of authenticity of educational experiences. It can create different levels of realism, feedback, and interaction using high-immersion VR.

Digital immersive technologies according to Tang (2024) promote divergent thinking and self-directed learning. Engagement through immersion provides interaction and participatory experiences that encourage learners to engage in learning responsively and develop critical thinking by providing chances to solve problems and make decisions.

Immersion, according to Schubert et al. (2001) is a cognitive process that leads to the emergence of *presence:* a state of consciousness that generates a sense of being in the virtual environment. For presence to occur, the virtual environment should be inclusive, extensive, surrounding, and vivid. The more similar the transformations in the virtual environment are to those in the real world, the higher the presence.

Kamińska et al. (2019) highlight the necessity of abstract thinking for learners, especially in science where concepts are not entirely tangible and might cause deficiencies in understanding fundamentals which consequently hinders further development and exploration of the learner.

Rojas-Sánchez et al. (2023) stressed that practical experiences for competent learners are difficult to apply in a traditional teacher-centered classroom environment for reasons related to time, space, danger, cost, or accessibility. This diminishes the major goal of education by its incapacity to offer students opportunities that foster the acquisition of knowledge, skills, and positive values, particularly in situations of risk or when experiments are not easily accessible in natural classroom environments and therefore hindering active engagement with targeted concepts.

1.2 Habits of mind

The concept of habits of mind emerged from the field of brain research and education (Alhamlan et al., 2017). It refers to the way our minds behave when confronted with a challenging that requires strategic reasoning, insightfulness, perseverance, creativity, and craftsmanship to resolve a complex problem (Costa and Kallick, 2000; Idris and Hidayati, 2017).

Habits of Mind (HoM) can be enhanced intentionally through learning and can generate effective learning through enhancing productive thinking. Costa and Kallick (2000) identified 16 habits of mind, however, Marzano et al. (1993) stressed self regulation, critical and creative thinking as fundamental components to life-long learning. In his fifth and most important dimension of learning. His framework emphasized the development of productive mental habits to enable learners think and function autonomously, critically and innovatively. In the study, HoM is operationalized through these three core dimensions, as they directly reflect students' cognitive and metacognitive engagement in immersive learning environments.

1.2.1 Self regulation

Self-Regulation (SR) is a cyclical process involving goal setting, strategic action and self reflection (Zimmerman, 2002). It refers to learners' ability to monitor and adapt their behaviors, thoughts, and emotions to achieve goals (De La Fuente et al., 2022). Following Zimmerman's tri-phasic framework, SR includes forethought, performance, and self-reflection phases. In virtual reality (VR) immersive scenarios, these phases occur automatically as students decide, observe progress, and adjust actions in real-time (Abdalkader, 2022; Makransky et al., 2021; Mitsea et al., 2023). SR therefore incorporates cognitive, motivational, and emotional factors—all critical components amplified by the self-direction and realism VR-based learning entails.

1.2.2 Critical thinking

Critical thinking (CRIT) is a metacognitive process that includes analysis, evaluation, and inference to make reasoned decisions or to solve complex problems (Dwyer et al., 2014; Jamaludin et al., 2022; Paul and Elder, 2019). It is the ability to look deep into the problem from different perspectives, to understand it, analyse it, and finally make a decision, of what the best actions to be taken that will handle it (Campo et al., 2023; Kusmaryono, 2023; Utomo et al., 2023). It consists of cognitive skills (e.g., identifying assumptions, evaluating evidence) as well as dispositional traits (e.g., open-mindedness, intellectual curiosity) (Valenzuela et al., 2017). In terms of biology education, CRIT gives students the ability to interpret data, weigh alternatives, and reason scientific argumentation. Engaging learning experiences in authentic, problem-based contexts as found in immersive experiences created through VR enable CRIT through ways of observing, reflecting, and making informed judgments as learners (Prawat, 1991; Yuan, 2023). Therefore, VR allows for the development of critical thinking skills while developing the mindsets used to critically inquire into content.

1.2.3 Creative thinking

CRET is defined as the capability to generate new, important, and contextually relevant ideas or solutions (Sternberg and Lubart, 1998; Usha, 2009). Creativity can be nurtured over time by enhancing specific skill sets and knowledge, and by finding the right environment for learners' cognitive processes, in addition to disposition factors (namely, motivations). Students' creativity is measured below in three ways: creative expression, knowledge construction, and creative problem solving (Karunarathne and Calma, 2024). CRET has divergent thinking, flexibility, and describes a person or learner's ability to synthesize knowledge in new ways. For science education, CRET allows for inquiry, innovation, adaptive problem-solving, etc. VR experiences in immersive environments seek to evocate creativity as they by default are using open-ended exploratory approaches to generate ideas, experiment and iterate (Tang, 2024). Immersive environments also scaffold internal motivation and cognitive flexibility as two important prerequisites of creativity by immersing learners in their exciting dynamic environments where the learner's conception of space and content uncertainty shift (Karunarathne and Calma, 2024; Lindberg et al., 2017).

There is evidence that students' HoM and cognitive learning outcomes in biology are influenced by the learning processes (Ariyati et al., 2024). Therefore, it is important for educators and teachers to develop knowledge about the components of SR, CRIT, and CRET in order to uncover the cognitive and metacognitive skills of students' HoM in order to advance their HoM.

1.3 Research objective and questions

The objective of the research is to examine the impact of virtual reality immersion in Biology classes, on East Jerusalem High school students' habits of mind.

Based on the above, the following research questions have been formulated:

RQ1: Are there statistically significant differences in high school students' HoM due to VRI-based method of teaching biology?

RQ2: How do high school students perceive the overall impact of VRI-based biology classes on their HoM?

1.4 Study hypotheses

Based on the above, the study hypotheses are:

H1: Higher levels of VRI in biology classes enhance students' SR.
H2: Higher levels of VRI in biology classes enhance students' CRIT.
H3: Higher levels of VRI in biology classes enhance students' CRET.

2 Methodology

This quasi- experimental explanatory mixed method design aimed to investigate the effects of VRI-based biology classes on East Jerusalem High School students' SR, CRIT, and CRET. The mixed design allows for the explanation of the goals of the study, and the exact effects of VRI on students' HoM during biology classes. Integration of quantitative data with qualitative insights helps address both the measurable effects and the underlying experiences and perceptions of the students about VRI and achieve methodological triangulation. Triangulation enables a rich understanding of the phenomenon by examining it from different angles. Validity and reliability of the findings were also achieved through employing data source triangulation which involved combining data from semi-structured interviews with participating students and common insights from focus groups and classroom observations. Data source triangulation was achieved by gathering perspectives from students to understand the impact of VRI on HoM comprehensively.

2.1 Study sample

The experiment was exclusively conducted on East Jerusalem government High School Students (10^{th}-12^{th} graders) aged between 15 and 18 based on random cluster sampling. The sample included 207 students taught by four biology teachers from three different high schools (two male schools and one female). The sample for the experiment was selected using a random cluster sampling approach. Initially, high schools in East Jerusalem were randomly chosen from an existing list. In the next phase, students were recruited: in schools with enough students, a random selection was made, whereas in schools with fewer students, all available students were included in the sample. Table 1 summarizes the demography of the sample.

2.2 Virtual reality intervention

The VR biology sessions were developed in accordance with the principles of constructivist learning theory (Fadli et al., 2024; Kurt and Sezek, 2021) which relies on students being active and experiential in their learning. As noted previously, constructivism

TABLE 1 Sample numbers and percentage based on gender, class, and school.

Variable	Category	Frequency	Total	Percent
Gender	Male	142	207	68.6
Gender	Female	65		31.4
Class	10th Grade	87	207	42.0
Class	11th Grade	55		26.6
Class	12th Grade	65		31.4
School	Shufat Boys	73	207	35.3
School	Al-Mutanabi Boys	69		33.3
School	Beit Hanina Girls	65		31.4

TABLE 2 Biology contents and number of sessions for each grade level.

Grade	Topics	Number of sessions
10 th	The Cell	8
11th	Nerve Impulse and The Cell	8
12th	Photosynthesis	6

supports the purposes of developing Habits of Mind (HoM) such as critical and creative thinking (Angraini et al., 2024; Kurt and Sezek, 2021; Pande and Bharathi, 2020). In the implementation of the VR biology sessions, the participating biology teachers cooperatively reviewed the national secondary biology curriculum and chose content areas which they agreed to be complex and abstract to students (and therefore often problematic for students in terms of understanding). All the teachers had developed experience in the VR implementation process, and they selected what they thought were the most appropriate Arabic-language immersive 3D educational scenes from the VR scene database, linked to the curriculum topics. The curriculum topics were adapted into explicit lesson plans consisting of a standardized sequence of instruction: (1) introduction of topic and learning outcomes; (2) immersive VR interaction; (3) reflection discussion/reflection; (4) activity application; (5) summary of the lesson.

The students participated in six to eight immersive biology sessions using Meta Quest 3 headsets, providing the students with high-quality 3D images, interactive spatial environments and spatial hand controllers in an educational context. The digital content was sourced from pre-existing educational platforms like http://www.youtube.com or http://www.mazaweb.com which provide immersive modules for high school science instruction. The biology sessions focused on certain key biological concepts through all three secondary grades – 10, 11, and 12. The intervention was implemented during the first semester (September to December) of the 2024–2025 school year. Table 2 provides a summary of topics per grade level and the number of sessions across the grade levels.

Participating biology teachers collaboratively reviewed the national secondary biology curriculum and selected topics characterized by abstract and complex content—commonly difficult for students to understand. The teachers, all trained in the VR implementation process, identified the most suitable Arabic-language immersive 3D educational scenes aligned with the curriculum. The topics were integrated into structured lesson plans that followed a consistent instructional sequence: (1) topic introduction and learning objectives, (2) immersive VR interaction, (3) reflective discussion, (4) application activities, and (5) lesson summarization.

2.3 Study tools

A comprehensive questionnaire used a Likert scale with five answer choices namely, *strongly agree, agree, neutral, disagree, and strongly disagree*, combined two validated tools to measure the different constructs related to the study:

1. To measure the dependent constructs of the study (SR, CRIT, and CRET): The study employed a validated questionnaire of HoM developed by Hidayati and Idris (2020) and based on Marzano (1992) and Marzano et al. (1993) habits of mind. This tool was used for the pretest part of the study.
2. To measure the effects of the independent construct VRI, Schubert et al. (2001) validated Igroup Presence Questionnaire–Short (IPQ-S) was added to the questionnaire to measure students' level of immersion during biology classes. This part was added for the posttest only. Table 3 shows constructs of the study and their items adapted from previous studies.

The item count is consistent with comparable studies that use short-form subscales for research in classrooms (e.g., De La Fuente et al., 2022; Utomo et al., 2023). Although short, the items were selected and validated for conceptual clarity, coverage, and readability for students.

2.3.1 Validity and reliability

The tool used for this research was adapted from already validated web-based tools SR, CRIT, and CRET. As these subscales had been previously validated, a psychometric revalidation was conducted based on the current study context and group of research participants (high school students in East Jerusalem).

As part of establishing construct validity, an Exploratory Factor Analysis (EFA) was performed using Principal Axis Factoring with Varimax rotation on the 13 items. The Kaiser-Meyer-Olkin (KMO) measure was 0.886, indicating excellent sampling adequacy (Kaiser, 1974). Resultantly, a significant Bartlett's Test of Sphericity, χ^2 (78) = 1,097.236, $p < 0.001$ indicated the correlation matrix was suitable for factor extraction.

There were 2 factors that were extracted, explaining a cumulative variance of 54.4%, which were rationalized by 2 factors on the screen plot. The items related to SR were distinguished and clustered onto Factor 1. Items related to CRIT and CRET were clustered onto Factor 2, indicating some conceptual overlap between cognitive and the creative domain. In sum, the broad themes were appropriately interpreted as factors.

Cronbach's alpha was used to determine internal consistency. Table 4 summarizes the results.

TABLE 3 Constructs and their items adapted from previous studies.

Construct	Abb	#	Item	Source or reference
Immersion VR	VRI	1	I felt that I had a sense of being there. (SP)	Schubert et al., 2001
		2	I felt that VR world surrounded me. (SP)	
		3	I was completely captivated by the virtual world. (INV)	
		4	I was aware of my real environment during the experience. (INV)	
		5	The virtual world seemed very realistic to me. (ER)	
		6	I felt the objects in the virtual world looked realistic. (ER)	
Self-regulation	SR	1	Recognizing self-thinking	Hidayati and Idris, 2020
		2	Making effective plans	
		3	Understanding and using the needed information	
		4	Becoming sensitive toward feedback	
		5	Evaluating the effectiveness of acts	
Critical thinking	CRIT	1	Being accurate and able to look for accuracy	
		2	Being clear and able to look for clarity	
		3	Being open	
		4	Being able to position oneself when there is a guarantee	
		5	Being sensitive and able to recognize friends' abilities	
Creative thinking	CRET	1	Being able to involve oneself in tasks although the answer and solution has not yet to be found	
		2	Trying hard to expand skills and knowledge	
		3	Creating new ways or point of view outside the common knowledge	

The overall reliability of the 13-item tool was α = 0.889 (strong). The reliability for the subscales was acceptable:

All acceptable levels of reliability exceed $\alpha \geq 0.70$ (Tavakol and Dennick, 2011).

TABLE 4 Cronbach's alpha reliability coefficients for each subscale.

Construct	No. of items	Cronbach's alpha (α)
SR	5	0.826
CRIT	5	0.795
CRET	3	0.743
Total instrument	13	0.889

2.4 Data collection

The final questionnaire was sent to the participating biology teachers as a Google form who sent it to the participating groups via WhatsApp groups which were created for the experiment. Two hundred and seven participants out of 207 successfully submitted the questionnaire. Data was stored, ensuring the anonymity of the participants and confidentiality of information.

Qualitative data was collected from observations, semi-structured interviews with ten participants, and discussion with three focus groups (FGs) of 8 participants each.

2.5 Data analysis

The study employed quantitative and qualitative methods of analysis.

2.5.1 Quantitative analysis

For the quantitative results, a paired sample T-test was conducted using SPSS to compare the pre-test and the post-test. The test examines whether there is a significant difference between Pre and Post-tests, making it suitable for evaluating the effect of VRI on students' HoM. However, tests of normality using the Shapiro-Wilk test showed that all p values were < 0.05 meaning that none of the variables were normally distributed. Hence, the non-parametric Wilcoxon Singed-Rank Test was employed.

2.5.2 Qualitative analysis

To explore students' insights and perceptions of experiencing VRI in biology classes, and the effects it had on their HoM, the following tools were used to enhance data triangulation, thereby increasing the credibility and trustworthiness of the findings.

2.5.2.1 Semi-structured interviews

The interview was designed to include all types of questions recommended by Qu and Dumay (2011), with the purpose of systematically delineating the topics in an interconnected manner.

An interview guide, to identify the most suitable questions that would answer the research questions, was developed and revised by experts and colleagues.

2.5.2.2 Focus group discussion

Three focus groups with random participants were held to allow for a deeper delve into the information and valuable common fresh insights reflected by the participants. The content of the discussion revolved around the study's major questions and related to the effects of VRI on HoM.

2.5.2.3 Observations

To provide a comprehensive understanding of how VRI impacts students in real-time, complementing the data from interviews and FGs, observations were also taken into consideration. A checklist, derived from the questionnaire, included signs of immersion in VRI and how it affected students' HoM was prepared.

2.6 Data collection

Qualitative data was gathered and analyzed through a systematic coding process that combined both *In Vivo* and descriptive coding to identify and report patterns within the data (Braun and Clarke, 2006). The coding process employed MAXQDA software to facilitate the integration of theoretical and emergent codes. To ensure consistency, an intercoder, who was familiarized with the study constructs, helped in coding samples of the interviews and FGs' scripts independently. An agreement on 17 out of 18 deductive subcategories (94%) was achieved. Observations, being less text-based, were discussed separately based on pictures and notes taken during the sessions (Mannay, 2015). The results of coding were compared and discussed until arriving at an agreement. The coding framework was refined accordingly. Initial codes and primary categories were shared with the participants to enhance accuracy (O'Connor and Joffe, 2020). Data was recorded and stored, ensuring the anonymity of the participants and confidentiality of information.

2.7 Coding process

Participants' narratives from interviews and FGs were transcribed and revised, then a codebook was prepared. The first cycle of coding revealed two emergent codes: *Generation of a dynamic Conceptual Visualization,* a process that learners employ to transform abstract ideas into visual representations to enhance understanding and communication (DeCaro et al., 2023). *Exploratory Oriented* where students explore novel activities in the form of problem solving before actual formal teaching takes place, enabling them to integrate new information with prior knowledge (DeCaro et al., 2023). The new emerging codes were added to the codebook under CRET and CRIT respectively.

Both deductive and inductive codes arising from participants' narratives were systematically managed within MAXQDA. Pattern coding in the second cycle was also conducted using the software, ensuring a structured and replicable categorization of themes.

In Vivo coding extracted interviewees statements, followed by descriptive coding whereby each statement was labeled with a brief description (Saldaña, 2021). This yielded numerous codes under thematic categories including inductive subcategories.

The second cycle coding included pattern coding where similar groups of descriptive codes were classified under suitable sub-categories.

Finally, thematic coding was employed to clarify the relationships between primary categories and their sub-categories.

2.8 Trustworthiness of the research findings

Trustworthiness was achieved through credibility, transferability, dependability, and confirmability. Credibility to ensure that findings represent accurate reflections of the participants according to Ahmed (2024) was achieved through the prolonged time spent with participating students and building trust with them. Two methods were used to add credibility via triangulation of three qualitative data sources: individual interviews, focus group discussions, and classroom observations. Themes were compared using the three qualitative data types for convergence, divergence, and complementarity of students' responses about their development of HoM in the VRI (Creswell and Poth, 2018). By triangulating the three different sources of data, this provided further validation of the emerging patterns and possible interpretation of findings. Transferability was ensured through rich quotations, comparisons, and continuous validation of interpretations ensured quality according to Chowdhury (2015) and Lincoln et al. (1985). Illustrative visualizations generated in MAXQDA offered rich and clear descriptions of the data, to allow readers evaluate applicability in other contexts. Dependability was achieved through a detailed methodology description and record of all the study activities (Chowdhury, 2015). MAXQDA documented all coding and analytical decisions to facilitated peer debriefing sessions, where two expert colleagues reviewed the coding framework and agreed on 90% of the thematic categories, as indicated by Holsti's method. Confirmability was achieved through participants feedback during observations, interviews and FGs to avoid bias (Ahmed, 2024). The systematic organization of data in MAXQDA provided an objective basis for interpretations, minimizing the influence of personal bias.

3 Results

3.1 Quantitative results

Quantitative analysis addresses the studies first question:

RQ1: Are there statistically significant differences in students HoM due to VRI-based method of teaching biology?

To answer this question, the paired samples *t*-test was conducted using SPSS, assessing whether the mean differences between pre-test and post-test scores are statistically significant.

As shown in Table 5, tests of normality using the Shapiro-Wilk test showed that all variables SR, CRIT, and CRET significantly deviated from normality ($p < 0.05$), violating the assumptions for parametric testing.

Therefore, the non-parametric Wilcoxon Singed-Rank Test was employed to assess the impact of VRI on students' SR, CRIT, and CRET. Wilcoxon Signed-Rank Test Results indicated that students significantly improved in all three output variables: Table 6 summarizes.

Comparing pre and post-test means results of (SR, CRIT, and CRET) showed that students' SR increased from $M = 14.94$ ($SD = 3.57$) at pre-test to $M = 19.16$ ($SD = 3.30$) at post-test, $Z = -9.13$, $p < 0.001$, $r = 0.63$, indicating a large effect. CRIT increased from a pretest $M = 15.85$ ($SD = 3.17$) to $M = 18.72$ ($SD = 3.95$), $Z = -6.74$, $p < 0.001$, $r = 0.47$, a medium-to-large effect. Similarly, CRET improved significantly, from $M = 9.48$ ($SD = 2.22$) to $M = 11.57$ ($SD = 2.15$), $Z = -7.89$, $p < 0.001$, $r = 0.55$, reflecting a large effect. This emphasized the effect of VRI intervention on students' HoM with the highest gains in SR.

Figure 1 illustrates the difference in students' mean scores in pre and post-tests in SR, CRIT, and CRET before and after VRI intervention.

Interpretation of r followed Cohen's (1988) guidelines: Values below 0.3 were considered small, between 0.3 and 0.5 medium, and above 0.5 large effects. Hence, quantitative results reflected the large effect of VRI-based biology classes on students' SR and CRET, and a medium to large effect on CRIT. Therefore, H1, H2, and H3 are supported.

3.2 Qualitative results

To answer the study's RQ2: How do students perceive the overall impact of VRI-based biology classes on their HoM?

The qualitative study aimed to explain the impact of VRI on students' HoM. CAMIL provides explanations of the way VRI affects cognitive outcomes through active participation in actual experiences according to Tang (2024). VRI-based biology classes aimed to study participants' natural behaviors and to allow for insights into authentic behaviors and interactions that might not be gained through interviews or FGs. Semi-structured interviews with participating students as well as FGs aimed to capture students' experiences, perceptions, and reflections on how immersion in virtual environments influenced their learning processes and cognitive development.

Table 7 from MAXQDA summarizes deductive and inductive results of the coding process extracted from semi-structured interviews with ten students and three FGs from different grade levels of the participating schools.

Deductive analysis revealed the same primary categories of VRI, SR, CRIT, and CRET. However, inductive analysis revealed two subcategories emerging under CRIT and CRET. *Generation of Conceptual Visualization* emerged as a dominant subcategory of CRET with a frequency of 49 instances representing 18% of the CRET primary category, and *Exploratory Oriented* emerged as a subcategory of CRIT with a frequency of 26 instances representing 11% of the primary category.

3.2.1 Immersion in virtual reality

Integrating VRI in biology classes revealed numerous manifestations of three subcategories: spatial presence (SP); involvement (INV); and experiential reality (ER). Numerous instances from direct observations, FGs and semi-structured interviews indicated students' deep level of immersion and engagement in the virtual world during different VR-based biology classes.

3.2.1.1 Spatial presence

Spatial presence (SP) was manifested through students' physical and verbal interactions with the virtual environment. Observations highlighted students' movements trying to reach virtual objects, stepping forward and backwards, and synchronized behaviors across groups. Students bent down simultaneously during a 3D scene exploration, creating a sense of shared immersion. Verbal comments further emphasized this, with one student stating, "*I feel a bit dizzy climbing the DNA ladder*" and another noting, "*The weather is fine here*" while immersed in a photosynthesis simulation in a cold December day.

3.2.1.2 Involvement

Involvement (INV) was reflected through deep engagement, attentiveness and persistence of students to complete VR tasks. Even weaker students reflected strong motivation to actively participate. One student expressed frustration at not having enough time, remarking, "*You said we have 5 minutes to finish the activity, but it's been only half a minute. Give me a chance to try another way to do it.*" Students in FG1 agreed that "*While interacting with the virtual environment, you forget whether you are sitting or standing, and you might bump into things because of how focused you are.*" This highlights how VRI activities enhanced intrinsic motivation and problem-solving focus, keeping students immersed and willing to invest time and effort beyond traditional class limits.

3.2.1.3 Experiential reality

Experiential reality (ER) was observed through students' descriptions of the virtual environment as reality itself. Many students commented, "*It felt real.*" or "*I feel I am in a real cell.*" A shy, academically weak student vividly recounted his immersive experience: "*I was inside the cell, seeing detailed interactions between ribosomes, the endoplasmic reticulum, and the Golgi apparatus. This helped me understand better than ever.*" Discussion with students in FG2 reinforced the same idea "*We saw the inside of the cell, and everything was moving around us. We were inside it, seeing things up close.*" This demonstrates how VRI transformed abstract concepts into vivid, interactive experiences, enhancing engagement, understanding and retention.

3.2.2 Habits of mind

The term HoM represents cognitive and behavioral patterns that influence problem solving, decision making, and learning.

TABLE 5 Results of test of normality.

Tests of normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
PRE_SR	0.14	207	0.00	0.96	207	0.00
POST_SR	0.10	207	0.00	0.97	207	0.00
PRE_CRIT	0.15	207	0.00	0.92	207	0.00
POST_CRIT	0.12	207	0.00	0.96	207	0.00
PRE_CRET	0.13	207	0.00	0.97	207	0.00
POST_CRET	0.18	207	0.00	0.95	207	0.00

[a]Lilliefors significance correction.

TABLE 6 Pre- and post-test descriptive statistics and Wilcoxon results for HoM constructs (N = 207).

Variable	Pre-test *M (SD)*	Post-test *M (SD)*	*M* difference	*Z*	*P*	*r*	Effect size
SR	14.94 (3.57)	19.16 (3.30)	Q4.22	−9.13	<0.001	0.63	Large
CRIT	15.85 (3.17)	18.72 (3.95)	2.78	−6.74	<0.001	0.47	Medium–Large
CRET	9.48 (2.22)	11.57 (2.15)	2.1	−7.89	<0.001	0.55	Large

Effect sizes were computed using the formula $r = Z\sqrt{N}$, where Z is the standardized test statistic from the Wilcoxon Signed-Rank Test and N is the sample size.

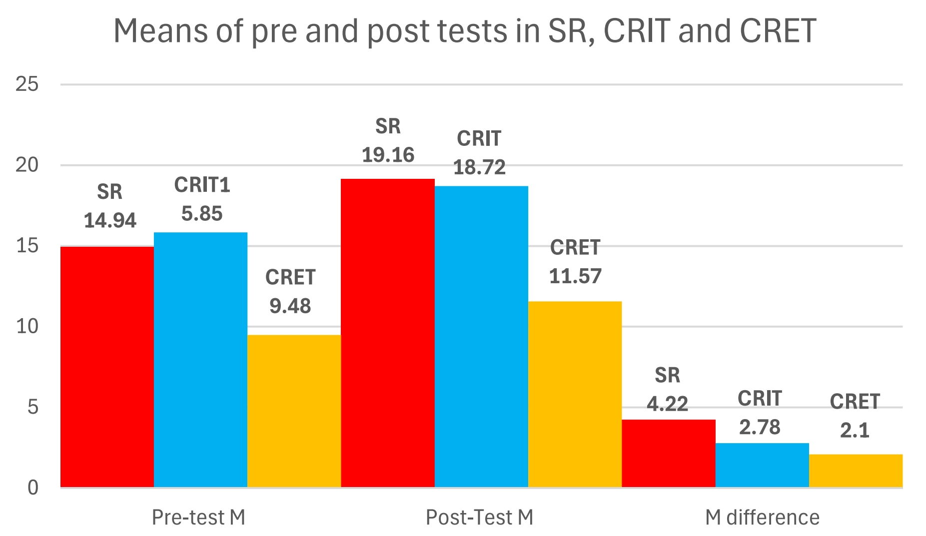

FIGURE 1
Means of pre and post-tests in SR, CRIT, and CRET and difference.

Therefore, it encompasses three primary categories: SR, CRIT, and CRET.

3.2.2.1 Self-regulation

Students' ability to employ meta skills that enable awareness, monitoring and adaptation of learning strategies through cognitive and meta cognitive processes is referred to as self-regulation. It is a way to control over oneself while goal directed. Analysis of interviews highlighted five subcategories within the Self-Regulation primary category.

3.2.2.1.1 Sensitivity to feedback

Students actively used feedback from teachers and peers during the VRI sessions. Students needed immediate feedback to adjust their actions in the virtual environment to achieve their goals. Student E. Z2 remarked, "*If I faced difficulty, I would ask the teacher or the students, listen to their guidance, and find the solution after trying.*" One shared insight of FG2 was, "*the teacher is indispensable. You need someone to explain the material and provide the necessary guidance to complete the tasks.*" This shows how VRI encourages students to seek and use feedback when they are goal-directed, driven by the force of intrinsic motivation to achieve a specific goal.

TABLE 7 Primary categories and sub-categories (frequencies and percentages).

Code system	Frequency	Percentage of primary categories	Subcategory	Frequency	Percentage of subcategory
Total codes				931	100%
Virtual reality immersion (VRI)	184	20%	Spatial Presence (SP)	74	40%
			Involvement (INV)	81	44%
			Experiential Reality (ER)	29	16%
Self-regulation (SR)	236	25%	Sensitivity to feedback	28	12%
			Self-evaluation of effectiveness	52	22%
			Management of resources	51	22%
			Planning effectively	41	17%
			Awareness of own thinking	64	27%
Critical thinking (CRIT)	233	25%	Taking positions assertively	26	11%
			Impulsivity Restrain	30	13%
			Open mindedness	27	12%
			Clarity-driven	32	14%
			Accuracy-oriented	63	27%
			Empathy with others' feelings and knowledge	29	12%
			Exploratory Oriented *(Inductive)*	26	11%
Creative thinking (CRET)	278	30%	Generates new ways for viewing situations	78	28%
			Generates own standards for evaluation	51	18%
			Pushing the limits of own knowledge and ability	52	19%
			Engagement in tasks with no clear solutions	48	17%
			Generation of Conceptual Visualization *(Inductive)*	49	18%

3.2.2.1.2 Evaluating own effectiveness of acts

Responding to feedback to adjust ineffective methods or seek guidance was a common act among students during interaction. Students paused during VR activities, sought feedback, and made necessary adjustments before re-immersing in the virtual world. Students' interviews reflected their matured levels of self-evaluation. Sh. I4 noted, "*In VR, I followed the cell step by step, and whenever I felt lost, I would ask my classmate or the teacher. When I returned, I felt much closer to finding the solution.*" This reflects students' ability to evaluate their performance through closely watching over their actions during VR sessions and making necessary adjustments to ensure achievement of objectives.

3.2.2.1.3 Management of resources

Students were observed checking their books before VRI sessions to identify what might be needed to achieve their goals successfully. In many cases, they asked clarifying questions that aimed to solve a conflicting idea. Interviews showed numerous instances reflecting awareness of the differing resources. K. Ah6 noted, *"You start reviewing the teacher's explanation and the textbook by yourself, then you begin comparing before and after the interaction in VR."* In FG2, most students highlighted the idea that, "*Interactive VR videos effectively enabled them to bridge the gaps in their coursebook and supplemented any content missed during the teacher's explanations*." This reflects matured components of self-regulated learning.

3.2.2.1.4 Effective planning

Sings of effective planning appeared clearer during the 2nd week. Students started giving more attention to lesson objectives, ask clarifying questions before planning how to achieve them. Interviews provided many cases that reflected effective planning. A. M7 noted, "*the most important thing is to know your goals before entering the virtual world and to set a plan for how to achieve them.*" In FGs 1&2 most students agreed that "*you start by planning what you want to understand... and then you go to where you planned.*" This shows how students internalized the importance of precise planning before they start tasks.

3.2.2.1.5 Recognizing self-thinking

VRI promoted metacognitive awareness, with students reflecting on their thought processes and problem-solving strategies. A student remarked, *"VR taught me that focus is the key to understanding and reaching the right solutions, and now I apply this in traditional classes."* Another expressed, *"I started thinking about the function of the nucleus. Why is there a nucleolus? Why does it have this shape?"* This awareness enhanced their ability to adjust learning strategies, increasing engagement and cognitive development.

3.2.2.2 Critical thinking

The study revealed a development of students' CRIT through VRI. The category of CRIT included six deductive subcategories, namely, accuracy oriented, clarity driven, open-mindedness, impulsivity restrain, and sensitivity to other's feelings and knowledge. The emerging inductive subcategory of "exploratory oriented" represented the seventh subcategory.

3.2.2.2.1 Accuracy oriented

Paying attention to details, verifying with key resources, and quickly correcting inaccuracies for clarity appeared clearly through students' continuous referencing to the book, the teacher, and classmates during VR application. Precision was observed through their participation during the discussion part: "*seeing something from all its angles, our understanding of it changes.*" E. Z2 noted, "*We saw each part. How it's formed, how it's structured, and how it interacts with the other parts*." During FGs' discussions, many students noted that, VRI improved their accuracy through providing them with "*the details of the details.*"

3.2.2.2.2 Clarity driven

VRI improved students' clarity in expressing ideas. They were observed asking clarifying questions before presenting their findings. MK3 noted, "*Today, I can answer questions clearly and in multiple ways from different perspectives, just like I learned from different angles*." FG3 students highlighted the insight that VRI deeply enhanced their understanding. Most students agreed that: *"Receptive clarity generates productive clarity."* Students agreed, *"Studying nerve impulse transmission from a textbook is exhausting, but in VR, steps became simple and clear."* This proves how VRI-based biology classes enhanced concept clarity which was reflected on students' performance clarity.

3.2.2.2.3 Open-mindedness

Students' tolerance to consider, evaluate, and accept ideas different from their own was observed during the discussion part of the sessions. Students submitted new or contradicting views to investigations based on scientific facts from trusted references. Students' responses during interviews emphasized the same idea. SH. I4 for example, noted that "*I don't mind if my perspective differs from others'. In the end, it's evidence or proof that determines who is right or who is wrong. I can explain my point of view alongside the opposing one."* Discussions with different FGs showed that VR became a reliable source for the evaluation of correctness or wrongness of views or ideas: "*When someone says something incorrect, we take them to the VR, and there, they figure out truth, whether they are right or wrong.*" This reflects how VRI based classes drove students toward open-mindedness and submitting different views for scientific proof.

3.2.2.2.4 Impulsivity restrain

Students' behaviors during VRI discussion parts, such as closing their eyes and raising their heads trying to recall VR happenings, and analyze it before talking to prove their points, were clearly observed. The same behavior was repeated during the interviews when they were asked to describe their feelings during VRI. A.H9 shared, "*I started double-checking my answers and verifying the accuracy of the information I have before responding in exams or in class.*" During FG2 Many students expressed, "*caring about the consequences of their decisions before they proceed*." This reflects enhanced students' self-control and their ability to restrain their impulsivity.

3.2.2.2.5 Taking positions assertively

Maturity of students' SR enhanced their awareness of specific details about the content. This awareness improved their ability to take stands in discussions and support it logically based on facts and knowledge they acquired from interacting with the VR biology content. Having the freedom to interact freely, students were able to support their stands from different perspectives. A.K5 remarked: "*when you see something with your own eyes, you'll be able to discuss it confidently."* This clarifies the difference between knowledge gained and knowledge dictated.

3.2.2.2.6 Sensitivity to others' feelings and knowledge

Empathy for others' feelings and knowledge was evident as students demonstrated empathy and respect while collaborating. They supported one another during application. Competent students were patiently cooperating with weaker ones or those who were struggling with the VR tool. During interviews, A. H10 commented, "*I gained the ability to explain the lesson to my classmates in a simplified way, even better than the textbook*." During FG1 discussion, most students agreed that "*Some students feel shy about asking the teacher to explain again when they don't understand. But now, through VR, we can help them without embarrassing them. VR gives you the feeling that you're playing, not studying*." This shows how students cared about other's feelings and perspectives.

3.2.2.2.7 Exploration-oriented (Inductive)

This inductive category emerged during VRI sessions with many students uttering "*look what I found!*" or "*I am exploring the chloroplasts in the leaf.*" Interviews reflected students' desire to discover, gather evidence and construct their knowledge on their own. They saw VRI as the best environment for learning through exploration and discovering. M. A1 noted, "*Instead of the teacher giving us the rules and facts, we can deduce the rules ourselves through VR, verify their accuracy, and apply them as well.*" Exploration was heavily discussed with all FGs and most students agreed that exploration was part of their VRI session, and that it seemed more interesting to explore, discover and apply through VRI.

3.2.2.3 Creative thinking

The study revealed that students' CRET was enhanced through interacting with VRI. Four deductive subcategories and one inductive were revealed. Deductive Categories included: generation of new ways for viewing situations, generation of own standards for evaluation, pushing the limits of own knowledge and abilities and engagement in tasks with no clear solutions. Inductive analysis revealed the category "*Generation of Conceptual Visualization*."

3.2.2.3.1 Generation of new ways for viewing situations

Students actively explored VR objects, zooming in and out, rotating, and analyzing them beyond task requirements. Discussions highlighted improved perception, with Sh. I4 stating, *"I thought DNA was stable, but in VR, I saw it constantly moving in every cell."* FG participants agreed, *"Textbook images are limited, but VR lets you experience processes differently."* This illustrates how VRI fosters deeper and more innovative understanding.

3.2.2.3.2 Generation of own standards for evaluation

Students clearly reflected their new standards for evaluation. Creating new criteria for evaluating their own performance; their coursebooks; and their teachers. Phrases like "*this is exactly what the teachers explained.*" Or "*This is missing in the book*" enabled students to make judgements based on their own experience. Interviewing students supported this when M. K3 said, "*I can now evaluate how accurate our coursebook is, especially in the topics related to the cell and the DNA.*" Discussions with FGs revealed that most students can now easily evaluate their understanding.

3.2.2.3.3 Pushing the limits of own knowledge and abilities

Students were observed to be persistent and insistent to complete the VRI tasks, and even eagerly asked for additional VRI time to allow them to try other approaches that might help complete the task successfully. J. AD8 remarked, *"During VRI, I didn't feel that anything was impossible, especially that I could repeat the experiment and try again as many times as I wanted."* FG3 agreed with the student's comment, "*I've come to realize that I can overcome any obstacle successfully. Interacting with VR encourages you to repeat and try again without getting bored. In the end, you come away with more information than you initially aimed for."* This reflects how VRI affected students' persistence to finish the task in hand with quality.

3.2.2.3.4 Engagement in tasks with no clear solutions

Some of the tasks given to students during VRI needed problem solving skills. Students immediately immersed in the interactive VR scenes, stayed determined to find alternatives and came up with creative solutions. When the task was about "why do you think some trees has colors other than green?" Student A.M7 answered,

> *"I started trying to think about why trees are always green, but in autumn, they turn orange or other colors. Then I remembered that humans also need different kinds of food during the seasons, so I thought maybe plants have the same reason. Or maybe the amount of sunlight affects it as well."*

FG3 students supported the idea that VRI raised their curiosity and encouraged them to keep interacting until they arrive to a logical solution or a better understanding. This highlights the idea that VRI helped students understand better and encouraged them to engage.

3.2.2.3.5 Generation of conceptual visualization (Inductive)

During discussions, students used to close their eyes and move their hands trying to revisit the VR scene when they were trying to get an answer that needed critical or creative thinking. J. AD7 noted, "*VRI videos rely on a detailed explanation of all the components of the organ, and in the end, you see them all working together. This way, you feel the connections between them, the picture becomes complete, and you never forget it.*" The same idea of how VRI helped them visualize and understand, was highlighted through all FGs. For example, one student asserted, "*I still remember the shapes and sounds so vividly that I can draw them from multiple angels.*" This clarifies the difference between VRI and traditional instruction by enabling students to better visualize abstract concepts.

To conclude, VRI enhanced HoM directly through its ability to provide students with clear, safe, attractive, and authentic experiences that helped them construct knowledge through exploration. The experience itself was autotelic, and it generated intrinsic motivation, allowing students to feel competent, comfortable, and skillful. This feeling improved students' self-confidence which enhanced SR greatly. This enhanced SR doubled the effect of VRI on CRIT and CRET.

3.3 Integrating quantitative and qualitative results

Both quantitative and qualitative results reflected how VRI-based biology classes significantly enhanced students' SR, CRIT, and CRET.

3.3.1 Enhanced SR

SR represented in students' ability to employ meta skills that enable awareness, monitoring and adaptation of learning strategies through cognitive and meta cognitive processes. It is a way to control over oneself while goal directed. Quantitative results showed that VRI-based biology classes enhanced students' SR ($r = 0.63$). Qualitative analysis of interview results aligns with the quantitative findings. Analysis of interviews and FGs highlighted five subcategories within the Self-Regulation primary category which counted 236 instances representing (25%) of the total instances.

3.3.2 Enhanced CRIT

Quantitative results reflected that VRI has a medium - high effect on students' CRIT (r = 0.47). Qualitative results supported this by revealing a development of students' CRIT through VRI. Qualitative results represented in 233 (25%) instances supported the enhancement of students' CRIT.

3.3.3 Enhanced CRET

Quantitative results reflected that VRI largely affected students' CRET (r = 0.55). Students' insights clearly reflected how VRI powerfully affected their CRET. Interaction with biology-contents enhanced their abilities to view things differently. Qualitative results showed 78 (28%) cases of the total codes reflecting students' generation of new ways for viewing situations. Interviews and FGs reflected how VR-based biology classes helped students view knowledge from a broader perspective, allowing them to connect various elements and draw meaningful conclusions. An adjusted view based on students' prior knowledge and the VRI content helped this enhancement.

To conclude, both quantitative and qualitative results supported the large effects of VRI-based biology classes on students' SR, CRIT, and CRET.

4 Discussion

4.1 Quantitative discussion

Quantitative results confirmed that VRI-based biology classes have a large significant impact on students' HoM. VRI-based biology classes helped overcome the barriers of the traditional teacher-centered classroom environment represented in time, space, danger, cost, or accessibility as noted by Rojas-Sánchez et al. (2023), and provided practical experiences for students. Thus, immersion in the virtual environment allowed students to actively interact with new fundamental biology concepts enhancing learners' behavioral and cognitive skills. This idea of how immersion helps students deeply understand the content and promote critical and creative thinking aligns with Solmaz et al. (2024) and Prawat (1991).

4.2 Qualitative discussion

Qualitative analysis provided numerous insights generated from observations, semi-structured interviews and FGs, about the mechanisms through which VRI enhances cognitive outcomes. Results are contextualized in existing literature, emphasizing how VRI affects SR, CRIT, and CRET. VRI-based biology sessions enabled students to engage with diverse perspectives, solve problems and participate with analytical activities that fostered their SR, CRIT, and CRET.

4.2.1 Effects of VRI on SR

Findings highlighted the effects of VRI on improving students' SR as responsible for fostering critical and creative thinking. This aligns with Marzano et al. (1993) who emphasized the development of SR as a life-long habit of mind that can create self-directed learners. A matured form of SR was manifested through students' ability to plan and set achievable goals effectively and continuously. This corroborates with Abdalkader (2022) definition of SR as the ability to choose a goal and try to achieve it by specifying the "how and what to do" to achieve it. Students reflected awareness of their thinking and self-evaluation of their performance, while assuming responsibility on their performance, mirroring (Marzano et al., 1993) first desired learning outcome. Awareness of own thinking was reflected through students' critical evaluative inquiries during discussion parts, attempting to adapt their strategies to effectively achieve their goals. A common perception of students during interviews and FGs was about how VRI changed their strategy for learning biology from raw memorization into comprehension. This echoes (Mitsea et al., 2023; Baranovskaya, 2015) definition of SR as an adaptive habit that enables learners to redirect their strategies based on new findings. Students' sensitivity to feedback was another common feature of VRI-based biology classes. Students remarked that they continuously sought feedback from different sources such as, textbooks, teachers, peers, or VR content to evaluate their performance and make adjustments to improve it. This is caused by higher levels of intrinsic motivation which echoes (De La Fuente et al., 2022) definition of SR as related to personal adjustment factors, diligence, and well-adjusted academic behavior which cannot be achieved without sensitivity to feedback. Metacognition was exhibited through students' ability to express their thoughts clearly and unambiguously. VRI helped students notice how to arrange a flow of thoughts in a clear and logical way which was later reflected in their own flow of thoughts. During interviews and FGs, students took time to think about the questions before they provided a detailed well-organized answer reflecting metacognitive processes such as planning, monitoring, and evaluation. This aligns with Baranovskaya (2015), Mitsea et al. (2023), and Zimmerman (2002) view of SR as the ability to employ a set of meta skills to enable awareness, monitoring, and adaptation of learning strategies.

4.2.2 Effects of VRI on CRIT

Qualitative findings confirmed VRI's ability to influence the different aspects of CRIT. Students' accuracy and clarity were manifested during VRI applications when students started to listen attentively to the teachers' instructions before hastily interacting. They asked clarifying questions and revisited their textbooks to compare with what they have learnt before making final decisions. This finds resonance in Jamaludin et al. (2022), Kusmaryono (2023), and Utomo et al. (2023) about how students looked deep into the problem from different perspectives, understood it, analyzed it, and finally made a decision about the best actions to be taken to handle. Open-mindedness was also reflected through group discussions. Students embraced different or opposing views and submitted them to discussions in which each student was trying to prove his or her own views based on persuasion and reliable sources which bolstered Campo et al. (2023) view of CRIT as a skill directed toward understanding and solving problems through evaluating alternatives and making decisions. When students' competence and self-confidence were enhanced, they fostered their assertiveness which appeared through the way they expressed their opinions, ideas, and beliefs confidently and respectfully during discussions and interviews.

In addition, the inductive subcategory of "exploratory oriented learning" can be generated through VRI. The idea of exploring knowledge rather than receiving it was highly emphasized through VRI-based biology interaction. Students enthusiastically reflected on the pleasures of discovering related and unrelated facts or exploring "*the details of the details*" as FG2 noted about ignored discussions by their textbooks or their teachers. Exploration can enhance comprehension, analysis, evaluation, problem solving, and decision making which demonstrates consistency with Campo et al. (2023), Dwyer et al. (2014), and Jamaludin et al. (2022) who highlighted exploratory learning as a catalyst for CRIT.

4.2.3 Effects of VRI on CRET

Qualitative findings also revealed the benefits of VRI-based biology classes on the different dimensions of students' CRET. Students' intense engagement in tasks with no clear solutions as a cognitive habit generated from improved self-regulation was clearly observed during discussions following VRI application. Parts of the discussions included issues with a problem-solving nature in which students showed active engagement reflecting on their experience through the VRI journey, rearranging their ideas in a different new spectrum through analysis, and came up with creative ideas such as "*viewing our bodies from inside the cells might help preventing or curing cancer.*" This underscores (Sternberg and Lubart, 1998) definition of creative thinking as students coming up with a new design through rearrangement of existing ideas. In addition, students pushed the limits of their own knowledge and abilities driven by VRI's motivating force and demonstrated willingness to participate in challenging tasks and work on them with persistence and insistence to improve performance until completed. This finds resonance in Behmanesh et al. (2022) about how increased interaction and levels of engagement lead to better outcomes. Students reflected their ability to define the problem, verify its validity based on scientific reasoning generated from VRI which mirrors Usha (2009) view about validating innovative ideas with scientific reasoning. Generating new ways for viewing things was reflected during and after VRI application through students' evaluation of the available alternatives. Gradually, their recklessness decreased and was replaced by a composed behavior in which they effectively defined their goals, explored alternatives, sought feedback from other students or from the teacher, then made decisions based on the data available before coming up with the best outcomes. This mirrors what Lindberg et al. (2017) assigned to produce creative work. In addition, generating, trusting, and maintaining own standards of evaluation was conveyed by students through completing the VRI tasks based on their own standards of quality. Although students were engaged in the same virtual environment, and interacted with the same 3D scenes, their presentations differed greatly in terms of creativity, language and knowledge based on their own different criteria for a good performance which echoed (Karunarathne and Calma, 2024) three themes for creativity. Finally, the inductive subcategory (Generating dynamic conceptual visualization) gained much weight through students' verbatims. Students transformed this useful VRI experience of dynamic visualization of complex content in biology into other subject areas like chemistry or physics trying to generate a visual representation for chemical reactions or for physical concepts. This improved their understanding and memorization.

To sum up, VRI-based biology classes reflected gradual improvement on students' scientific habits of mind (SR, CRIT, and CRET). The immersion approach helped students deeply understand the content and therefore promote higher-order thinking.

4.3 Integrating quantitative and qualitative discussion

Quantitative results statistically highlighted the effects of VRI-based biology classes on students' HoM when compared with traditional biology classes. This aligns with Prawat (1991) about the ability of immersion to help students better understand the subject matter and foster their higher order thinking skills.

Students' SR was enhanced due to VRI intervention. Students became more self-regulated by controlling over their own thinking in choosing achievable goals and effectively planning for achieving them. This finds resonance in Abdalkader (2022) definition of SR. Quantitative results statistically confirmed the significant differences in students' scores after the application of VRI-based biology classes. Students' self-confidence improved through personal adjustment factors provided by VRI aligning with De La Fuente et al. (2022), and their behaviors became goal-directed aligning with Bayer et al. (2016). Students' insights and reflections about the experiment of learning biology constructively in a student-centered classroom strongly supported this. Students highlighted the importance of regulating their habits of learning to enhance their CRIT and CRET skills. Therefore, both quantitative and qualitative results highlighted the role of VR in developing their HoM.

In addition, quantitative results highlighted a medium-large effect of VRI on students CRIT. It helped students analyze, evaluate and infer, which increased probabilities for arriving at logical solutions to a problem which aligns with Dwyer et al. (2014). Qualitative results supported this through students' insights and reflections about the experiment of learning biology constructively in a student-centered classroom. Interviews and FGs with students manifested the importance of understanding the topic for analyzing, evaluating and finding solutions to problems. This finds resonance in it Jamaludin et al. (2022), Kusmaryono (2023), and Utomo et al. (2023) about how CRIT requires looking deep into the problem from different perspectives to analyze it and make decisions about the best way to solve it. VRI was able to help students understand biology contents and fostered their CRIT.

Finally, quantitative findings evidenced the effects of VRI on students' CRET. This corroborates with Prawat (1991) about how immersion helps students fully comprehend the subject matter and foster HoM. VRI improved students' motivation and skills which resulted in encouraging their CRET according to Lindberg et al. (2017). Qualitative insights supported this in different ways. Through understanding abstract concepts, students' knowledge and skills fostered their cognitive processes and personality and finally stimulated their creativity. This aligns with Karunarathne and Calma (2024). Students' insights about VRI provided a stimulating learning environment which encouraged their creativity as suggested by Lindberg et al. (2017).

5 Theoretical implications

The study contributes to the growing body of research on the effects of VRI on students' cognitive outcomes by providing quantitative and qualitative empirical findings.

Findings of the study align with CAMIL, suggesting that immersive learning environments enhance both cognitive and affective engagement in scientific topics which leads to fostering HoM. The mixed nature of the study provided a comprehensive understanding of how VRI-based biology classes fostered cognitive and metacognitive HoM enhancement in high school education.

The study bridged the gap between the instructional and motivational roles of VRI as a method of teaching biology through its autotelic experience which can affect students' self-regulation, critical, and creative thinking.

6 Practical implications

The study provides valuable practical implications for researchers, curriculum designers, and educators seeking to enhance science education through immersive methods:

The positive results of the effects of VRI on students' HoM in biology classes and the effects it creates on their attitudes toward learning biology should be tested on other scientific high school subjects such as physics, chemistry, mathematics and technology specifically when teaching complex abstract topics.

Curriculum designers should reconsider designation of the curriculum based on the principles of CAMIL. Moreover, program engineers should provide suitable VR applications that meet the content of different school subjects for all grades. In addition, curriculum designers should include activities that allow critical and creative thinking.

Science teachers are advised to engage in training courses about the integration of VR in their classes to be able to integrate VRI in science classes competently, especially when introducing complex foundational concepts to ensure students' effective and constructive perception. Teachers should engage in training courses about the integration of VR in their biology classes.

7 Conclusion

The results of this study suggest that Virtual Reality Immersion within biology classes could further enhance the cognitive and affective engagement of students. Respondents indicate that the immersive qualities of VRI can lead to increasing student motivation and perseverance which are also core indicators of Habits of Mind, and self-regulation, critical thinking, and creative thinking specifically were of interest in this study.

Although the fun, gamified nature of VR may have contributed to the reported enhanced engagement, it is unclear to what extent the novelty, gamification, or instructional design enacted the results. The complementary mixed method findings of the study indicated that students were starting to consider more strategic approaches to their learning, such as setting goals, and sustaining effort, particularly in the more challenging concepts. As this was limited in the scope of the sample and the timeframe in which this limitation applied, these trends should be cautiously interpreted.

Nonetheless, VRI appears to have significant potential for the promotion of deeper cognitive engagement in tandem with sound instructional design. Future research longitudinally, and in different learning contexts, is needed to capture the full potential of VRI.

Virtual reality immersion (VRI) as a novel tool usually connected with enjoyment through its ability to immerse students in games, encouraged them to use it in biology classes as an extension to that feeling of enjoyment. VR's ability to immerse students enjoyably "as if playing a game" increased their engagement with the biology content sparking their motivation to accomplish biology tasks and activities as if winning a game. This also resulted in persistence and resistance to failure. Therefore, students reconsidered their strategies for studying biology in the same manner of employing strategies to win a game. Choosing achievable goals and effectively planning to achieve it during biology classes was derived from their strategies for winning a game. Deeper comprehension of the subject matter was equivalent to the pleasure gained by overcoming challenges of a game through VRI and winning it.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Institutional Review Board (IRB) at An-Najah National University (45 CFR 46.102) - Protocol num: Fgs/Hum.Feb.2025/70. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the minor(s)' legal guardian/next of kin for the publication of any potentially identifiable images or data included in this article.

Author contributions

NN: Visualization, Data curation, Validation, Investigation, Supervision, Conceptualization, Project administration, Methodology, Software, Funding acquisition, Writing – review & editing, Resources, Formal analysis, Writing – original draft. AA: Investigation, Software, Writing – review & editing, Supervision.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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