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Impact of Virtual Reality Immersion in Biology Classes on Habits of Mind of East Jerusalem Municipality High School Students: Examining Mediating Roles of Self-Regulation, Flow Experience, and Motivation

Nader Neiroukh * and Abedalkarim Ayyoub *

Faculty of Humanities and Educational Sciences, An-Najah National University, Nablus P.O. Box 7, Palestine
* Correspondence: naderneiroukh@gmail.com (N.N.); ayyoub@najah.edu (A.A.)

Abstract

This quantitative study investigates the effects of virtual reality immersion on enhancing scientific habits of mind (critical and creative thinking) through the mediation of flow experience, motivation, and self-regulation in high school biology classes in East Jerusalem. The random multi-stage cluster sample consisted of 347 high school students from three schools who learned biology concepts constructively during the first semester using VR-based instruction, complying with the principles of the Cognitive Affective Model of Immersive Learning (CAMIL). The results of PLS-SEM revealed that VRI significantly affected critical and creative thinking directly and indirectly. Cases of partial and complete mediation intervened, showing the effects of mediators on enhancing habits of mind through a sequence of mediation flowing from flow experience through motivation to self-regulation, which functioned as a key intermediary factor in the relationship between virtual reality immersion and habits of mind. Based on the results of the study, the complex structure warrants further investigation. The results of the study suggest that VRI's impact on critical and creative thinking was intensified through mediation effects. In addition, the findings confirm that flow experience and motivation played essential roles in fostering a conducive learning environment that supports cognitive skill development. The results highlight that the enhancement of self-regulation was a necessary step for the enhancement of critical and creative thinking. The study recommends integrating VRI into teaching biology to enhance students' higher-order thinking skills. Further studies on self-regulation should explore adaptive interventions that strengthen self-regulatory strategies to maximize the cognitive benefits of virtual reality immersion.

Keywords: virtual reality immersion; motivation; flow experience; self-regulation; habits of mind; critical thinking; creative thinking; East Jerusalem schools

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1. Introduction

Virtual reality immersion (VRI) has emerged as a transformative technology in education, providing learners with an interactive and immersive learning environment that fosters engagement. Its cognitive and behavioral benefits in enhancing students' habits of Mind (HoM), namely self-regulation (SR), critical thinking (CRIT), and creative thinking (CRET), are highlighted by recent research (Guerra-Tamez et al., 2021; Marzano et al., 1993).

CAMIL provides a theoretical foundation for understanding how VRI influences cognitive outcomes through its impact on cognitive and emotional processes. It highlights that immersion and interactivity stimulate mental and emotional processes, which, in turn, enhance learning outcomes (Makransky et al., 2021).

In science education, abstract concepts are not entirely tangible, which might cause deficiencies in fundamental comprehension and, therefore, hinder further development and exploration (Kamińska et al., 2019). Solmaz et al. (2024) argue that the cognitive and behavioral advantages of VR can help educators to reduce the introductory barriers of new concepts that students usually struggle with. VRI enables students to explore complex ideas through creating an authentic computer-simulated environment of the learning experience, which they can live in, explore, and interact with safely and independently (Cevikbas et al., 2023; Hu et al., 2016).

There is evidence that HoM and cognitive learning outcomes in biology are affected by learning processes. VRI-based biology classes are thought to be autotelic for the fun they provide to the learner. They can foster intrinsic motivation that is capable of developing students' SR, CRIT, and CRET (Ariyati et al., 2024).

Therefore, VRI has become a promising method for enhancing HoM in biology classrooms by creating, engaging, and cognitively enriching learning experiences.

1.1. Theoretical Framework

Recent studies on engagement support the idea that interactive teaching methods generate higher levels of student engagement (Kurt & Sezek, 2021). In a survey about the use of VR in educational environments, Scavarelli et al. (2021) reflected optimism about the use of VR-based instruction for its effectiveness and ability to enhance 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. Enhancing the quality of science teaching and learning processes, as well as HoM, typically involves engaging learners in scientific practices to foster an understanding of the 'how' and 'why' of their CRIT (Wang et al., 2024).

Today, educators can integrate a combination of media in the classroom to increase student interaction (Chang et al., 2011), therefore increasing engagement or immersion, leading to better outcomes (Behmanesh et al., 2022; Haleem et al., 2022). VR in education has 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 & Yan, 2024; Marougkas et al., 2023).

HoM is a mixture of skills, attitudes, and experiences of the past and is very supportive of students' performance in everyday life (Idris & Hidayati, 2017). It 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.

Virtual Reality Immersion (VRI)

VRI is a state of mind that refers to the degree to which senses are absorbed in a virtual simulation, including enjoyment, energy, and involvement (Berkman & Akan, 2019). Implementing VR in education provides a more immersive and engaging learning experience. VR takes learners to difficult-to-access places, such as historical monuments, outer space, or even within the human body. Thus, 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 their critical thinking by giving them 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.* Presence is a psychological phenomenon or a state of consciousness that generates a sense of being in the virtual environment.

1.2. Habits of Mind (HoM)

HoM refers to the way our minds behave when confronted with a challenging situation that requires strategic reasoning, insightfulness, perseverance, creativity, and craftsmanship to resolve a complex problem (Costa & Kallick, 2000a, 2000b; Idris & Hidayati, 2017).

1.2.1. Self-Regulation (SR)

SR refers to a learner's ability to employ a set of meta skills that enable awareness, monitoring, and adaptation of learning strategies through cognitive and metacognitive processes to maintain psychophysiological balance (Baranovskaya, 2015; Mitsea et al., 2023; Zimmerman, 2002). It is the ability to judge the consistency of one's actions with internal and external demands, which enables the learner to adaptively redirect themselves (Mitsea et al., 2023).

1.2.2. Critical Thinking (CRIT)

CRIT is the ability to look deep into a problem from different perspectives, understand it, analyze it, and finally make a decision about the best actions to be taken to handle it (Jamaludin et al., 2022; Kusmaryono, 2023; Utomo et al., 2023). It is directed towards understanding and solving problems, evaluating alternatives, and decision making (Campo et al., 2023). Dwyer et al. (2014) define critical thinking as "a metacognitive process that consists of sub-skills such as analysis, evaluation, and inference, which, if used appropriately, increase probabilities for arriving at logical solutions to a problem."

Prawat (1991) indicated that a common goal of most educators is to improve students' higher-order thinking skills. The immersion approach, according to Prawat (1991), helps students to deeply understand content and promotes higher-order thinking. In other words, immersion enhances critical and creative thinking.

1.2.3. Creative Thinking (CRET)

CRET refers to the ability to produce original and appropriate work that is useful and adaptive to the task constraints. It is the ability to rearrange existing ideas in new combinations to come up with a new design (Sternberg & Lubart, 1998). According to Usha (2009), it is the ability to conceive an innovative idea and verify its validity with scientific reasoning. Some problems require creative thinking and cannot be solved based on scientific reasoning alone. Creativity can be improved over time by enhancing specific skills and knowledge and stimulating an environment for individuals' cognitive processes and personality factors, including motivations.

Lindberg et al. (2017) suggested that individual skills and motivation, as well as the external environment, are essential for producing creative work. They indicated that giving students chances to learn specific skills encourages creativity.

To conclude, there is evidence that HoM and cognitive learning outcomes in biology are affected by learning processes (Ariyati et al., 2024). Therefore, educators and teachers must focus on the components of SR, CRIT, and CRET to gain insights into students' cognitive and metacognitive skills and enhance them accordingly.

1.3. Mediating Variables

The initial study model first proposed only FE and MT as mediators between VRI and HoM. However, initial analysis of the proposed model revealed that the only indirect significant path between VRI and HoM was through SR. Neither FE nor MT had substantial direct effects on the study outcomes. There were no significant direct effects of either FE or MT on the study outcomes, except for the path of MT $\rightarrow$ SR. Therefore, the model was refined to include SR as a tertiary mediator. Thus, in the adjusted model, SR functions as the final sequential mediator and as an outcome. This multi-layered mediation is grounded in CAMIL, which recognizes the sequential influence of immersive features such as FE and MT on internal psychological processes before observable learning gains emerge.

1.3.1. Flow Experience

FE is a self-reinforcing cycle of energy, motivation, and personal growth (Mirvis & Csikszentmihalyi, 1991). It is a state of complete immersion and optimal experience in an activity. It is characterized by a high level of concentration, a sense of control, a merging of action and awareness, and intrinsic enjoyment in the task at hand. It creates a case of deep concentration, lack of self-consciousness, a feeling of control over what one is doing, complete focus on the task at hand, and a breakthrough in performance (Guerra-Tamez et al., 2021). It is a general phenomenon that is not exclusive to specific activities and, therefore, not limited to mere intrinsically motivated activities (Mahnke et al., 2012). When engaged in an activity, students may become so completely absorbed that they lose track of time, their surroundings, and everything else except the task at hand (E. Lee, 2005). Flow experience refers to the set of elements driving this, such as the sense of absorption in the activity, the right level of challenge, the lack of perception of time passing, and the spontaneity of thoughts and actions (Macchi & De Pisapia, 2024).

Macchi and De Pisapia (2024) hypothesized that VRI enhances higher levels of flow because of its immersive and stimulating nature. VR has the potential to bring about ‘flow’ through introducing the element of perceived challenge.

1.3.2. Motivation (MT)

MT is a driving force in the form of a strong desire, will, or tendency to achieve the highest level of success through high-quality work (Lase & Halawa, 2024; Purnama et al., 2019). Motivation is a critical part of success in education and later life. Thompson et al. (2022) noted that a higher degree of self-efficacy appears to be positively associated with students’ attitudes towards learning. Effective instruction has the potential to boost self-efficacy, represented as ‘confidence’, when listening to authentic lectures. In the process of teaching and learning, the motivational variable has a potentiating effect on students’ learning. Motivation gives reasons for people’s actions, desires, and needs to obtain the objective of learning. Learners’ motivation is probably one of the most essential elements for learning, which is inherently hard work. Learning involves pushing the brain to its limits and, thus, can only happen with motivation (Filgona et al., 2020). Motivation can be either intrinsic or extrinsic. IMT happens when motivation is caused by inherent satisfaction with or enjoyment of the activity or a desire to feel better (Zeng et al., 2022).

1.3.3. Self-Regulation as a Predictor of Critical Thinking and Creative Thinking

According to Ariyati and Fitriyah (2024), SR has a significant influence on controlling students’ emotions, thoughts, and actions; therefore, self-regulated students will have metacognitive skills that can enhance their CRIT and CRET.

Hyytinen et al. (2021) concluded that SR is crucial to CRIT and a function that guides this complex thinking process. SR refers to an intentional and adaptive process that allows students to plan, adapt, and monitor their thoughts, emotions, and behaviors to the demands of the task. Akcaoğlu et al. (2023) believe that SR is related to metacognitive skills in that it determines the methods and timing for the planning, monitoring, and evaluation processes that will be carried out. S.-T. Lee (2009) examined the relationships between metacognition, SR, and CRIT in an experimental study and found that SR is a significant predictor of students' CRIT dispositions. In another study on 'EFL learners' SR, CRIT, and language achievement', Ghanizadeh and Mizaee (2012) found that the enhancement of SR strategies leads to the development of CRIT abilities.

Another study that explored the predictive power of SR and academic hope in CRET among undergraduate students, Ghbari and Harahsheh (2024), found that SR is a good predictor of CRET. They recommended considering students' SR to foster their CRET.

To provide context for this study, Supplementary Table S1 presents recent empirical and conceptual research that explored how virtual reality learning environments affect students' thinking and learning processes.

As summarized in Table S1, prior research provides strong evidence that self-regulation, motivation, and flow experience each play significant roles in predicting critical and creative thinking. However, these studies tend to isolate variables or examine them outside immersive learning environments. Many VR interventions have focused on cognitive outcomes, however, only a few have explicitly integrated them with constructs like flow experience. To extend this body of work, this study examines a sequential mediation model incorporating flow experience, motivation, and self-regulation as pathways linking virtual reality immersion to habits of mind (CRIT and CRET). The present study addresses this critical gap by examining these variables together within immersive VR biology lessons using a mixed-method approach.

1.4. Research Objective and Questions

The objective of this study is to examine the impact of VRI-based biology classes on East Jerusalem high school students' HoM, mediated by MT, FE, and SR.

Based on the above, the following research questions are formulated:

RQ1: Are there statistically significant direct effects of VRI as a method of teaching biology on students' HoM?

RQ2: Are there statistically significant indirect effects of VRI as a method of teaching biology on students' HoM through the mediation of FE, MT, and SR?

1.5. Problem Statement

The number of high school students enrolling in the scientific stream in Palestine is linked to the limitations of traditional teaching methods in explaining abstract scientific concepts, according to the Ministry of Education and Higher Education (2010) and Kurt and Sezek (2021).VRI offers a potential solution by enhancing engagement, cognitive skills, and scientific thinking (Elmqaddem, 2019; Ochs & Sonderegger, 2022). VR facilitates experiential learning by transforming abstract concepts into immersive experiences, increasing MT and SR, and fostering habits of mind (HoM) essential for scientific thinking (Mills & Fullagar, 2008; Solmaz et al., 2024). However, the impact of VRI on HoM has not been sufficiently examined. This study investigates how VRI enhances HoM by improving students' engagement and fostering their CRIT and CRET, ultimately encouraging more students to pursue the scientific stream.

1.6. Study Hypotheses

VRI-based biology classes directly enhance students' HoM.

1.6.1. Direct Effect Relationships

H1a. *Higher levels of VRI directly enhance CRIT.*

H1b. *Higher levels of VRI directly enhance SR.*

H1c. *Higher levels of VRI directly enhance CRET.*

H1d. *Higher levels of VRI directly enhance FE.*

H1e. *Higher levels of VRI directly enhance MT.*

H2. *FE directly enhances MT.*

H3. *MT directly enhances SR.*

H4a. *SR directly enhances CRIT.*

H4b. *SR directly enhances CRET.*

On the other hand, VRI-based biology classes can indirectly enhance students' HoM through primary (one mediator), secondary (two mediators), or tertiary (three mediators) means.

1.6.2. Primary Mediation Hypotheses (One Mediator)

H5. *The relationship between VRI and SR is partially mediated by MT.*

H6a. *The relationship between VRI and CRIT is partially mediated by SR.*

H6b. *The relationship between VRI and CRET is partially mediated by SR.*

H7. *The relationship between VRI and MT is partially mediated by FE.*

H8. *The relationship between FE and SR is partially mediated by MT.*

H9a. *SR partially mediates the relationship between MT and CRIT.*

H9b. *SR partially mediates the relationship between MT and CRET.*

1.6.3. Secondary Mediation Hypotheses (Two Mediators)

H10a. *VRI enhances CRIT through MT and SR.*

H10b. *VRI enhances CRET through MT and SR.*

H11. *VRI enhances SR through FE and MT.*

H12a. *FE enhances CRIT through MT and SR.*

H12b. *FE enhances CRET through MT and SR.*

1.6.4. Tertiary Mediation Hypotheses (Three Mediators)

H13a. *VRI enhances CRIT through FE, MT, and SR.*

H13b. *VRI enhances CRET through FE, MT, and SR.*

VRI affects HoM (CRIT and CRET), mediated by FE, MT, and SR. Direct and indirect relationships were based on different theoretical frameworks and empirical studies. VRI is grounded in theories of immersive learning, such as CAMIL, which adopts a constructivist view of learning by emphasizing the central roles of immersion and engagement during VRI instruction. FE as a mediator between VRI and HoM and between VRI and MT was based on Csikszentmihalyi's theory of flow. FE emphasizes that immersed learners fall into complete absorption in what they are performing, a state derived from enjoyment and engagement. MT resulting from the autotelic nature of performance, which generates the state of flow according to Csikszentmihalyi (2000), explains how VRI and flow add to the levels of MT according to Deci and Ryan (1985). The dual role of SR as the final sequential mediator and part of the HoM variables is a key variable in the study. HoM, encompassing SR, CRIT, and CRET as the dependent variables of the study, was grounded in Marzano et al.'s (1993) five most critical life-long dimensions of learning.

Locke (1987), in his Social Cognitive Theory, explained how SR functions as a mediator between the components in the triadic reciprocal causation model: personal factors, behavioral patterns, and environmental influences. This enhances the ability of SR to function as a sequential mediator between VRI and HoM.

The following figure depicts the conceptual model for the proposed relationships between the independent variable VRI and the dependent variable HoM, as mediated by flow experience, motivation, and self-regulation.

Figure 1 shows the dual role of SR as an outcome of VRI, and as the final sequential mediator that channels the influence FE and MT to the final outcomes.

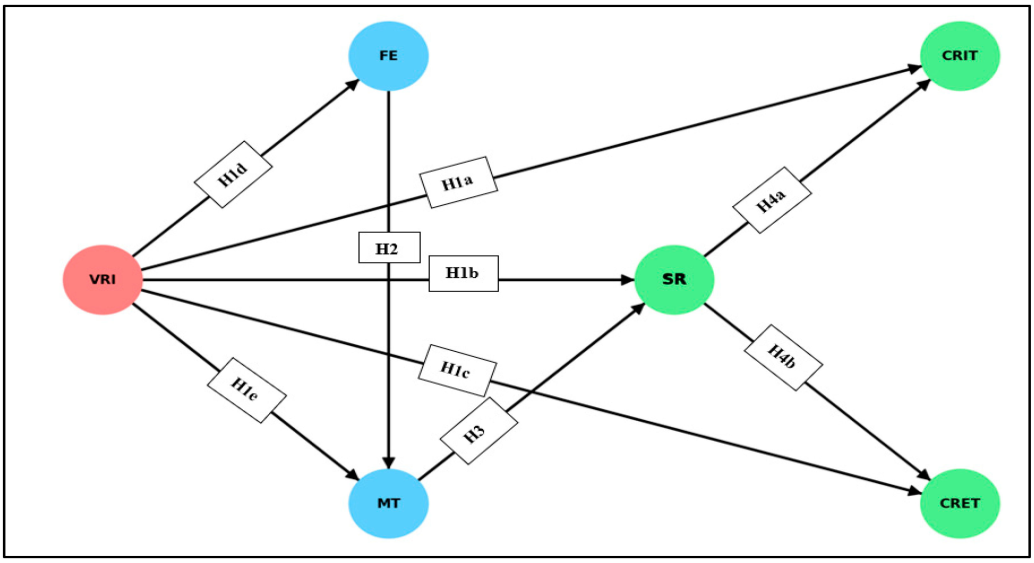

Figure 1. Proposed conceptual model.

2. Methodology

2.1. Research Design

This quantitative sequential explanatory study aims to elucidate the exact nature of the relationships in the SEM that cause VRI to enhance students' HoM directly or indirectly through FE, MT, and SR during biology classes. The following describes the research design and procedures.

2.2. Study Tools

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

1. The independent construct VRI: Schubert et al. (2001) validated the Igroup Presence Questionnaire–Short (IPQ-S) to measure students' level of immersion during biology classes.
2. The dependent constructs of HoM (SR, CRIT, and CRET): The study employed a validated questionnaire of HoM developed by Sriyati (2011) and validated by Hidayati and Idris (2020) and based on Marzano's (1992) and Marzano et al.'s habits of mind. The study employed a validated questionnaire on Habits of Mind (HoM) originally developed by Sriyati (2011), as cited in Hidayati and Idris (2020).
3. The mediating variables (FE and MT): Guerra-Tamez (2023) validated and advanced a questionnaire on FE and MT that measures the partial effects of the mediating variables FE and MT on HoM, which we adopted.

Table 1 presents the study constructs and their corresponding items, which were adapted from validated instruments in prior research (e.g., Schubert et al., 2001; Guerra-Tamez, 2023; Sriyati, 2011).

Table 1. Constructs and their items were adapted from previous studies.

Construct	Abb	#	Item	
Immersion VR	VRI	1	I felt that I had a sense of being there (SP).	(Schubert et al., 2001)
		2	I felt that the VR world surrounded me (SP).	
		3	I was utterly 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).	
Flow Experience	FE	1	I enjoyed the experience through VR technology.	(Guerra-Tamez, 2023)
		2	I found the VR experience gratifying.	
		3	I felt in total concentration during the experience.	
		4	I felt that time passed too fast.	
		5	This class, through VR technology, exceeds my expectations.	
Motivation	MT	1	It is interesting to use VR technology in class.	
		2	My performance was good using VR technology in class.	
		3	After using VR technology for a while, I felt competent.	
		4	I was very relaxed while using VR technology in class.	
		5	I am skilled in using VR technology in class.	

Table 1. *Cont.*

Construct	Abb	#	Item	
Self-Regulation	SR	1	Recognizing self-thinking.	(Sriyati, 2011)
		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 have not yet been found.	
		2	Trying hard to expand skills and knowledge.	
		3	Creating new ways or points of view outside the common knowledge.	

2.2.1. Validity and Reliability

The validity of the combined questionnaire was maintained through expert reviews and pilot testing, ensuring that the instrument accurately measured the intended constructs. Reliability tests, such as Cronbach's alpha, were conducted to confirm the consistency of the combined tool.

2.2.2. Translation Process

The final English version of the questionnaire, comprising 29 items, was translated into Arabic by two competent English teachers to ensure its suitability for high school students. A competent Arabic teacher revised the translation, then a back translation was performed by a fourth English teacher. A pilot test of the final form of the tool was conducted on a small representative sample from different schools and grade levels to check the clarity, difficulty, and appropriateness of the items. Finally, some minimal changes to the final Arabic form of the tool were made based on feedback given from the pilot group.

2.3. Study Context

The experiment was exclusively conducted on East Jerusalem government high school students based on random cluster sampling.

East Jerusalem government high schools adopt either the Palestinian curriculum (*tawjihi*), where schools are usually separated based on gender (either male or female), and include the following three stages: 10th to 12th grades. Schools adopting the Israeli curriculum (*Bagrut*), on the other hand, are usually mixed and include the following four stages: 9th–12th grades. Nevertheless, the coursebooks of both types of schools present duplicate biology content with slight variations.

2.3.1. Study Sample

The sample included 349 students taught by four biology teachers from three different high schools (two male and one female school) in East Jerusalem, who were randomly chosen for the experiment. The study targeted schools adopting the Palestinian curriculum; therefore, a random multi-stage cluster sampling method was used to recruit participants for this study. First, three secondary schools were randomly selected from a total of seven schools that follow the Taujihi curriculum. These schools represented primary clusters in the sampling process. In the second stage, students were selected from grades 10, 11, and 12 within each school. In schools with a large student population, participants were selected using simple random sampling from each grade level. However, in schools with smaller enrollment numbers, all students from the relevant grades were included to ensure adequate representation. No specific background data were collected on the students prior to exposure to VR or their digital literacy skills. This represents a potential source of variability in how the participants experienced the intervention.

The biology teachers in the sample (two male and two female) were highly qualified, holding a BA degree in Biology and an MA degree in teaching science methods, with over ten years of experience teaching biology to high school students.

Table 2 summarizes the demographic information of the student sample, categorized by school, grade level, gender, number of participating students, and group allocation.

Table 2. Demographic information of the sample (initials are fictitious).

School	Grade	School Gender	# of Students	# of Group
Shu’fat Comprehensive School	10th 11th 12th	M	72 50 67	2 2 2
Beit Hanina Secondary School	10th 11th 12th	F	30 30 30	1 1 1
Al Mutanabbi Comprehensive School	10th 11th 12th	M	32 22 16	1 1 1
Total			349	12

The VR biology classes were planned according to the principles of constructivism. This is believed to enhance HoM, especially SR, CRIT, and CRET (Angraini et al., 2024; Kurt & Sezek, 2021; Mvududu & Thiel-Burgess, 2012; Pande & Bharathi, 2020; Sengul, 2024; Stigall & Sharma, 2017; Vijayakumar Bharathi & Pande, 2024). All participating groups followed a general framework of lesson plans, which included topic introduction, VR interaction, discussion, application activities, and lesson summarization. The biology teachers selected complex and abstract topics for VR instruction, aiming to improve student comprehension.

The contents of the secondary biology coursebooks were scanned by competent biology teachers from the participating schools to decide upon the relevant educational 3D scenes to be employed for the experiment.

Several basic biology topics were chosen to be covered within 6–8 sessions each. The biology teachers emphasized topics that often posed challenges for students, including abstract concepts such as ‘Cell division and mitosis, DNA, Nerve Impulse, and Photosynthesis’.

The teachers noted that VRI-based biology sessions, as proposed, might provide a solution for abstract concepts that students tend to struggle with.

Groups of 20–34 students attended 50-min sessions using Meta Quest 3 VR sets. The digital content was sourced from pre-existing educational platforms like www.youtube.com (accessed during the period, September 2024 and January 2025) and/or www.mozaweb.com (accessed on 21 July 2025), which provide immersive modules for high school science instruction. Materials were accessed regularly during the period between September 2024 and January 2025.

The above topics were also supported by Hadiprayitno et al. (2019) as being challenging for secondary students due to their abstractness. However, they noted that the effects of VRI on these abstract challenging topics are measurable and can be measured within the range of time available for the study.

For every VRI-based biology lesson, the Intended Learning Outcomes (ILOs) were given to students in advance. Each ILO stated what learners would discover on their own, competently. Activities, VR scenes, and assessments were then selected or designed to align with these outcomes.

Table 3 outlines a general instructional framework designed to guide the planning of VR-based biology sessions.

Table 3. A general framework for planning VR-based biology sessions.

Part	Minutes	Procedures
1	10–12	The teacher introduces the topic, highlights the most critical issues, and frames the learning experience with an open-ended question or challenge related to the 3D scene, encouraging students to explore and uncover learning ILOs through their interaction and inquiry.
2	8–12	Students watch an explanatory 3D video about the topic.
3	8–12	Students interact directly with a 3D scene or watch an additional interactive video related to the topic to uncover the learning ILOs constructively.
4	10	Students discuss results, discoveries, or solutions with the teacher, who provides feedback on the findings and wraps them up for the whole class.
5	3–5	Students reflect on the experiment.

2.3.2. Data Collection

The final Arabic version of the questionnaire, in Google Form format, was sent to the participating biology teachers at various schools at the end of the experiment, except for the name field, which was required to be answered. Biology teachers sent the questionnaire to the participating groups via WhatsApp groups, which were created for the experiment. In total, 347 participants out of 349 successfully submitted the questionnaire. Data was stored, ensuring the anonymity of the participants and the confidentiality of their information.

2.3.3. Data Analysis

To examine the complex cause–effect relationships between different constructs of the study, Partial Least Squares (PLS-4) statistical software (Version 4.1.0.9), designed for Structural Equation Modeling (SEM), was employed. The software combines factor analysis and multiple regression analysis, maximizing the explained variance of the dependent variable to enable more general representations of measurement and latent variable models. PLS-SEM is a robust statistical method used to examine hypotheses regarding the causal relationships between both observed and latent variables (Sarstedt et al., 2022).

2.3.4. Control Variables

Gender and prior experience with VR as an educational tool were examined as potential moderating variables. This background information was collected through a self-reported item in the questionnaire. Moderation analyses were conducted to explore the hypothesized relations in the model. However, the results indicated no statistically significant moderation effects. Consequently, these variables were excluded from the final structural model to maintain parsimony and to focus on the core constructs of the study. Nonetheless, their potential relevance in different contexts is acknowledged in the limitations section.

These methods helped in analyzing quantitative data and interpreting the relationships between the variables.

3. Results

Partial Least Squares Structural Equation Modeling (PLS-SEM) was employed to assess both the direct and indirect effects of VRI on HoM through FE, MT, and SR as sequential mediating variables. PLS4 4.1.0.9 is an effective software for analyzing complex relationships with mediating variables. The analysis aims to test the hypothesized model and evaluate the predictive relevance of the constructs.

Figure 2 shows the results of the SEM presenting their standardized path coefficients with their corresponding *p*-values.

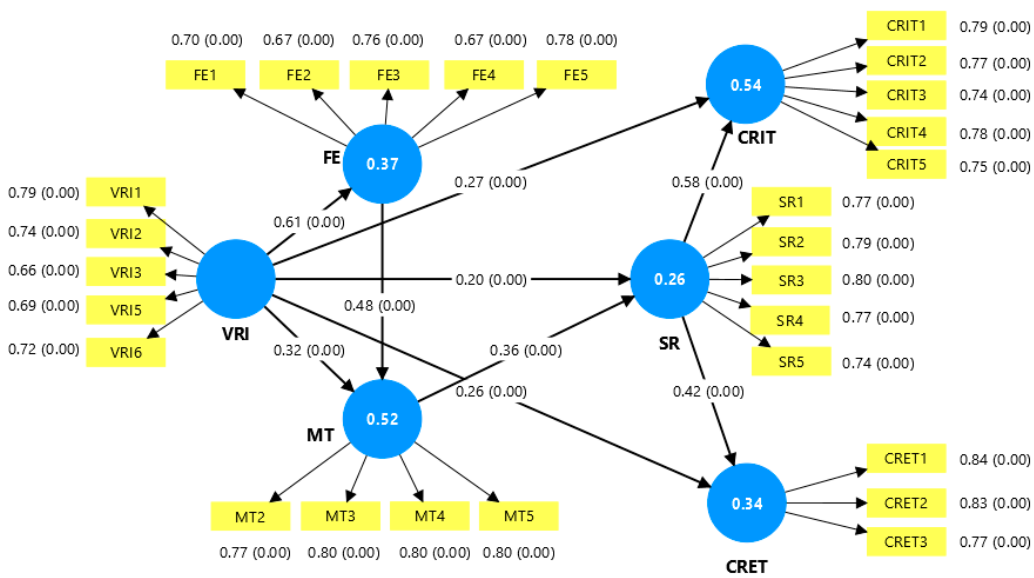

Figure 2. Results of the conceptual model.

3.1. Measurement of Model Assessment

To ensure that the observed indicators reliably and validly measure the latent constructs, validity and reliability were examined.

3.1.1. Reliability and Convergent Validity

To assess the measurement model and internal consistency reliability, Cronbach's alpha and composite reliability were examined.

As Table 4 shows, the constructs of the study showed an acceptable consistency, with Cronbach's alpha values of >0.65, except for two (VR4 = 0.271 and MT1 = 0.549); therefore, they were excluded (Hair et al., 2019). Composite reliability values ranged between 0.75 and 0.83, indicating good, consistent measures of the constructs (Hair et al., 2019). Convergent validity was also supported by the average variance extracted (AVE) for different constructs, which was higher than 0.50 (Hair et al., 2019).

Table 4. Reliability and convergent validity.

Variable	Cronbach's α	Rho_a	Rho_c	AVE	*p*
CRET	0.74	0.75	0.85	0.66	0.00
CRIT	0.83	0.83	0.88	0.59	0.00
FE	0.76	0.77	0.84	0.51	0.00
MT	0.8	0.81	0.87	0.63	0.00
SR	0.83	0.83	0.88	0.6	0.00
VRI	0.77	0.77	0.84	0.52	0.00

3.1.2. Discriminant Validity

The HTMT ratio and Fornell–Larcker criterion were used to check the uniqueness of the constructs of the study.

The results presented in Table 5 supported the robustness of the measurement model and confirmed that each latent variable represents a unique construct, free from significant overlap with other variables.

Table 5. HTMT and Fornell–Larcher criteria for discriminant validity.

Variable	CRET	CRIT	FE	MT	SR	VRI
CRET	***0.81***	0.84	0.46	0.51	0.67	0.57
CRIT	0.66	***0.77***	0.51	0.60	0.83	0.65
FE	0.36	0.41	***0.72***	0.85	0.48	0.80
MT	0.4	0.49	0.68	***0.79***	0.60	0.78
SR	0.53	0.69	0.39	0.49	***0.77***	0.53
VRI	0.44	0.52	0.61	0.62	0.43	***0.72***

Note: Diagonal italicized bold elements are the square roots of the average variance extracted (AVE). Above the diagonal, the elements represent the correlations between the constructs. Below the diagonal are the HTMT values (Ayyoub et al., 2023).

3.2. Structural Model Assessment

3.2.1. Model Fit

Bollen–Stine bootstrapping was conducted to check the model fit (Bollen & Stine, 1992).

The Bollen–Stine test showed a slight discrepancy (<0.08) between observed and predicted correlations (Bollen & Stine, 1992).

3.2.2. Collinearity Assessment (VIF Values)

The values of VIF according to Hair et al. (2019) should be close to three or below. The results of multicollinearity at the construct level ranged between 1.309 and 1.733, <3.3, indicating low multicollinearity among all predictor variables and their ability to contribute independently to explaining the variance of the dependent variables (Hair et al., 2019). This supports the HTMT and Fornell–Larcker results by providing additional evidence that the constructs are distinct, despite the high correlation between CRET and CRIT.

3.2.3. Path Coefficients: (Direct Effects and Hypothesis Testing)

The results of the path coefficients reflect the strong and positive relationships between the constructs of the study. Table 6 summarizes the results.

Table 6. Direct effects.

Path	H #	β	t	*p*
VRI → CRIT	H1a	0.27	7.07	0.00
VRI → SR	H1b	0.20	3.55	0.00
VRI → CRET	H1c	0.26	5.11	0.00
VRI → FE	H1d	0.61	13.77	0.00
VRI → MT	H1e	0.32	6	0.00
FE → MT	H2	0.48	8.56	0.00
MT → SR	H3	0.36	6.61	0.00
SR → CRIT	H4a	0.58	14.11	0.00
SR → CRET	H4b	0.42	8.33	0.00

As Table 6 shows, all direct effects were positive and significant (Hair et al., 2021), where:

$\beta < 0.10$ → Small effect
$0.10 \geq \beta < 0.30$ → Moderate effect
$\beta \geq 0.30$ → Strong effect

All *p*-values ($p < 0.05$) and all *t*-values for all direct pathways were mainly higher than 1.96: ($t > 1.96$, $p = 0.00$), which supports the significance and strength of the reported paths. Hence, all direct hypotheses (H1a–H4b) were positive and significantly effective. This answers RQ1, as follows:

Are there statistically significant direct effects of VRI as a method of teaching biology on students' HoM?

PLS-SEM analysis confirmed that VRI directly impacted students' CRIT, SR, and CRET, which was evidenced by the moderate positive significance of H1a, H1b, and H1c.

However, further analysis of the direct effects of VRI on mediators reflected more substantial effects.

H1d: The direct effect of VRI on FE ($\beta = 0.61$, t = 13.768, $p < 0.05$) revealed a strong, positive, significant direct effect. Immersion through VR during biology classes strongly enhanced students' flow experience. Hence, H1d was supported.

H1e: The direct effect of VRI on MT ($\beta = 0.32$, t = 6, $p < 0.05$) also revealed a substantial impact of VRI on students' motivation.

Other direct effect hypotheses, including H2: FE → MT ($\beta = 0.48$, t = 8.56, $p < 0.05$), H4: MT → SR ($\beta = 0.36$, t = 6.61, $p < 0.05$), H4a: SR → CRIT ($\beta = 0.58$, t = 14.11, $p < 0.05$), and H4b: SR → CRET ($\beta = 0.42$, t = 0.322, $p < 0.05$) were all strong and significant. Hence, they were all supported.

The absence of significant relationships among FE → SR, FE → CRIT/CRET, and MT → CRIT/CRET highlights the role of the sequential mediators FE, MT, and SR in enhancing the total effects of VRI on HoM. It also underscores the crucial effect of SR as the final sequential mediator in transmitting the effects of VRI on CRIT/CRET through mediators. This requires examining the role of mediation through indirect effects.

3.2.4. Total Indirect Effects

To evaluate indirect effects of VRI on CRIT and CRET through the mediators FE, MT, and SR, an analysis of indirect pathways was conducted.

3.2.5. Indirect Effects (Primary, Secondary, and Tertiary)

Table 7 presents the results of the indirect effects analysis, including primary, secondary, and tertiary mediation pathways:

Table 7. Indirect effect hypotheses.

Primary Indirect Effects				
	H	β	*t*	*p*
VRI → MT → SR	H5	0.12	4.74	0.00
VRI → SR → CRIT	H6a	0.12	3.49	0.00
VRI → SR → CRET	H6b	0.09	3.37	0.00
VRI → FE → MT	H7	0.29	7.22	0.00
FE → MT → SR	H8	0.17	4.96	0.00
MT → SR → CRIT	H9a	0.21	5.62	0.00
MT → SR → CRET	H9b	0.15	5.00	0.00
Secondary Indirect Effects				
VRI → MT → SR → CRIT	H10a	0.07	4.42	0.00
VRI → MT → SR → CRET	H1b	0.05	4.28	0.00
VRI → FE → MT → SR	H11	0.11	4.57	0.00
FE → MT → SR → CRIT	H12a	0.10	4.43	0.00
FE → MT → SR → CRET	H12b	0.07	3.98	0.00
Tertiary Indirect Effects				
VRI → FE → MT → SR → CRET	H13a	0.05	3.78	0.00
VRI → FE → MT → SR → CRIT	H13b	0.06	4.14	0.00

Primary Indirect Effect Hypotheses

The seven primary mediated pathways had positive, significant effects that ranged between weak and moderate magnitudes.

1. H5: VRI → MT → SR (β_indirect = 0.12, $p < 0.05$; β_direct = 0.20, $p < 0.05$). VRI influences SR directly and indirectly through the partial mediation of MT. The total effect of VRI on SR is β = 0.32, indicating that while motivation is an important mediator, VRI still has a notable direct impact on SR. Therefore, H5 is supported.

2. H6a. VRI → SR → CRIT (β_indirect = 0.12, $p < 0.05$; β_direct = 0.27, $p < 0.05$) and H6b: VRI → SR → CRET (β_indirect = 0.09, $p < 0.05$; β _direct = 0.26, $p < 0.05$). H6a and H6b are both supported. VRI affects students' critical thinking and creative thinking both directly and indirectly through the partial mediation of SR. The total effect of VRI on CRIT (β = 0.39) and CRET (β = 0.35) indicates that while part of the effect occurs directly, a meaningful portion is explained through SR.

3. H7: VRI → FE → MT (β_indirect = 0.29, $p < 0.05$; β_direct = 0.32, $p < 0.05$). Hence, H7 is supported. VRI influences students' MT both directly and indirectly via the partial mediation of FE.

4. H8, H9a, and H9b are supported as having a full mediating effect. H8: FE → MT → SR, for example, the path FE → SR is not significant ($p > 0{,}05$), implying that FE can only affect SR through MT, indicating a full mediation case of MT. The indirect path via MT (β = 0.17, t = 4.957, $p < 0.05$) reflects a moderate indirect magnitude of FE on SR through the full mediation of MT. Therefore, H8, H9a, and H9b are supported. FE cannot directly enhance SR. FE enhances students' MT, which fully mediates the relationship between FE and SR.

Secondary Indirect Effects (Two Mediators)

Five pathways in the model included two mediators, as follows:

1. H10a: VRI → MT → SR → CRIT and H10b: VRI → MT → SR → CRET: There are direct effects of VRI on CRIT (β = 0.27, t = 7.07, $p < 0.05$) and CRET (β = 0.26, t = 5.11, $p < 0.05$). However, VRI has a small, significant, partial indirect effect on CRIT through MT and SR (β = 0.05, t = 4.275, $p < 0.05$), as well as on CRET (β = 0.05, t = 4.275, $p < 0.05$).

The total significant effect of the direct and indirect paths (β = 0.32, $p < 0.05$) and (β = 0.31, $p < 0.05$) reveals a strong significant partial effect of VRI on CRIT and CRET through the mediators MT and SR. Therefore, H10a and H10b are supported.

2. H11: VRI → FE → MT → SR. The direct effect of VRI on SR (β = 0.20, t = 6.002, $p < 0.05$) is enhanced by the indirect path FE → MT (β = 0.11, t = 4.57, $p < 0.05$). This path also results in a strong indirect effect of VRI on SR partially mediated by FE→ MT (β = 0.31, t = 6.002, $p < 0.05$)

3. H12a and H12b: FE → MT → SR → CRIT/CRET. The results reveal a small indirect effect of FE through the sequence of mediators MT → SR on CRIT/CRET. Therefore, mediation can be classified as full. This indicates that FE cannot directly affect CRIT and CRET, but rather enhances students' MT, which subsequently improves their SR, ultimately leading to enhanced CRIT. Therefore, H12a and H12b are supported.

This analysis of secondary pathways explains the mechanisms of the sequential mediation of FE → MT → SR, emphasizing the role of SR as the only and final channel through which the indirect effects of VRI can affect CRIT and CRET.

Tertiary Indirect Effects (Three Mediators)

There are two cases of tertiary mediation between VRI and HoM (CRIT/CRET). Both pathways reflected a small but significant impact on CRET (H13a: β = 0.05, t = 3.778, $p < 0.05$) and CRIT (H13b: β = 0.06, t = 4.139, $p < 0.05$). Therefore, H13a and H13b are supported. Although the indirect significant effects of VRI on CRIT/CRET are minor, they provide a comprehensive understanding of the mechanisms through which mediators function sequentially, underscoring the crucial function of SR as the final sequential mediator.

The indirect effect analysis reveals that VRI significantly enhances HoM through the sequential mediators (FE → MT→ SR). The most substantial indirect effect is VRI → SR → CRIT (β = 0.25, $p < 0.05$), confirming the key mediating role of SR.

3.2.6. Total Effects

The impact of both direct and indirect effects together on the dependent variables in the model reflects a comprehensive view of the strength of the different pathways in the model connecting endogenous VRI and exogenous variables.

As presented in Table 8, the total effects of VRI on CRIT (β = 0.52), CRET (β = 0.44), and SR (β = 0.43) were significantly more potent than the direct effects of VRI → CRIT (β = 0.27), VRI → CRET (β = 0.26), and VRI → SR (β = 0.20), which highlights the crucial role of mediators in enhancing the total effects and amplifying these total effects to highlight the critical effect caused by the sequential mediators FE, MT, and SR in developing higher cognitive skills such as CRIT and CRET.

Table 8. Total effects.

	β	**T**	***p***
VRI → CRET	0.44	9.59	0.00
VRI → CRIT	0.52	12.71	0.00
VRI → SR	0.43	9.57	0.00

3.2.7. Coefficient of Determination (R^2)

The effectiveness of the independent variable in explaining the variance in the dependent variable in the study ranged between small and large. Table 9 illustrates the results of R^2.

Table 9. Coefficient of determinants across variables.

	R^2	R^2 Adjusted	*p*
CRET	0.34	0.33	0.00
CRIT	0.54	0.54	0.00
FE	0.37	0.37	0.00
MT	0.52	0.52	0.00
SR	0.26	0.26	0.00

R^2 values of 0.02, 0.13, and 0.26 correspond to small, medium, and large effect sizes, respectively. These criteria are widely used in social and behavioral sciences for evaluating the explanatory power of models. Based on (Cohen, 1988), these criteria show the following:

CRIT and MT demonstrate a moderate to ample explanatory power, highlighting the model's effectiveness in predicting these variables. CRET and FE fall within the medium effect size range, suggesting that while the predictors provide a reasonable level of explanation for CRET and FE, additional factors might enhance their explanatory power. However, SR (0.26) meets Cohen's threshold for a large effect size, implying that the predictors meaningfully explain their variance.

The results indicate that the model provides a strong explanatory power for CRIT and MT, while CRET, FE, and SR show moderate to strong predictive capabilities based on Cohen's (1988) benchmarks.

3.2.8. Predictive Relevance Q^2 and Model Accuracy

All constructs of the current study have $Q^2 > 0$, confirming the model's predictive relevance. Furthermore, most indicators demonstrate lower RMSE values compared to the LM, suggesting that PLS-SEM model processes medium predictive power across key constructs (Shmueli et al., 2016).

Table 10 shows that only FE1, FE5, MT4, and SR5 yielded larger prediction errors.

Table 10. Q^2 predict and PLS predict MV.

Construct	Q^2 Predict (Overall)	PLS Predict (Q^2 Predict for Items)	PLS Predict RMSE	LM RMSE	Interpretation
CRET	0.19	0.154 (CRET1), 0.103 (CRET3)	0.904, 0.861	0.72	Medium predictive power, moderate error
CRIT	0.26	0.177 (CRIT4), 0.133 (CRIT1)	0.774, 0.775	0.68	Ample predictive power, low error
FE	0.37	0.277 (FE3), 0.143 (FE4)	0.783, 0.926	0.62	Ample predictive power, low error
MT	0.37	0.277 (MT3), 0.179 (MT2)	0.72, 0.736	0.60	Ample predictive power, lowest error
SR	0.17	0.147 (SR4), 0.051 (SR5)	0.857, 0.745	0.73	Medium predictive power, high error

Although the model requires minor refinement to enhance indicators with a small to moderate predictive power or to transition from a moderate to strong predictive relevance, predictive relevance analysis underscores the model's practical applicability due to its meaningful predictive ability. This aligns with the study's goal in structuring a framework to explain the effects of VRI on HoM (CRIT and CRET) through a series of mediators (FE → MT → SR). Hence, RQ1 and RQ2 are further supported as the model explains a significant variance in HoM, validated by effect sizes and predictive power.

3.2.9. Effect Size (f^2)

Effect size (f^2) is a measure of the relative impact of an independent variable on a dependent variable in PLS-SEM. It quantifies how much an exogenous (predictor) variable contributes to explaining the variance of an endogenous (outcome) variable when added to the model.

Table 11 summarizes the effects based on (Cohen, 1988).

Table 11. Effect size (f^2).

	f^2	T	*p*	Power
FE → MT	0.3	3.29	0.00	Large
MT→ SR	0.11	2.85	0.00	Medium
SR → CRET	0.22	3.34	0.00	Medium
SR → CRIT	0.59	4.59	0.00	Large
VRI → CRET	0.08	2.36	0.02	Small
VRI → CRIT	0.13	3.33	0.00	Medium
VRI → FE	0.6	4.13	0.00	Large
VRI → MT	0.14	2.69	0.01	Medium
VRI → SR	0.03	1.64	0.01	Small

According to Cohen (1988), values of 0.02, 0.15, and 0.35 correspond to small, medium, and large effect sizes, respectively. The table shows that the f^2 results for the model explain the variance of the dependent variables. FE and MT (f^2 = 0.3) indicate that FE has a medium contribution to explaining MT. MT has a small, significant contribution to the explanation of SR (f^2 = 0.11). SR can largely contribute to the explanation of CRIT (f^2 = 0.59), but a medium contribution to CRET (f^2 = 0.22).

VRI has a small but significant contribution to explaining CRET (f^2 = 0.08), but it contributes largely to explaining FE (f^2 = 0.60). Moreover, VRI has a small but significant contribution to explaining MT (f^2 = 0.14). Finally, VRI has a significantly small contribution to explaining SR (f^2 = 0.03).

This suggests that VRI alone may not significantly explain direct changes in SR. The specific indirect analysis showed that mediators such as MT (VRI → MT → SR) or (VRI → FE → MT → SR)) significantly contribute to the explanation of the relationship.

These findings reinforce the importance of mediation effects in the model, supporting RQ2 by demonstrating that VRI indirectly influences HoM through FE, MT, and SR.

4. Discussion

CAMIL explains how cognitive immersion through VR affects the final desired outcomes through the provision of interaction and participatory experiences. This encourages learners to engage in learning responsively and develop self-regulatory habits that can finally affect their critical and creative thinking by providing chances to solve problems and make decisions, according to Tang (2024). This current study examined the impact of VRI on desired scientific habits of mind, namely, SR, CRIT, and CRET, through a sequence of mediators: FE, MT, and SR. The results of the analysis provided valuable insights into the mechanisms through which VRI can effectively enhance higher cognitive skills in education.

4.1. Direct Effects of VRI

The direct effect results confirmed that VRI-based biology classes have a moderate, direct, significant impact on students' SR, CRIT, and CRET. VRI-based biology classes helped to overcome the barriers of the traditional teacher-centered classroom environment represented in time, space, danger, cost, and accessibility, as noted by (Solmaz et al., 2024), 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 to deeply understand content and promotes critical and creative thinking aligns with (Kamińska et al., 2019), Solmaz et al. (2024), and (Prawat, 1991).

However, the PLS-SEM results reflected strong total effects of VRI on SR, CRIT, and CRET, resulting from the mediators' intervention.

4.2. Mediation Effects

The results of the indirect and specific indirect effect analyses revealed the significant indirect enhancement caused by the mediators FE, MT, and SR. The absence of direct significant effects of either FE or MT on CRIT/CRET made the final sequential mediator SR function as a harbor through which the impact of FE and MT was significantly transferred to CRIT/CRET. This conforms the findings of Hyytinen et al. (2021) about SR being crucial for fostering CRIT and Ghbari and Harahsheh (2024) about SR as being a predictor for CRET, reinforcing the idea that students' ability to regulate their learning plays a crucial role in fostering higher-order thinking skills.

4.2.1. The Role of FE in Fostering MT Through VRI

VRI had a substantial direct effect on FE ($\beta = 0.61$). VRI biology classes caused students to be fully absorbed in the virtual environment of the biology content, enhancing high levels of engagement and deep concentration, corroborating with Mahnke et al. (2012). VRI instruction provided students with immersion and higher levels of engagement, which facilitated the constructive perception of complex biology concepts, thereby supporting the ideas and findings of Marougkas et al. (2023) about immersive learning. Educators can use VRI to introduce complex biology content to students, ensuring that they develop a sense of self-competence about it. This mirrors Thompson et al. (2022) regarding students highly valuing VRI as an effective instructional method that improved their attitudes towards learning.

Furthermore, FE had a substantial direct effect on MT ($\beta = 0.47$). Being completely engaged in the virtual environment, students became inherently satisfied and enjoyed interacting with the simulated scenes. This created a type of intrinsic motivation that was caused by the force of the flow experience. Improved self-regulation resulted in the formation of students' goal-setting skills, persistence to complete the tasks at hand, and resistance to failure. This corroborates VRI's view of VRI as being positively associated with students' positive attitudes towards learning.

4.2.2. The Role of MT in Enhancing SR

The findings also confirmed the substantial impact of VRI on MT ($\beta = 0.32$) caused by students' satisfaction or enjoyment for the sake of the activity itself or the joy and satisfaction gained from it. This aligns with Zeng et al. (2022) and implies that VRI can generate high levels of MT, which enhance SR, and subsequently CRIT and CRET. Educators can plan and implement interactive classes to create higher levels of motivation that can finally impact students' higher-order thinking skills.

MT functioned as an intermediary variable in the relationship between VRI and SR, which accounted for 53% of the total effect. This emphasizes the role of VRI in inducing intrinsic motivation either directly or through FE, which, in turn, sparks motivation as inherently enjoyable, which directly relates to extrinsic motivation according to Mills and Fullagar (2008), and finally enhances students' SR.

This final effect of motivation gained directly from both VRI and FE directly affected SR, enhancing students' ability to plan, monitor, and evaluate their behavior. This echoes

(Mitsea et al., 2023; Zimmerman, 2002) regarding SR as being positively related to personal adjustment factors, diligence, and well-adjusted academic behavior. Students then redirect themselves according to their self-evaluation and, as part of the adaptation of their learning strategies, confirm (Baranovskaya, 2015; Mitsea et al., 2023; Zimmerman, 2002) ideas about SR as judging the consistency of actions, which enables the learner to redirect themselves adaptively. This enhanced form of students' SR directly affects their critical and creative thinking.

4.2.3. The Role of SR as a Mediator in Enhancing CRIT and CRET

SR is the final sequential mediator through which variables like FE and MT can foster CRIT and CRET. In other words, SR is enhanced directly through VRI and indirectly through the sequence of FE and MT, before it finally transmits the effect onto CRIT and CRET. This implies that educators can arrange immersive learning experiences through VRI to generate an enhanced FE, which intrinsically enhances MT. The effects of FE and MT amplify the direct impact of VRI on SR, which transfers the amplified total effects to higher-order thinking skills. SR, a cognitive skill based on meta-skills that enable awareness of one's thinking, monitoring, and adaptation of learning strategies through cognitive and metacognitive processes (Zimmerman, 2002), is moderately impacted by VRI through a direct pathway. However, it functions as both an endogenous variable and as a mediator that transfers the effects of other mediators onto critical and creative thinking. This aligns with Zimmerman's view of SR as a self-directed process that enables learners to transform their mental abilities into academic skills. The role of SR as a mediator, predictor, and precursor to critical and creative thinking was highlighted in the findings of many recent studies (Akcaoğlu et al., 2023; Ariyati & Fitriyah, 2024; Hyytinen et al., 2021; S.-T. Lee, 2009), confirming the role of SR as a precursor to critical and creative thinking. In addition, according to Costa and Kallick (2000a, 2000b), creating self-directed learners is the goal for teaching HoM. Therefore, educators can employ VRI to enhance SR skills, which significantly predicts the enhancement of higher-order thinking skills.

Although some of the observed indirect effects of the study revealed small to moderate effects, especially those including secondary and tertiary mediation, they are still considered educationally valuable gains. When students face challenging abstract concepts in biology classes, modest gains in MT and SR are still regarded as applicable and can still accumulate over time. Moreover, CAMIL emphasizes that even minor sequential psychological effects of immersion, such as a slight increase in motivation, can increase and lead to significant learning benefits over time. Therefore, even small or moderate impacts should be positively valued, especially in subjects that handle abstract concepts, such as biology.

The study was conducted within the context of three schools in Jerusalem; however, its findings offer insights that may still apply in broader educational settings. Global educational trends emphasize student-centered and technology-enhanced learning environments. Consequently, common challenges in engaging students while they are learning complex topics such as biology might be overcome through the pedagogical potential of immersive environments in different educational environments. However, cultural and curriculum differences should be taken into consideration when adapting the tool internationally.

To conclude, analysis revealed that VRI can significantly enhance SR, CRIT, and CRET directly and indirectly. While the direct effects showed how VRI can moderately impact HoM, the total effects reflected a substantial impact through the sequence of mediators FE, MT, and SR, with SR having the most critical mediating role. This supports that VRI, as grounded in CAMIL theory, helps students to gain knowledge constructively through active and interactive methods (Kavanagh et al., 2017) and improve cognitive outcomes.

5. Study Limitations

This study took place in East Jerusalem municipal high schools, where VR is still in its infancy as an educational tool. Many schools still lack labs designed for VR applications and teachers who are qualified to integrate it professionally into their subject matter. Furthermore, the lack of educational applications that suit different grade levels to meet different curriculum designs represents a limitation of the study. Three-dimensional biology content had to be chosen carefully before application. In addition, training the participating teachers on how to integrate VR effectively into their classes represents another limitation for the study.

This study was conducted in three secondary schools located in East Jerusalem, a context with unique cultural, political, and educational characteristics. The findings of the study provide important insights into the role of virtual reality immersion, flow, motivation, and self-regulation in enhancing students' habits of mind; however, the results may not be directly generalized to other regions or educational systems. Therefore, future research is encouraged to replicate this model in diverse cultural and institutional contexts to test its applicability and strengthen its external validity.

Another limitation is the full reliance on self-reported questionnaire data to assess the different constructs of the study. While the instrument is validated and widely used, it does not measure students' observable learning gains, such as achievement. To enhance construct validity, future studies are advised to integrate subjective and objective measures.

In addition, the involvement of teachers in sending the link to the questionnaire to the participating students to facilitate its distribution and the retrieval of their responses may have influenced the students' willingness to respond honestly. All ethical protocols were followed to reduce this potential source of bias. For example, the questionnaire was addressed to the researcher (not the teachers), ensuring anonymity and emphasizing the honesty of responses. However, we still acknowledge a potential source of bias related to the involvement of teachers. This form of teacher-mediated data collection should be considered when interpreting the findings, and future studies may benefit from using more neutral or anonymous platforms to minimize potential response bias.

The restricted time for conducting the study and the number of VR sets posed other limitations for applying VRI to other biology content, which would have enabled more noticeable, generalizable results.

Moreover, fostering habits of mind requires a considerable amount of time to be realized, achieved, and internalized as healthy habits in learners. The experiment lasted for one semester, which might not reveal the effects of VRI on students' self-regulation, critical, and creative thinking.

Although controlling variables (gender and previous experience with VR) showed a non-significant influence on the outcome variables, future research should continue to explore how individual differences might interact with immersive learning designs in different educational and cultural contexts.

Future research should consider these notes in terms of time, place, and applications, such as adopting a longitudinal methodology and including other scientific subjects to facilitate more generalizable results.

6. Recommendations

The findings of the study reflect VR as a promising tool for educational outcomes; however, practical implementation must consider the varying contexts of school environments. Resource constraints might limit the full adoption of the VR tool, especially with under-funded schools. Our recommendations should be seen as flexible and adaptable. Under-funded schools can start with more affordable alternatives such as computer simulations, mobile-based VR, or even cheaper sets of VR tools. Such schools can find creative ways to introduce the tool based on their context.

VR, as an interesting and engaging method of teaching, is a promising technological tool that has the potential to prepare students who can face the challenges of their age. It can help students to acquire and process knowledge intelligently as part of their adaptation process to the technological world. However, the tool is still in its infancy, which necessitates careful consideration of different aspects to ensure active application of the tool and powerful results. Therefore, the following recommendations stem from challenges faced by the present experiment:

1. Biology teachers are advised to integrate VRI into biology classes, especially when introducing complex foundational concepts, to ensure students' practical and constructive perception.
2. Teachers should engage in training courses about the integration of VR into their biology classes.
3. Curriculum designers should reconsider the designation of the curriculum based on the principles of CAMIL. Moreover, program engineers should provide suitable VR applications that meet the content demands of different school subjects for all grades.
4. Curriculum designers should include activities that allow critical and creative thinking.
5. Future cross-cultural research should be conducted to help validate and expand the model of the study into broader cultural contexts.

7. Conclusions

The study aimed to explore the effects of VRI-based biology classes on high school students' HoM, considering the mediating roles of FE, MT, and SR, complying with CAMIL principles. The findings confirmed the positive effects of VRI on enhancing critical and creative thinking through enhancing students' self-regulatory habits. PLS-SEM statistics reflected the usefulness of VRI in fostering students' HoM in biology. A higher level of student engagement in virtual biology environments resulted in a deeper understanding of complex contents, which motivated students to regulate themselves and fostered their CRIT and CRET abilities.

VRI has transformative potential for traditional education by creating a student-centered classroom in which students engage actively, enjoyably, and responsively in the construction of knowledge. Higher engagement generated higher levels of motivation, encouraging students to persist in their tasks and resist failure. Engagement through VR during biology classes created students who were reflective of their thoughts and performance and flexible about adapting their strategies to creatively meet their goals. Clarity and accuracy gained from VR experiences affected students' clarity and accuracy and encouraged assertive and confident analyses of complex concepts. Greater engagement and better comprehension encouraged students to go beyond their abilities, trying to think divergently by examining different alternatives to come up with creative results.

The study complied with the constructivist principles, especially CAMIL which emphasizes the critical role of learners as being active in constructing their own knowledge. However, VRI proved not only to enhance students' knowledge, but also to foster their critical and creative thinking through fostering their self-regulatory thinking and learning habits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci15080955/s1, Table S1: Recent empirical and conceptual research that explored how virtual reality learning environments affect students' thinking and learning processes.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author due to ethical restrictions and the confidentiality of student and school-related information.

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