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Virtual reality-supported learning: Effects on students' conceptual understanding and digital competence

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Abstract

Cell biology poses representational challenges for high school students because cellular structures are microscopic, spatially complex, and difficult to understand through static two-dimensional diagrams. This study examined whether a structured virtual reality (VR)-supported biology intervention using the BIO-VR application could improve grade 10 students' conceptual understanding of eukaryotic cell structure and function while also developing their digital competence. A two-phase quantitative design was employed in Hanoi, Vietnam. The preliminary phase surveyed 40 biology teachers and 305 grade 10 students to assess information and communication technology and VR readiness. The intervention phase used a quasi-experimental nonequivalent control group design with two intact grade 10 classes (N = 84). Digital competence was examined descriptively within the VR group. Students' self-assessments and teacher observations showed upward shifts across four rubric dimensions: device operation, information seeking and evaluation, digital safety, and technical problem-solving. The study demonstrates that theory-informed, teacher-guided VR integration can enhance conceptual understanding and was associated with descriptive within-group shifts in digital competence in secondary biology, offering an implementation model for immersive learning in Vietnamese upper secondary education.

Keywords: virtual reality, cell biology, conceptual understanding, digital competence

INTRODUCTION

Cell biology is a core component of secondary science education, but it remains difficult for many students because its central objects and processes are microscopic, spatially complex, dynamic, and inaccessible to direct observation. To understand eukaryotic cells, learners must connect organelles, membrane systems, intracellular organization, and structure-function relationships across multiple representational levels. In typical classrooms, these topics are often taught through textbooks, teacher explanations, slides, videos, and two-dimensional diagrams. Although these resources introduce terminology and basic biological functions, they frequently present cells as static, flat, and visually simplified entities. As a result, students may recall organelle names and functions without developing a coherent mental model of how cellular components are spatially arranged and functionally interconnected. Prior research has shown that students may retain oversimplified or inaccurate conceptions of cells when learning is mediated mainly through conventional representations (Thompson et al., 2020), and similar difficulties have been reported in cell and molecular biology education where learners must reason about invisible and three-dimensional processes from traditional diagrams (Bennett & Saunders, 2019; Reen et al., 2022; Reinke et al., 2021).

This representational problem is closely related to the design of multimedia and immersive learning environments. According to the cognitive theory of multimedia learning, meaningful learning requires students to select relevant information, organize verbal and visual representations, and integrate them with prior knowledge (Mayer, 2021). However, richer visualization does not automatically lead to deeper

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Contribution to the literature

- This study provides classroom-based evidence that a structured, teacher-guided immersive VR intervention can support stronger immediate conceptual understanding of eukaryotic cell structure and function among upper-secondary students in a low-prior-VR-exposure context.
- It extends the VR-supported science education literature by examining digital competence alongside conceptual learning and documenting descriptive improvements in device operation, information seeking and evaluation, digital safety, and technical problem-solving.
- It offers a theory-informed implementation model that integrates immersive three-dimensional visualization with orientation, guided exploration, teacher scaffolding, and post-VR consolidation for the pedagogically meaningful use of VR in secondary biology education.

understanding. When learning environments contain excessive information, insufficient guidance, or unfamiliar controls, they may increase extraneous cognitive load rather than support conceptual integration. In immersive virtual reality (IVR), this issue is especially important because virtual reality (VR) can enhance presence, agency, and engagement while also demanding learners' attention, navigation, and self-regulation. The cognitive affective model of immersive learning (CAMIL) explains VR learning through interactions among immersion, presence, agency, motivation, self-efficacy, cognitive load, and self-regulation (Makransky & Petersen, 2021). Therefore, the educational value of VR should be examined not as technological novelty, but as part of a coherent instructional design that guides attention, structures exploration, and supports reflection (Makransky & Mayer, 2022).

Immersive VR has attracted increasing attention in science and STEM education because it enables learners to experience phenomena that are too small, abstract, dangerous, expensive, or otherwise inaccessible in ordinary classrooms. Through head-mounted displays, students can observe simulated objects from multiple perspectives, move within three-dimensional environments, and interact with spatial structures in ways that static diagrams or non-interactive videos cannot provide. Reviews and meta-analyses suggest that immersive VR can support learning outcomes, motivation, engagement, and spatial understanding when it is aligned with clear instructional goals and appropriate scaffolding (Coban et al., 2022; Di Natale et al., 2020; Matovu et al., 2023; Radianti et al., 2020; Won et al., 2023). At the same time, recent reviews emphasize that VR effects vary depending on content domain, learner characteristics, interactivity, instructional guidance, task design, and comparison condition (Acevedo et al., 2024; Lawson et al., 2024). The central question is thus not whether VR is inherently superior to conventional instruction, but under what pedagogical conditions VR can support specific forms of conceptual learning.

Cell biology is a suitable domain for examining this question because understanding cells requires students to build spatially organized and functionally connected mental models of phenomena that cannot be directly observed at classroom scale. Biology-focused studies provide encouraging evidence that VR can support learning and engagement in cell-related topics, including virtual cell tours, osmosis, inquiry-based cell games, VR escape-room learning, and multimedia-learning-informed representations of cellular structures (Bennett & Saunders, 2019; Christopoulos et al., 2023; Laubscher et al., 2024; Reinke et al., 2021; Thompson et al., 2020). Nevertheless, several gaps remain. Many studies have been conducted in higher education, laboratory settings, or technology-rich environments, whereas fewer have examined teacher-guided implementation in ordinary secondary classrooms where students and teachers may have limited prior VR experience. Moreover, many VR studies emphasize achievement, motivation, presence, or acceptance, while paying less attention to students' digital competence as an educational outcome.

Digital competence is an important consideration in contemporary technology-supported education. It involves not only access to digital devices but also the ability to operate technologies, evaluate digital information, act safely and responsibly, and solve technical problems. The DigComp framework conceptualizes digital competence as a multidimensional construct involving information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving (Vuorikari et al., 2022). This perspective is relevant to VR-supported biology learning because students are not merely passive recipients of digital content; they operate immersive devices, navigate simulated environments, follow safety routines, interpret digital representations, and respond to technical issues. In Vietnam, digital competence has become increasingly important in the context of national digital transformation, yet recent evidence indicates that it remains an area requiring continued development (Nguyen et al., 2024). School-based VR implementation is also shaped by infrastructure, cost, classroom organization, teacher readiness, curriculum alignment, and technical support (Boel et al., 2023; Fransson et al., 2020).

Against this background, the present study investigates a structured VR-supported biology intervention using the BIO-VR application and Oculus Quest 2 headsets with grade 10 students in Hanoi, Vietnam. The study focuses on eukaryotic cell structure and function and combines immersive visualization with guided exploration, teacher facilitation, and post-VR consolidation. It employed a two-phase quantitative design: a preliminary readiness survey with biology teachers and grade 10 students, followed by a quasi-experimental comparison between VR-supported instruction and conventional instruction. The study was guided by three research questions:

1. To what extent does VR-supported instruction improve grade 10 students' conceptual understanding of eukaryotic cell structure and function compared with conventional instruction?
2. What descriptive within-group changes in students' digital competence were observed during the structured VR-based biology intervention?
3. What practical implementation observations emerged from integrating BIO-VR into upper secondary biology teaching in a resource-supported but low-prior-VR-exposure context?

By addressing these questions, the study contributes classroom-based evidence on VR-supported cell biology learning, connects conceptual understanding with digital competence development, and offers a teacher-guided model for integrating immersive technology into secondary science education.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

IVR as an Instructional Technology in Science Education

IVR refers to computer-generated three-dimensional environments in which learners use head-mounted displays and controllers to observe and interact with simulated objects. In science education, this affordance is valuable because many phenomena are microscopic, spatially complex, dangerous, expensive, or inaccessible in ordinary classrooms. IVR can place learners inside a phenomenon and allow them to inspect objects from multiple viewpoints. Reviews indicate that head-mounted IVR is relevant for spatial inspection, experiential exploration, laboratory simulation, and skill development (Concannon et al., 2019; Jensen & Konradsen, 2018).

However, IVR should not be treated as an automatically superior medium. STEM education studies report positive but variable effects on learning, engagement, motivation, and spatial understanding (Pellas et al., 2020, 2021). Meta-analyses in school contexts show that VR can improve learning outcomes when aligned with curricular goals and when tasks require visualization or interaction beyond conventional representation (Lara-Alvarez et al., 2023; Villena-Taranilla et al., 2022). Engagement is not equivalent to conceptual understanding: learners may enjoy immersive experiences without processing scientific principles. Effective IVR implementation therefore depends on instructional design, teacher scaffolding, assessment alignment, and classroom feasibility. Teachers' intention to use IVR is shaped by perceived usefulness, self-efficacy, technical confidence, and institutional support (Bower et al., 2020; Khukalenko et al., 2022; Scherer et al., 2019). IVR should therefore be conceptualized as a teacher-mediated learning environment rather than a stand-alone innovation.

VR-Supported Conceptual Learning in Cell and Molecular Biology

Cell biology is suitable for IVR because students must understand microscopic, three-dimensional, and functionally connected systems that cannot be directly observed at classroom scale. Learning about eukaryotic cells requires more than memorizing organelle names and functions. Students need to understand how cellular components are spatially arranged and how they interact. Conventional diagrams and teacher explanations can introduce terminology, but they often flatten cells into simplified two-dimensional images, encouraging students to view the cell as a static collection of isolated parts.

VR can address this challenge by allowing students to explore cellular structures from multiple perspectives and experience the cell as an organized spatial environment. Biology and molecular science studies report that VR-supported lessons can make abstract cellular structures more concrete, memorable, and engaging (Bennett & Saunders, 2019; Coan et al., 2020; Reen et al., 2021). Nevertheless, immersive visualization alone is insufficient. Students may focus on novelty or visual detail without connecting observations to biological concepts. Research on immersive science simulations shows that VR may increase presence while reducing learning if it imposes excessive cognitive demands (Makransky et al., 2019). Pre-training can help by activating relevant prior knowledge before exploration (Meyer et al., 2019). Thus, VR-supported cell biology should include orientation, guiding questions, teacher prompts, and consolidation.

Cognitive and Affective Mechanisms in Immersive Learning

The theoretical basis of this study combines cognitive and affective perspectives on immersive learning. From the cognitive theory of multimedia learning, students learn when they select relevant information, organize verbal and visual representations, and integrate them with prior knowledge (Mayer, 2021). IVR may support these processes by making spatial and dynamic information more accessible. However, perceptual richness can also distract learners if the environment includes unnecessary detail or if learners must simultaneously manage controls, navigation, and scientific interpretation.

From the CAMIL, IVR effects are shaped by immersion, presence, agency, motivation, self-efficacy, cognitive load, and self-regulation (Makransky & Petersen, 2021). These variables help explain why the same technology may produce different outcomes across learners and contexts. Empirical studies show that immersion can increase liking and presence, but learning gains depend on active processing and generative strategies (Makransky et al., 2021). Teaching-as-learning activities, explanation prompts, and structured tasks can support generative processing in desktop and immersive VR (Klingenberg et al., 2020). Recent work also emphasizes that immersion and interactivity are distinct design features and should be paired with scaffolds for noticing, comparing, predicting, explaining, and reflecting (Petersen et al., 2022, 2023). Accordingly, BIO-VR was designed as a structured sequence involving orientation, guided observation, teacher questioning, and consolidation.

Digital Competence as an Outcome of VR-Supported Biology Learning

Digital competence refers not only to device access but also to the capacity to use digital technologies purposefully, safely, critically, and responsibly. Reviews describe digital competence as multidimensional, involving operational skills, information literacy, communication, digital content creation, safety, and problem-solving (Spante et al., 2018; Zhao et al., 2021). The DigComp framework similarly identifies information and data literacy, communication and collaboration, digital content creation, safety, and problem-solving as core areas (Vuorikari et al., 2022).

This perspective is important for VR-supported biology because students are not passive viewers of digital content. They operate headsets, navigate immersive space, identify scientific information, follow safety routines, and respond to technical issues. These actions correspond to operational, informational, safety-related, and problem-solving dimensions of digital competence. Recent assessment research indicates that digital competence should be measured through structured indicators rather than inferred from general technology familiarity (Godaert et al., 2022; Pedaste et al., 2023; Tzafilkou et al., 2022). In school contexts, meaningful technology integration also depends on teachers' pedagogical and evaluative capacity, not device access (Claro et al., 2024). Therefore, VR-supported biology can be examined as both a science-learning experience and a context for developing digital competence.

Integrated Theoretical Framework of the Present Study

This study addresses three gaps. First, much IVR evidence comes from higher education, laboratories, or technology-rich contexts, so more classroom-based research is needed in ordinary secondary schools where teachers manage curricular time, safety, devices, and varied student readiness. Second, cell biology is appropriate for immersive visualization, yet more evidence is needed on whether VR improves secondary students' understanding of eukaryotic cell structure and function. Third, many VR studies focus on achievement, motivation, engagement, or presence, while digital competence is less often examined as a parallel outcome.

The present framework integrates three perspectives. The representational perspective views IVR as a tool for making microscopic and spatial biological structures accessible. The instructional design perspective emphasizes pre-training, guided exploration, teacher facilitation, generative tasks, and post-VR consolidation. The digital competence perspective views VR-supported learning as an opportunity for students to develop operational, informational, safety-related, and problem-solving abilities through authentic technology use. Accordingly, BIO-VR is expected to support conceptual understanding when students observe organelles, identify spatial relationships, connect structures with functions, and verbalize explanations. It is also expected to support digital competence when students operate VR devices, evaluate digital representations, follow safety procedures, and solve basic technical problems. The study therefore examines BIO-VR as a structured instructional environment connecting educational technology, biology learning, and digital competence development in upper secondary education.

METHOD

Research Design

This study used a two-phase quantitative design to evaluate VR-supported biology instruction in upper secondary education. Phase 1 was a descriptive readiness survey with biology teachers and grade 10 students, examining prior exposure to information and communication technology (ICT) and VR. Phase 2 used a quasi-experimental nonequivalent control group design to test whether the BIO-VR intervention improved students' conceptual understanding of eukaryotic cell structure and function and their digital competence.

A quasi-experimental design was selected because the intervention was conducted in an authentic school setting where random assignment of individual students

Table 1. Preliminary ICT and VR readiness

Indicator	Sample	Result: Percentage (%)
Teachers who had heard about and explored VR	40 teachers	5.0
Teachers who had heard about VR but had not explored it	40 teachers	25.0
Teachers who had never heard about VR	40 teachers	70.0
Teachers who had never used VR software in teaching	40 teachers	95.0
Teachers who had never used a VR headset in teaching	40 teachers	100
Students who had experienced VR in learning	305 students	6.0
Students who had never experienced VR in learning	305 students	94.0

Table 2. Baseline characteristics of the experimental and control groups

Variable	Control group (10F)	Experimental group (10S)	Statistical comparison
Number of students	42	42	
Female	21	22	$\chi 2$ (1, N = 84) = 0.048, p = .827, ϕ = .024
Male	21	20	
First-semester biology average	6.1	6.2	Descriptive difference = 0.10

was not feasible. In educational technology research, intact classes are often retained for administrative, ethical, and ecological reasons. Such designs can provide useful evidence when baseline equivalence is examined, comparison conditions are clearly defined, outcome measures are aligned with learning objectives, and procedures documented (Gopalan et al., 2020; Handley et al., 2018; Reichardt, 2019). Two intact grade 10 classes were assigned to experimental and control conditions. The experimental group learned with BIO-VR and Oculus Quest 2 headsets, whereas the control group received conventional instruction on the same content. Baseline comparability was examined using first-semester biology averages, prerequisite knowledge scores, and initial digital competence self-assessments (What Works Clearinghouse, 2022).

Context, Participants, and Preliminary VR Readiness

The preliminary phase involved 40 biology teachers and 305 grade 10 students from nine high schools in Hanoi. The questionnaires examined teachers' awareness and classroom use of VR and students' previous experience with VR-based learning. As shown in **Table 1**, the results indicate a low prior-exposure context for school-based VR implementation.

The quasi-experimental phase was conducted at Hanoi Academy International Bilingual School, a private international bilingual school in Hanoi. The school had more favorable ICT infrastructure than many public schools, and this context made classroom use of Oculus Quest 2 headsets feasible. At the same time, prior classroom exposure to VR remained limited among the participating students and teachers. Therefore, the implementation context should be understood as a resource-supported upper-secondary school with low prior VR experience, rather than as representative of all Vietnamese public schools.

The sample size was determined by the two intact grade 10 classes participating in the quasi-experimental phase (42 students per class; N = 84). Because the study was conducted in an authentic school setting where individual random assignment was not feasible, the achieved sample was justified by the intact-class design and associated practical constraints. Consistent with Lakens (2022), these constraints and the final sample are reported transparently rather than supplemented with a post hoc power analysis.

Baseline characteristics of the experimental and control groups are summarized in **Table 2** to document group comparability before the intervention.

The groups had equal sample sizes and similar sex distributions, χ^2 (1, N = 84) = 0.048, p = .827, φ = .024. The recorded first-semester biology class means (Ms) were 6.10 in the control group and 6.20 in the experimental group, corresponding to a descriptive difference of 0.10 points. Because individual grade records and prerequisite-test scores were unavailable in the archived dataset, no inferential baseline achievement comparison was conducted. Digital competence was not compared between groups because it was assessed only in the experimental group. To reduce teacher-related variation, the same biology teacher taught both groups. Both classes studied the same topic, followed the same objectives, and completed the same number of instructional sessions. The key difference was the instructional medium: immersive exploration of eukaryotic cell structures in the experimental group and textbook images, teacher explanation, diagrams, and discussion in the control group.

Instructional Intervention and Comparison Condition

The intervention focused on eukaryotic cell structure and function in grade 10 biology. The experimental group received VR-supported instruction using BIO-VR and Oculus Quest 2 headsets across four sessions. The content covered the nucleus, cytoplasm, mitochondria, endoplasmic reticulum, Golgi apparatus, ribosomes, and cell membrane.

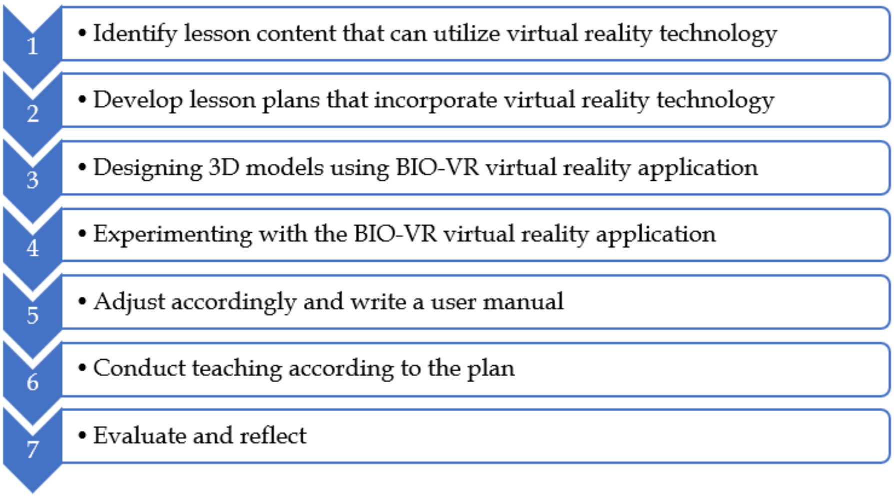

Figure 1. Design and implementation process of the BIO-VR-supported instructional intervention (the authors' own work)

Figure 2. Classroom implementation of the BIO-VR-supported cell biology lesson (Photograph taken by the authors during the classroom intervention)

BIO-VR was embedded in a structured instructional sequence rather than used as a stand-alone demonstration. The teacher introduced learning objectives and activated prior knowledge. Students then received orientation on headset use, controller operation, safe movement, and interaction with the virtual environment. During guided VR exploration, they observed organelles from multiple perspectives and identified spatial relationships among cellular components. The teacher used guiding questions to direct attention to structure-function relationships. Post-VR consolidation included teacher explanation, discussion, and learning tasks.

To ensure that VR was integrated as a pedagogical intervention rather than as a stand-alone technological demonstration, the BIO-VR lessons were developed through a systematic design and implementation process. The process began with selecting curriculum content that required spatial visualization, followed by lesson planning, 3D model development, pilot testing, refinement of the application and user guide, classroom implementation, and post-lesson evaluation. This sequence was intended to align immersive visualization with learning objectives, teacher scaffolding, student safety, and assessment of both conceptual understanding and digital competence. The overall process is summarized in **Figure 1**.

During the experimental sessions, students worked individually and in small groups while sharing Oculus Quest 2 headsets under teacher supervision. The teacher first provided technical orientation and safety instructions, and then guided students to explore cell structures, identify organelles, and relate spatial features to biological functions. The classroom arrangement allowed non-immersed students to follow the projected VR view, discuss observations, and complete inquiry-

Table 3. Reliability and item-quality evidence for outcome measures

Instrument	Reliability/technical index	Value	Interpretation
Digital competence rubric	Inter-rater reliability (κ)	0.82	Strong agreement
Achievement pre-test	KR-20	0.79	Acceptable reliability
Achievement post-test	KR-20	0.81	Good reliability
Achievement items	Difficulty index	0.45-0.75	Acceptable item difficulty
Achievement items	Discrimination index	> 0.30	Adequate item discrimination

based learning tasks while waiting for their turn. **Figure 2** illustrates the classroom implementation of the BIO-VR-supported lessons.

The intervention was conducted across four curriculum sessions. Because the headsets were shared, each student completed guided immersive turns while non-immersed students followed the projected VR view, discussed observations, and completed inquiry tasks. The average immersive headset time was approximately 4-5 minutes per student per session, resulting in about 16-20 minutes of direct headset-based VR exposure per student across the four-session intervention.

Safety procedures were included because head-mounted VR may cause discomfort, disorientation, or cybersickness. Students were instructed on safe use, appropriate movement, and reporting discomfort. The teacher and two observing teachers monitored students, consistent with evidence that VR sickness is influenced by headset characteristics, exposure duration, content design, and user-related factors (Saredakis et al., 2020).

The control group received conventional instruction on the same biology content, taught by the same teacher and organized around the same learning objectives, guiding questions, discussion, and consolidation tasks. Students used textbook images, two-dimensional diagrams, board presentation, teacher explanation, and worksheet-based activities to identify cell structures and explain organelle functions. Thus, the groups were comparable in content, teacher, instructional time, questioning, discussion, and consolidation; the experimental condition added immersive three-dimensional exploration through BIO-VR and headset operation.

Instruments

Four instruments were used: an ICT and VR readiness questionnaire, an achievement test, a student digital competence self-assessment rubric, and a teacher observation rubric. Instrument development followed principles of educational measurement, including content alignment, expert review, reliability checking, and item analysis (Boateng et al., 2018; DeVellis & Thorpe, 2022; Furr, 2021).

The readiness questionnaire was used as a descriptive checklist of teachers' awareness and prior use of VR-related tools and students' prior experience with VR in learning. Because the checklist items reflected heterogeneous aspects of awareness and use rather than a single reflective construct, internal-consistency coefficients were not interpreted for this instrument.

Conceptual understanding was measured using a multiple-choice achievement test on eukaryotic cell structure and function. The test assessed recognition of cellular structures, understanding of organelle functions, and ability to connect structure with function. A prerequisite knowledge test examined baseline equivalence. After the intervention, both groups completed a 15-minute post-test consisting of 10 multiple-choice items. The pre-test and post-test showed acceptable reliability, with KR-20 coefficients of .79 and .81, respectively. Item difficulty ranged from .45 to .75, and discrimination indices were above .30.

Digital competence was assessed using a four-component rubric covering operation of digital devices, information seeking and evaluation, digital safety, and technical problem-solving. Each component was rated at three levels: M1 for basic competence, M2 for proficient competence, and M3 for advanced competence. Students in the experimental group completed the self-assessment before and after the intervention. Two observing teachers independently rated students during VR-supported lessons. Three experts reviewed the rubric for relevance and clarity, and inter-rater reliability was strong (Cohen's kappa = .82).

The reliability and technical quality of the instruments are reported in **Table 3**.

Data Collection and Analysis

First, the ICT and VR readiness survey was administered to teachers and students from nine high schools. Second, available pre-intervention characteristics of the two participating classes were documented, including class size, sex distribution, and recorded first-semester biology class Ms. Third, the four-session intervention was implemented. Students in the experimental group completed the digital-competence self-assessment before and after the intervention, and two teachers observed their competence during the VR-supported lessons. Fourth, both groups completed the immediate achievement post-test.

Data were analyzed using descriptive and inferential statistics. Frequencies and percentages summarized readiness survey responses. Descriptive statistics summarized participant characteristics, baseline measures, achievement scores, and rubric levels. Reliability was examined using Cronbach's alpha for

Table 4. Students' self-assessment of digital competence before and after the intervention (%)

No	Component	Before M1	Before M2	Before M3	After M1	After M2	After M3
1	Operating digital devices	76.2	21.4	2.4	9.5	54.8	35.7
2	Information seeking and evaluation	40.5	52.4	7.1	7.1	42.9	50.0
3	Digital safety	40.5	52.4	7.1	16.7	40.5	42.9
4	Technical problem-solving	83.3	16.7	0.0	28.6	50.0	21.4

readiness questionnaires, KR-20 for achievement tests, and Cohen's kappa for observation ratings. Item difficulty and discrimination were calculated for the achievement test.

For conceptual understanding, post-test achievement scores were compared between the experimental and control groups. Although ANCOVA would have been preferable for a nonequivalent control-group design, individual-level prerequisite/pre-test scores were not available in the final archived dataset. Therefore, the achievement analysis was reported as an immediate post-intervention comparison, supported by documented baseline similarity between the two intact classes. Descriptive statistics, mean difference, 95% confidence interval (CI), independent-samples t-test, and Cohen's d were reported. Homogeneity of variance was examined using Levene's test. The absence of individual-level baseline covariate data is acknowledged as a limitation.

Because digital competence was measured only in the experimental group, these data were analyzed as exploratory within-group descriptive evidence. As the M1-M3 rubric levels constituted ordered categories, frequencies and percentages at each level were treated as the primary nonparametric summaries. For a supplementary compact overview of the distributions, the levels were numerically coded as M1 = 1, M2 = 2, and M3 = 3 and combined into a weighted descriptive index calculated as [1n (M1) + 2n (M2) + 3n (M3)]/N. This coding was not interpreted as evidence that adjacent rubric levels were equally spaced, and the index was not used for parametric inference.

Ethical Considerations

Before data collection, the VNU University of Education, Hanoi reviewed the protocol and determined that it was exempt from full ethics review as minimal-risk classroom-based educational research conducted within regular instruction. The study nevertheless followed the institutionally approved safeguards applicable to research involving minors.

Before the study began, all grade 10 students were informed about the purpose of the research, the procedures involved, the voluntary nature of their participation, and their right to withdraw from the study at any time without any academic penalty or negative consequence. Written informed assent was obtained from the students. As the participants were under 18 years of age, written consent was also obtained from their parents or legal guardians before participation.

All data collected during the study were anonymized and used only for research purposes. No personally identifiable information was included in the analysis or reported in the manuscript. During the VR activities, students were supervised by the teacher/researcher to ensure their physical and psychological safety. Students were instructed to stop using the VR equipment immediately if they experienced dizziness, eye strain, discomfort, or any other adverse symptoms.

For classroom photographs included in the manuscript, including **Figure 2**, consent was obtained from the students and their parents or legal guardians. Images were selected and presented in a way that protected students' identities, and no identifiable image was used without explicit permission.

RESULTS

Changes in Digital Competence After the Intervention

Digital competence was measured in the experimental group before and after the VR-supported intervention. Four components were assessed: operating digital devices, information seeking and evaluation, digital safety, and technical problem-solving. Each component was rated at three levels: M1 = basic, M2 = proficient, and M3 = advanced. The results showed improvement across all components (**Table 4**).

Based on student self-assessment, the largest increase at the advanced level occurred in information seeking and evaluation. The proportion of students at M3 increased from 7.1% before the intervention to 50.0% after the intervention. Operating digital devices also improved substantially, with M3 increasing from 2.4% to 35.7%. Digital safety increased from 7.1% to 42.9% at M3, while technical problem-solving increased from 0.0% to 21.4%. At the same time, the proportion of students at the basic level decreased sharply in every component.

Teacher assessments confirmed the same general pattern (**Table 5**). The percentage of students rated at M3 in information seeking and evaluation rose from 4.8% to 45.2%. In operating digital devices, the M3 rate increased from 2.4% to 26.2%. In digital safety, it rose from 2.4% to 23.8%, and in technical problem-solving, from 0.0% to 16.7%. The decline in M1 ratings was also consistent across all four dimensions.

Table 5. Teacher assessment of students' digital competence before and after the intervention (%)

No	Component	Before M1	Before M2	Before M3	After M1	After M2	After M3
1	Operating digital devices	78.6	19.0	2.4	16.7	57.1	26.2
2	Information seeking and evaluation	52.4	42.8	4.8	7.1	47.7	45.2
3	Digital safety	57.1	40.5	2.4	23.8	52.4	23.8
4	Technical problem-solving	59.5	40.5	0.0	31.0	52.4	16.7

Table 6. M scores of digital competence components before and after the intervention

Component	Student self-assessment before	Student self-assessment after	Teacher assessment before	Teacher assessment after
Operating digital devices	1.26	2.26	1.24	2.10
Information seeking and evaluation	1.67	2.43	1.52	2.38
Digital safety	1.67	2.26	1.45	2.00
Technical problem-solving	1.17	1.93	1.40	1.86

Note. M1, M2, and M3 were numerically coded as 1, 2, and 3, respectively; each value is a weighted descriptive index calculated as [1n (M1) + 2n (M2) + 3n (M3)]/N; because the rubric levels are ordinal, the index does not establish equal intervals between adjacent levels; & frequencies and percentages in **Table 4** and **Table 5** are the primary results, and no parametric significance test was applied to the index values

Table 7. Distribution of post-test scores in the control and experimental groups

Score (X_i)	Control group		Experimental group	
	Frequency	Percentage (%)	Frequency	Percentage (%)
1	0	0.0	0	0.0
2	1	2.4	0	0.0
3	1	2.4	0	0.0
4	4	9.5	1	2.4
5	8	19.0	4	9.5
6	15	35.7	9	21.4
7	9	21.4	13	31.0
8	2	4.8	8	19.0
9	1	2.4	4	9.5
10	1	2.4	3	7.1
M	5.93		7.12	

Table 4 and **Table 5** present the primary distributional evidence through frequencies and percentages at the ordered M1, M2, and M3 levels. As supplementary descriptive information, M1, M2, and M3 were coded as 1, 2, and 3, respectively, and combined into a weighted descriptive index. For student self-assessment, the index shifted from 1.26 to 2.26 for operating digital devices, from 1.67 to 2.43 for information seeking and evaluation, from 1.67 to 2.26 for digital safety, and from 1.17 to 1.93 for technical problem-solving. Teacher-rating indices showed similar descriptive shifts: from 1.24 to 2.10, from 1.52 to 2.38, from 1.45 to 2.00, and from 1.40 to 1.86, respectively. These indices summarize the direction of the category distributions and should not be interpreted as interval-scale estimates of change (**Table 6**).

Student self-assessment and teacher observation showed a similar descriptive pattern, but this should be interpreted as descriptive triangulation rather than evidence of convergent validity because both sources may have been influenced by expectancy and novelty effects. Across both sources, the largest distributional shift toward M3 occurred in information seeking and evaluation. Upward shifts were also observed in device operation and digital safety. Technical problem-solving shifted toward higher levels but retained the largest concentration of students at M1 and M2, suggesting that advanced troubleshooting may require more extended practice.

Effects on Conceptual Understanding of Eukaryotic Cell Structure and Function

After the intervention, both groups completed a 15-minute achievement post-test consisting of 10 multiple-choice items on eukaryotic cell structure and function. The score distribution showed a clear advantage for the experimental group. Control group scores were concentrated mainly between 5 and 7, whereas experimental group scores shifted toward higher bands, particularly 7 to 9. The experimental group had no students scoring below 4, while the control group included students scoring 2 and 3 (**Table 7**).

Performance classification provided a more interpretable picture of achievement differences. In the control group, 14.3% of students were classified as weak/poor and 54.8% as average. Only 26.2% were classified as good and 4.8% as excellent. In contrast, the experimental group had only 2.4% of students in the weak/poor category and 31.0% in the average category. Half of the experimental students reached the good

Table 8. Performance classification of post-test results by group (%)

Group	Weak/poor	Average	Good	Excellent	Total
Control group	14.3	54.8	26.2	4.8	100
Experimental group	2.4	31.0	50.0	16.7	100

Note. Performance categories on the 10-point test were defined as follows: weak/poor: 0-4, average: 5-6, good: 7-8,& excellent: 9-10

Table 9. Descriptive and inferential statistics for post-test achievement

Parameter	Control group	Experimental group	Difference/test value
n	42	42	
M score	5.93	7.12	1.19
SD	1.49	1.43	
Mean difference, 95% CI			1.19 [0.56, 1.82]
Levene's test			p = .786
Independent-samples t-test			t (82) = 3.73, p < .001
Effect size			Cohen's d = 0.81, 95% CI [0.37, 1.26]

category, and 16.7% reached the excellent category (**Table 8**).

After the intervention, the experimental group obtained a higher post-test score than the control group. The experimental group achieved M = 7.12, standard deviation [SD] = 1.43, whereas the control group achieved M = 5.93, SD = 1.49. The mean difference was 1.19 points on a 10-point test, 95% CI [0.56, 1.82]. The independent-samples t-test indicated that this difference was statistically significant, $t(82) = 3.73$, $p < .001$. The effect size was large, Cohen's d = 0.81, 95% CI [0.37, 1.26]. Homogeneity of variance was supported, Levene's p = .786. Because individual-level prerequisite scores were unavailable, this result should be interpreted as an immediate post-intervention difference rather than as an ANCOVA-adjusted causal estimate (**Table 9**).

These findings indicate that students who learned through the structured BIO-VR intervention demonstrated stronger immediate conceptual understanding of eukaryotic cell structure and function than students who received conventional instruction. The improvement was evident not only in the M score but also in the distribution of performance. The experimental group had fewer low-scoring students and more students in the good and excellent categories.

DISCUSSION

This study examined whether a structured VR-supported biology intervention could improve grade 10 students' conceptual understanding of eukaryotic cell structure and function while also supporting digital competence. Three findings emerged. First, the preliminary survey showed that immersive VR was unfamiliar to most participating biology teachers and students. Second, students who learned with BIO-VR achieved significantly higher post-test scores than those receiving conventional instruction. Third, the experimental group showed descriptive upward shifts across all four dimensions of digital competence, with similar patterns in student self-assessment and teacher observation interpreted as descriptive triangulation rather than convergent evidence. Overall, the results suggest that immersive VR can be educationally valuable when embedded in a guided instructional sequence rather than introduced as a novelty tool.

VR Readiness and the Implementation Gap in School Biology

The readiness data revealed a clear gap between the growing policy and research interest in educational digital transformation and actual classroom experience with immersive technologies. Most teachers had never used VR software in biology teaching, none had used head-mounted VR in classroom practice, and most students had never experienced VR for learning. The intervention was implemented in a resource-supported school context where VR exposure was still limited, not in a setting where students and teachers were already accustomed to immersive tools. This distinction is important for interpreting generalizability.

This result aligns with reviews showing that although VR research has expanded rapidly, implementation in ordinary classrooms remains uneven and depends on infrastructure, teacher readiness, institutional support, and pedagogical integration (Hamilton et al., 2021; Radianti et al., 2020; Won et al., 2023). Recent reviews also note that many immersive learning studies are conducted in higher education, laboratories, or short-term experimental settings, while evidence from regular school classrooms remains comparatively limited (Lawson et al., 2024; Matovu et al., 2023). The present study therefore contributes practical evidence from a low-exposure VR context. For educational technology research, this matters because the effectiveness of immersive tools should be judged not only by their technical potential but also by their feasibility in authentic teaching conditions.

Effects on Conceptual Understanding of Cell Biology

The experimental group outperformed the control group on the post-test of eukaryotic cell structure and function. The difference was statistically significant and the effect size was large. The achievement distribution also shifted upward: fewer students in the VR-supported group remained in weak or average categories, while more reached good or excellent levels. This pattern suggests that BIO-VR did not merely benefit a small number of high-performing students; rather, it improved the overall achievement profile of the class.

This finding is consistent with meta-analytic evidence that immersive VR can improve learning outcomes, although its effects vary according to domain, learner characteristics, instructional design, interactivity, and comparison condition (Coban et al., 2022; Wu et al., 2020). It also supports science education reviews indicating that VR is especially useful when learners must understand phenomena that are microscopic, abstract, spatially complex, dynamic, dangerous, or otherwise inaccessible through ordinary classroom experience (Matovu et al., 2023; Won et al., 2023). Cell biology fits this condition because students must understand organelles, intracellular organization, and structure-function relationships that cannot be directly observed at school scale.

The findings also extend biology-focused VR research. Thompson et al. (2020) found that VR could help high school students develop more complex conceptions of cells. Christopoulos et al. (2023) reported that an active VR escape-room approach supported short-term biology knowledge more effectively than a passive video-based approach. Laubscher et al. (2024) showed that a multimedia-learning-informed VR experience improved students' understanding of mammalian cell structures compared with traditional slideshow instruction. The present study adds evidence from Vietnamese upper secondary biology and suggests that guided immersive visualization can support conceptual understanding under realistic classroom conditions.

Explaining the Learning Effect Through Immersive Learning Theory

The positive learning effect can be interpreted through the cognitive theory of multimedia learning. Meaningful learning occurs when students select relevant information, organize verbal and visual representations, and integrate them with prior knowledge (Mayer, 2021). BIO-VR may have supported these processes by allowing students to inspect organelles as three-dimensional, spatially arranged structures rather than relying only on flat textbook diagrams. This affordance is particularly relevant for helping students connect cellular form, location, and function.

However, the results should not be interpreted as evidence that immersion alone improves learning. VR and multimedia research shows that immersive environments can increase presence, interest, and engagement, but these affective responses do not automatically lead to deeper understanding (Makransky & Mayer, 2022; Parong & Mayer, 2018). Lawson et al. (2024) also caution that media-comparison studies may confound the effects of VR with differences in content, interactivity, task design, or instructional support. In the present study, BIO-VR was embedded in a structured sequence that included pre-VR orientation, guided exploration, teacher questioning, and post-VR consolidation. Therefore, the learning gains should be understood as the result of combining immersive representation with instructional scaffolding.

The findings are also consistent with the CAMIL, which explains VR learning through the interaction of immersion, presence, agency, motivation, cognitive load, and self-regulation (Makransky & Petersen, 2021). In BIO-VR lessons, students navigated a virtual cell, inspected organelles from multiple perspectives, and responded to teacher prompts. These activities may have increased agency and supported active exploration. At the same time, because students had limited prior VR experience, guidance was necessary to reduce distraction, novelty effects, and unnecessary cognitive load. This interpretation supports the view that immersion and interactivity should be treated as design features that require appropriate scaffolding, not as independent guarantees of learning (Petersen et al., 2022, 2023).

Digital Competence as a Parallel Outcome

A distinctive contribution of this study is that it examined digital competence alongside conceptual understanding. The experimental group improved in operating digital devices, information seeking and evaluation, digital safety, and technical problem-solving. The similar pattern across student and teacher ratings provides useful descriptive triangulation, but it does not eliminate shared-bias concerns.

The strongest gains occurred in information seeking and evaluation and in operating digital devices. This is plausible because students had to wear and adjust headsets, operate controllers, navigate a simulated environment, identify relevant biological information, and connect virtual observations with scientific explanations. These activities correspond to international conceptions of digital competence as the confident, critical, safe, and responsible use of digital technologies for learning and participation (Law et al., 2018; Vuorikari et al., 2022). They also align with computer and information literacy perspectives that emphasize using digital technologies to investigate, create, communicate, and solve problems in meaningful contexts (Fraillon et al., 2020).

Technical problem-solving improved but remained the weakest dimension. This result is theoretically reasonable. Device operation and safety routines can develop through short-term guided exposure, whereas troubleshooting requires repeated practice, diagnostic reasoning, and greater learner autonomy. Falloon (2020) argued that digital competence involves technical, cognitive, social, and ethical dimensions, not merely device use. The present findings therefore suggest that short-term VR-supported lessons can strengthen several practical aspects of digital competence, but longer and more varied implementation may be needed to develop advanced problem-solving.

Pedagogical Implications and Limitations

The findings suggest that conceptual learning and digital competence should be integrated rather than treated as separate goals in technology-supported science education. In BIO-VR, students learned biology through digital interaction and developed digital competence through subject-specific tasks. This supports an integrated model in which VR functions as a representational and epistemic tool, not simply as a motivational add-on (Cooper et al., 2024; Makransky & Petersen, 2023).

Several implications follow. First, VR should be used selectively for topics where immersive visualization adds clear instructional value. Eukaryotic cell structure and function is appropriate because learners must understand microscopic structures, spatial organization, and structure-function relations. Second, VR should not be implemented as an isolated demonstration. Orientation, guided observation, teacher questioning, learning tasks, and consolidation are needed to transform immersive experience into conceptual understanding. Third, teachers remain central to effective implementation. They must manage devices, regulate cognitive load, maintain safety, direct attention, and connect virtual experience with scientific explanation.

This study also has limitations. It used a quasi-experimental design with two intact classes from one school, so causal inference remains limited despite baseline equivalence and common teacher instruction. Because BIO-VR was implemented as a structured instructional package, the study cannot isolate the effect of immersion from the effect of teacher scaffolding, task design, guided observation, and post-VR consolidation. Therefore, the observed achievement difference should be interpreted as the effect of a VR-supported instructional package rather than the independent effect of immersive technology alone. The intervention was short and assessed immediate outcomes only; delayed post-tests are needed to examine retention and transfer. The achievement test contained 10 multiple-choice items and may not fully capture deeper reasoning. Future research should include open-ended explanations, concept maps, interviews, or performance tasks.

The study did not systematically collect feasibility indicators such as cost, detailed technical-failure logs, cybersickness rates, time-on-device logs, or formal teacher interviews. Therefore, the implementation findings should be interpreted as practical classroom observations rather than a full feasibility evaluation. Digital competence was assessed only within the experimental group through self-assessment and teacher observation; therefore, the observed upward shifts should be interpreted as exploratory descriptive evidence rather than causal effects of VR. Because the observers were part of the implementation context and students completed self-ratings after a novel learning experience, expectancy effects may have inflated perceived digital-competence gains. Future studies should include a control-group digital-competence measure, blinded or independent raters, performance-based tasks, and interaction logs. In addition, the supplementary weighted index was based on numerical coding of ordinal rubric levels. Although this index provided a compact description of the distributions, it did not establish equal distances between M1, M2, and M3. It should therefore be interpreted only alongside the frequencies and percentages reported in **Table 4** and **Table 5**, rather than as an interval-scale estimate of change.

CONCLUSION

This study examined whether a structured VR-supported biology intervention using BIO-VR could enhance grade 10 students' conceptual understanding of eukaryotic cell structure and function; it also documented descriptive within-group shifts in digital competence. Three findings are central. First, the preliminary survey showed that immersive VR was still unfamiliar to most participating biology teachers and students. Second, students who learned with BIO-VR achieved significantly higher post-test scores than those in the conventional instruction group. Third, the experimental group showed descriptive upward shifts across four dimensions of digital competence. Taken together, these findings suggest that VR can contribute to science learning when it is embedded in a guided instructional sequence, aligned with curriculum objectives, and supported by teachers, rather than used as a novelty tool.

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Ethical statement: The study was conducted in accordance with the academic integrity and research ethics regulations of VNU University of Education, Hanoi. Participation was voluntary and anonymous. Informed consent was obtained from all participants before their involvement in the study, ensuring their understanding of the research objectives, processes, and their right to withdraw at any time without consequences. The study followed applicable institutional ethical guidelines for research involving human participants. Students were informed about the purpose and procedures of the study, the voluntary nature of their participation, and their right to withdraw at any time without academic penalty. As the participants were grade 10 students and under 18 years of age, informed consent was obtained from the students and their parents or legal guardians. All data were anonymized and used only for research purposes. If any classroom images are included in the manuscript, consent for their use was obtained, and no personally identifiable information is disclosed.

AI statement: ChatGPT by OpenAI (using the GPT-5.5) was used solely for language-related support, including paraphrasing, grammar checking, wording, and clarity during manuscript revision. The tool was not used to generate research data, conduct statistical analysis, create or manipulate figures, or determine the interpretation of findings. The author reviewed, verified, and finalized all content and the authors took full responsibility for the manuscript.

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