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Virtual Reality Immersive Simulations for a Forensic Molecular Biology Course—A Quantitative Comparative Study

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Abstract: Molecular biology is a complex, abstract, subject that can be challenging for higher education students to comprehend. The current manuscript describes the design, implementation, and evaluation of two immersive VR simulations of a DNA lab and a crime scene investigation (CSI) for a forensic molecular biology course in the context of the "TESLA" Erasmus+ project. It illustrates the instructional design and technical aspects of the VR simulations' development. The experimental study employed a comparative quantitative research design. The guiding research questions examined how instructional modalities (online vs. face-to-face) affect learners' perceptions of VR-based training in higher education and the key factors influencing learners' intention for their adoption. Forty-six (n = 46) undergraduate students completed a 17-item questionnaire, which served as the main data collection instrument. Results demonstrate that both online and face-to-face VR-based instruction can effectively convey core concepts, thus challenging the traditional notion that face-to-face interaction is inherently superior. Its implications underscore the potential of VR simulations to supplement or even substitute traditional teaching methods, particularly for complex science subjects.

Keywords: virtual reality; virtual worlds; online learning; distance education; digital education; molecular biology; science education; higher education; comparative study

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1. Introduction

There are several challenges related to teaching and learning molecular biology. For instance, molecular biology topics and learning materials can be complex, abstract, and difficult for students to comprehend and visualize [1]. Furthermore, molecular biology topics can be considered as prerequisite knowledge in various disciplines such as biology and ecology, agriculture, medicine, philosophy, and ethics [1]. Therefore, there is a need for customizing the molecular biology curriculum to link it with physical sciences and other STEM (Science, Technology, Engineering and Mathematics) fields [2]. Among the different proposed solutions is to use immersive technologies, like Virtual Reality (VR), to engage students actively by using problem-solving techniques in realistic environments and simulated tasks [3].

The 3D Virtual Learning Environment (3DVLE) can be an effective tool for education, especially in applied sciences. Immersive applications in Virtual Reality (VR) empower teachers to expand students' learning experience and address the limitations of traditional teaching methods [4]. VR is also an essential technology to use for teaching abstract topics and science concepts that are inherently difficult to teach in a classroom-based environment [5,6]. Furthermore, VR with its inherent affordances, can engage students in immersive learning experiences in which skills can be developed through experimentation and repetition, without restrictions, consequences, or limitations, as in the physical world [7].

In recent years, there have been significant advances in VR technology and there has been an increase in studies investigating the use of VR in learning and teaching [8–10]. Especially, multiuser, social-VR platforms, apart from domain-specific competences, enable also the development of transversal, horizontal skills across multiple knowledge domains such as communication, problem-solving and cooperation among all actors involved in education [11,12]. Its positive effects can be recorded both inside classrooms, in the physical world, as well as in online, distance learning, settings [12]. Therefore, researchers and scholars around the world considered this great potential of utilizing VR in different educational domains, especially after the COVID-19 pandemic due to the increased trend of using e-learning around the world [13].

Different studies investigated aspects related to usability and substantial issues related to using VR in relevant educational fields. Early efforts demonstrated the benefits of 3D virtual environments for biology education [14]. For instance, Reen et al. [15] noted that there is an immediate need to develop and implement immersive learning approaches in molecular biology to support sustainable development for university students and academic research careers. Mayne and Greena [16] documented a multidisciplinary experimental study in which a VR crime scene investigation (CSI) was implemented and evaluated by both undergraduate/postgraduate students and staff. They demonstrated that VR applications support learning of practical CSI skills. VR-based practical sessions have the potential to add value to molecular biology science courses, by offering a cost-effective and practical experience as well as the ability to work in isolation and in a variety of different scenarios. In a similar study, Manescu et al. [17] developed a 3D virtual learning platform for teaching molecular biology science. They concluded that the benefits presented by VR in education are interesting, especially in the context in which the COVID-19 pandemic forced large masses of students to be away from their usual attendance-based learning environment [17]. Khalilia et al. [18] implemented and examined interactive learning strategies and activities with a 3DVLE for teaching CSI. After undergraduate students tested it, the study concluded that VR is a helpful tool to practice modern learning strategies and skills in learning forensic science and CSI. Previous efforts by Ewais et al. [19] presented a case study for using VR in a human anatomy course. However, there is still a shortage of studies on the implementation of VR in biological science education and there is a need for more investigation.

In the context of Palestine, teaching and learning molecular biology face obstacles such as the lack of DNA analysis labs in most universities, the high costs associated with equipping molecular biology laboratories, and the real potential risks of students' presence in the laboratories. In addition, the COVID-19 pandemic forced institutions towards online education. The COVID-19 pandemic has led to significant changes in the delivery of education globally, with online engagement and accelerated uptake of novel teaching and assessment modalities into majority practice within institutions [20]. Furthermore, the special geopolitical circumstances in Palestine and restrictions imposed by the limited mobility between Palestinian cities. To meet all these challenges, realistic scenarios in VR were incorporated into the biology curriculum by creating scenarios that simulate DNA analysis in a virtual learning environment.

In general, the educational use of VR in Palestine is still limited. As a step toward enriching research related to utilizing VR in educational context in Palestine, a team of researchers from several Palestinian and European universities, including the authors of this study, and participants to the Erasmus+ Capacity Building in Higher Education project called "Virtual Reality as innovative and immersive learning tools for HEIs in Palestine—TESLA", have developed an instructional framework for using VR to teach STEM courses, including biology, physics, forensic, and molecular biology sciences. This framework describes course learning activities and evaluation results compared with conventional in-class teaching methods [21].

This paper's objective is twofold. First, it reports on the collaborative efforts between pedagogical experts, VR scientists and developers to design, develop, and implement VR simulations for forensic molecular biology in partner universities. Second, it presents the obtained quantitative evaluation results related to the developed VR forensic module in terms of instructional quality and learners' attitudes toward the use of VR forensic simulations, including the strong and the weak aspects identified in the developed VR scenarios.

The structure of the paper is as follows. Section 2 presents the development approach that was adopted by the project development team. Accordingly, the developed prototype is described. More details about the interaction and activities that can be performed by the students are explained. After that, the setup of the validation step, data consistency, and sampling adequacy are presented. Section 3 shows the results obtained from participants and the adopted data analysis approach to validate the effectiveness of the developed VR forensic module. Section 4 discusses the analyzed data and shows the implications of the study. Finally, Section 5 concludes the conducted research work and offers recommendations for future research.

2. Materials and Methods

2.1. VR Simulation Design and Development

To develop a forensic module in VR, a custom instructional design model towards deep meaningful learning was developed in the context of the TESLA project [22]. The proposed model was built on the grounds of Assure, TPACK, and Kirkpatrick's models [23]. The 6-step Assure model served as an umbrella for the whole instructional design approach and development processes. The second adopted model, TPACK, was used for designing the pedagogical scenario and enhancing the interaction design of the learning materials such as 3D objects with their animation, videos, slides, etc. Finally, Kirkpatrick's model was incorporated as an evaluation framework in the 6th step of the Assure model. Specifically, it was used for analyzing and evaluating the results of the training workshops for Palestinian instructors.

The project's instructional design was specified and developed during different preparation and training workshops which included the following: (1) determining specific topics from the forensic molecular biology course, (2) defining pedagogical objectives and intended learning outcomes, and (3) determining the assessment methods. As such, a generic simulation scenario was defined to provide students with contemporary forensic methods in molecular biology. The scenario enabled students to explore virtual crime scenes, examine them professionally and collect biological forensic evidence. Also, students were able to critically analyze the gathered evidence in a DNA lab, draw conclusions, and synthesize a report to explain key findings of the investigated crime.

Based on the simulation design document that contained the scenario, the technical team of the project specified the technical development requirements. These requirements include different sections such as hardware specifications, software aspects and software development methodology. Hardware aspects are related to specifications for 3D application servers, web server, database servers, and networking hardware. The software aspects are related to outputs and tools for 3D content designing apps, generation and scripting languages, MySQL databases. The adopted methodology was Agile so that different stakeholders could participate together, give feedback, co-design, and co-develop the VR simulations in iterative phases [24].

The first step in the development is the analysis phase which presents functional and non-functional requirements, user and system requirements, data flow diagrams, use case diagrams and sequence diagrams. Next, in the design phase, sketches for scenes and 3D models, interactions and navigation paths inside the 3DVLE, sequences of student activities were specified. Learning materials such as documents, video lectures, illustrations, presentations, web resources, related links, open-source content on the Internet, research papers and discussion topics as well as assessment quizzes were produced for integration in the virtual world. Software tools such as Microsoft PowerPoint, Adobe Captivate 9 and Articulate Storyline 360, were used to develop these learning materials. Additional tools for designing the 2D and 3D contents were Blender 2.90, Sketchup 20, Adobe Photoshop 2020, Illustrator 24 and InDesign 15. Furthermore, the development team used C# in OpenSim (DivaDistro 9.0) with MySQL database for scripting interactions between objects and avatars and to set up the learning activities to be performed inside the 3DVLE.

2.2. Forensic Molecular Biology VR Prototype

The developed 3D virtual learning environment (3DVLE) consists of two areas: (1) a crime scene area and (2) a molecular biology lab area. The crime scene area has a courtyard with yellow striped tape around the scene from three sides as depicted in Figure 1. Also, the crime scene area has 3D components including a dead body, a police officer maintaining the crime scene and witnesses as non-player characters (NPCs). It contains also biological forensic evidence containing DNA molecules, such as bloodstains, cigarette butts, hair, and a bloody knife.

Figure 1. Crime scene area in the virtual immersive environment.

On the other hand, the molecular biology (DNA) lab has 3 rooms, each equipped with tools and equipment set on tables (Figure 2). These are (1) the biological evidence handling and DNA preparation extraction room, (2) the DNA amplification room, and (3) the data analysis and interpretation room. In each space, students are supposed to execute a list of predefined activities. Inside the lab, there is a laboratory manager wearing a lab coat. In addition, there are laboratory technicians in each lab wearing lab coats, gloves, and other safety equipment. The manager and technicians help students in conducting the experiments inside each room.

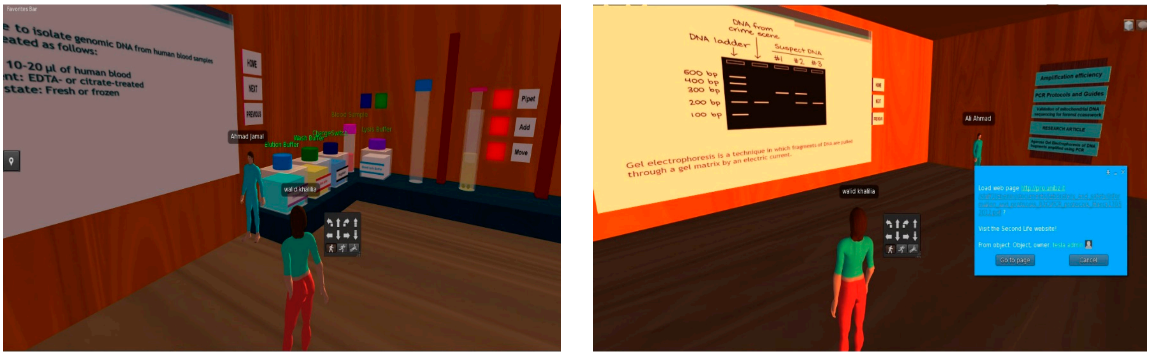

Figure 2. Virtual molecular biology lab in the VR environment.

2.3. Simulation Scenario and Activities

Upon completing the simulated scenario, the intended learning outcomes for the students were as follows:

- Identify forensic evidence (blood samples) in a crime scene.
- Propose and apply appropriate evidence collection methods.
- Handle effectively genomic DNA from the collected human bloodstains.
- Perform diagnostic DNA profiling and analyzing tests using laboratory equipment.
- Interpret diagnostic DNA analysis test results accurately.
- Moreover, students will be able to develop the following transversal skills:
- Ability to analyze and solve problems.
- Ability to communicate and cooperate in professional settings.

Students visited the crime scene area synchronously at the beginning of a virtual field trip. The NPC assistant (course's teacher) welcomes and encourages them to access or revisit essential information and guidelines to avoid damaging the evidence in the scene during their visit. After that, the students role-play by assuming the role of detective. Different questions are given to the students by the assistant NPC during the tour. Based on the answers to this diagnostic test, the students will be directed to either watch instructional videos for more explanations or will be admitted exploring and collecting evidence.

During the collection of evidence, different textual guidelines are offered to students such as cleaning the tools used for collecting evidence, avoiding contaminating swabs, wearing gloves, a mask, and eye protection while collecting biological evidence, and changing gloves frequently.

After collecting the evidence, the NPC assistant encourages the students to visit the DNA lab area. First, in the DNA extraction room and with the support from the laboratory manager and technicians, the students should isolate genomic DNA from the collected human blood samples, prepare the lysate procedure to bind the DNA to the magnetic beads, and so on. After that, the laboratory manager guides them to the DNA amplification room and asks them different questions to support the students in keeping different copies of DNA samples. More learning materials will be offered to the students who provide wrong answers to help them comprehend their mistakes and their knowledge gaps. Finally, by having enough copies of DNA to analyze, the students are guided to the data analyses room where they should perform electrophoresis properly. In addition, different forms of multimedia materials (including, text-based questions, slides, and videos) are displayed to help the students in completing their tasks.

Finally, based on students' progress, individual reports are generated which are subsequently available to instructors. In each login session, the report includes the student's ID, avatar name, login and logout time, total scores, number of correct and wrong answers in each quiz, and the completed learning materials (slides, audio, video, report) that have been viewed during the session.

2.4. Evaluation of the VR Forensic Module

The guiding research questions of this study were the following:

RQ1: How did instructional modalities (online vs. face-to-face) affect learners' perceptions of Virtual Reality-based training in forensic molecular biology courses?

RQ2: What are the key factors influencing learners' intention to adopt Virtual Reality-based training solutions in forensic molecular biology courses?

The evaluation was conducted inside both universities' labs, equipped with computers and internet connection. The experiment took place during the laboratory session (1 h and 30 min) and included different steps as depicted in Figure 3. Participants in these the two groups (face-to-face and online) were selected and distributed randomly.

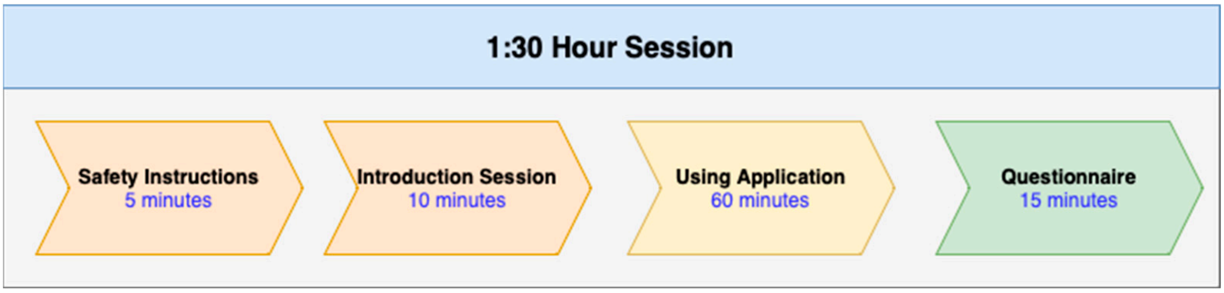

Figure 3. Evaluation sequence and procedure.

Safety instructions related to how to use hardware and tools and how to deal with the 3D forensic module were provided by the teacher to the students within 5 and 10 min, respectively. Afterwards (approximately for 60 min), the teacher asked students to start exploring the developed 3D forensic module which prompted them to collect evidence from the crime scene and analyze it in the DNA lab. Also, the students were asked to complete predefined tasks, and they were exposed to questions that urged them to brainstorm, think critically, and solve problems. Following completion of the training session, a link to the evaluation questionnaire was distributed. While filling in the questionnaire, the teacher left the computer room to avoid bias in the evaluation process. Also, it was explicitly mentioned that there are no correct or wrong answers so that students felt more relaxed and confident in answering the questions truthfully.

The online questionnaire was prepared by the quality assurance and quality control teams of the TESLA project. The questionnaire was divided into three parts and is provided in Appendix A. The first part presents questions that are related to demographic data, whereas the second part examines the quality of the developed 3D learning scenario. The third part represents attitudes toward the use of VR/3D in the learning forensic molecular biology courses. The questionnaire was completed by 46 students in 2 Palestinian universities, Al-Istiqlal and AAUP (Figure 4). Both groups performed the evaluation following the exact same steps in both modes. For instance, the face-to-face group executed the experiment while the teacher was present. During the online session, students performed the experiment while the teacher was available remotely as an avatar inside the virtual world. The teacher's role in both sessions consisted of the following tasks: providing safety instructions, introducing the 3D forensic module, demonstrating how to use hardware and software tools, and offering technical or instructional support upon request. In both conditions, the teacher supports students so that all of them can navigate, communicate and cooperate inside the crime scene. This simulates the traditional forensic course.

Figure 4. VR module evaluation process at AAUP during a face-to-face session.

3. Results

3.1. Data Analysis

The primary data were analyzed using the *R* programming language (v. 4.3.1). The dataset was inspected for missing or incomplete values [25] and none were found. Potential outliers were examined using both graphical (boxplots) and analytical (z-scores) methods with no significant issues requiring correction or exclusion [25]. The entire dataset is provided as Supplementary Material.

To determine the underlying constructs within the instrument, Exploratory Factor Analysis (EFA) (Table 1) was conducted [26]. Both the Kaiser criterion (eigenvalues > 1) and the scree plot supported a two-factor solution. The first factor, labeled "Perceived Quality of the Virtual Environment", is characterized by high loadings on questions pertaining to the overall impression of the virtual classroom such as the quality of the 3D objects, animations, and texts. In a sense, this construct reflects users' perceptions of the technical aspects and the aesthetic appeal of the 3D Virtual Learning Environment (3DVLE). The second factor, termed "Adoption Perception", is primarily associated with items related to the learning experience itself. These include the role of the teacher and the degree to which the 3DVLE was perceived as interesting and useful for learning. It, therefore, captures users' perceptions towards its wider adoption in education.

Table 1. Exploratory factor analysis.

Item	Factor 1 *	Factor 2
Q1. How would you rate the content of the scenario in terms of relevance and accuracy?	−0.64	−0.07
Q2. How would you rate the visual quality of the 3D objects in the scenario?	−0.55	−0.33
Q3. How would you rate the smoothness and realism of the animations in the scenario?	−0.47	−0.43
Q4. How would you rate the overall quality of the learning materials in the scenario?	−0.59	−0.16
Q5. How would you rate the clarity and readability of the texts in the scenario?	−0.33	−0.6
Q6. To what extent did your activities in the 3D virtual environment help you understand the presented topics?	−0.67	0.29
Q7. Do you feel that this tool positively impacted your learning by helping you develop new transversal skills such as collaboration and problem-solving?	−0.58	−0.04
Q8. What is your overall impression of learning in a 3D virtual environment?	−0.74	−0.01
Q9. How would you rate your overall immersive learning experience in the virtual environment?	−0.59	0.43
Q10. To what extent do you believe teacher's presence is necessary when undertaking learning activities in a virtual environment?	−0.23	−0.11
Q11. Would you consider using a similar educational 3D Virtual Environment for future training?	−0.53	0.33
Q12. How likely are you to recommend this learning approach to other students?	−0.57	0.1

* Note: Loadings above 0.4 are considered significant.

Following the EFA, a Confirmatory Factor Analysis (CFA) was conducted to verify the factors' structure [26]. The results supported the two-factor solution with relatively high loadings for each construct (Table 2). The emergence of these factors indicates that users' perceptions of the 3DVLE are multi-faceted, encompassing both the quality of the environment itself and the effectiveness of the learning experience within the environment. This is in line with the relevant literature [27,28] which suggests that a technologically advanced virtual environment alone does not ensure a successful learning experience; the pedagogical framework and its execution are equally critical.

Table 2. Confirmatory factor analysis.

Item	Factor 1 *	Factor 2
Q1. How would you rate the content of the scenario in terms of relevance and accuracy?	0.85	-
Q2. How would you rate the visual quality of the 3D objects in the scenario?	0.78	-
Q3. How would you rate the smoothness and realism of the animations in the scenario?	0.75	-
Q4. How would you rate the overall quality of the learning materials in the scenario?	0.8	-
Q5. How would you rate the clarity and readability of the texts in the scenario?	0.68	-
Q6. To what extent did your activities in the 3D virtual environment help you understand the presented topics?	0.85	-
Q7. Do you feel that this tool positively impact-ed your learning by helping you develop new transversal skills such as collaboration and problem-solving?	0.8	-
Q8. What is your overall impression of learning in a 3D virtual environment?	0.9	-
Q9. How would you rate your overall immersive learning experience in the virtual environment?	0.82	-
Q10. To what extent do you believe teacher's presence is necessary when undertaking learning activities in a virtual environment?	-	0.72
Q11. Would you consider using a similar educational 3D Virtual Environment for future training?	-	0.8
Q12. How likely are you to recommend this learning approach to other students?	-	0.85

* Note: Loadings above 0.4 are considered significant.

Internal consistency reliability for each construct was assessed using Cronbach's alpha (α). The reliability coefficient for Perceived Quality of the Virtual Environment ($\alpha = 0.77$) indicates a good internal consistency, while the coefficient for Adoption Perception ($\alpha = 0.68$), although slightly below the conventional threshold ($\alpha > 0.70$), still suggests acceptable internal consistency [29]. The Shapiro–Wilk test for normality revealed significant deviations from normality for several variables, indicating the appropriateness of non-parametric tests for subsequent analyses [30]. Descriptive statistics, including means, standard deviations, and frequencies, were computed to summarize the data and assess key assumptions. Comparisons between groups were conducted using the Mann–Whitney U test for continuous variables and the chi-square test for categorical variables [31]. Spearman's rank-order correlation coefficient (r) was calculated to investigate relationships between the constructs within the sample [31]. Where applicable, effect sizes (R^2) were computed to gauge the practical significance of the observed correlations.

3.2. Findings

3.2.1. Demographics

The sample (Tables 3 and 4) comprised predominantly male participants, with the online group having a slightly higher representation (69.57%) compared to the face-to-face group (60.87%). The gender distribution aligns with typical patterns observed in technology-related studies where male participants often outnumber females [32]. The age distribution was similar between the groups, with most participants aged between 18 and 23 years. The majority of participants in both groups fell within the 18–22 age range, with a slightly higher mean age observed in the face-to-face group (M = 20.96, SD = 1.97) compared to the online group (M = 20.65, SD = 2.21).

Table 3. Descriptive statistics for participant demographics and prior experience.

Group/Category	Face-to-Face		Online	
	n	Percent	*n*	Percent
Gender				
Males	14	60.87	16	69.57
Females	9	39.13	7	30.43
Age group				
18–20 years old	8	34.78	12	52.17
21–23 years old	12	52.17	8	34.78
24 years old and above	3	13.04	3	13.04
Experience with computer-based games				
No experience	1	4.35	0	0
Beginner	2	8.7	0	0
Intermediate	9	39.13	3	13.04
Advanced	8	34.78	12	52.17
Expert	3	13.04	8	34.78
Experience with Virtual Reality				
No experience	2	8.7	0	0
Beginner	5	21.74	12	52.17
Intermediate	10	43.48	4	17.39
Advanced	5	21.74	6	26.09
Expert	1	4.35	1	4.35

Table 4. Descriptive statistics for participant demographics and prior experience.

Group/Category	Face-to-Face					Online				
	M	Med	Std Dev	Min	Max	M	Med	Std Dev	Min	Max
Age group	20.96	21	1.97	18	24	20.65	20	2.21	18	24
Experience with computer-based games	3.43	3	0.99	1	5	4.22	4	0.67	3	5
Experience with virtual 3D virtual environments	2.91	3	1	1	5	2.83	2	0.98	2	5
Perceived Quality of the Virtual Environment	3.35	3.45	0.85	2	5	2.95	3	0.82	1	4
Adoption Perception	2.5	2.67	0.67	1	3	2.43	3	0.66	1	3

A notable difference, however, emerged in the participants' experience with computer-based games with the participants of the online group considering themselves to be more experienced (advanced = 52.17%, experts = 34.78%) as opposed to their fellow students in the face-to-face group (intermediate = 39.13%, experts = 13.04%). Experience with Virtual Reality (VR) applications also differed between the groups. The face-to-face group had a more balanced distribution of experience levels (intermediate = 43.48%; advanced = 21.74%). On the contrary, the online group had a higher percentage of beginners (52.17%), indicating less overall familiarity. The disparities in experience suggest that each group brings different strengths to the table. The online group's proficiency with computer-based games might make them more agile and effective in the 3DVLE which, in turn, could influence their engagement and performance in the instructional simulations. Conversely, the face-to-face group's balanced experience with VR applications suggests that they may have a better foundational understanding of VR, making them potentially more adept at leveraging the educational aspects of the simulations. Therefore, when designing and implementing educational VR tools, it would be beneficial to consider these differing strengths, i.e., tailoring the VR simulations to accommodate both the gaming skills that participants may have and their foundational experience with VR. For instance, initial training sessions could be differentiated: one focusing on familiarizing students with the specific VR tools and another enhancing the VR interaction skills [33].

Interestingly, as illustrated in Table 5, despite the online group reporting more experience with computer-based games and less experience with VR (M = 2.95, SD = 0.82), they rated the virtual environment less favorably than the face-to-face group (M = 3.35, SD = 0.85). This discrepancy could be attributed to their higher expectations for VR quality stemming from their video game experience or their relative discomfort with the unfamiliar VR technology. However, both groups reported similar perceptions of the learning effectiveness of the VR simulations (Face-to-Face: M = 2.5, SD = 0.67; Online: M = 2.43, SD = 0.66) suggesting that despite the differences in user experience, the educational impact of the VR simulations was comparable.

Table 5. Mean ratings for VR experience and adoption perception by instructional modality.

	Face-to-Face	**Online**
1.1 How would you rate of the content of the scenario?	2.95	3.65
1.2 How would you rate the quality of the 3D objects?	3.17	3.43
1.3 How would you rate the quality of the animations?	3.21	3.21
1.4 How would you rate the quality of the learning material (in the scenario) in general?	3.30	3.6
1.5 How would you rate the quality of the texts (in the scenario)?	3.39	3.52
1.6 Did your activities in the virtual world help you comprehend the presented topics?	2.73	3.39
1.7 Do you feel that this tool positively impacted your learning by helping you develop new transversal skills such as collaboration and problem-solving?	2.39	2.56
1.8 What is your overall impression of having a class in TESLA virtual world?	2.82	3.69
1.9 How interesting did you find your time in the virtual world?	2.95	3.13
2.1 Is there a need of a real teacher to be present in the classroom when learning in the virtual world?	2.43	2.47
2.2 Would you use a similar educational Virtual World in the future?	2.34	2.43
2.3 Would you recommend this Virtual World to other students?	2.52	2.6

3.2.2. Impact of Instructional Modalities on Learners' Perceptions

The chi-square (Table 6) test did not reveal any statistically significant associations between participants' background characteristics and instructional format. However, the near-significant result for computer game experience ($p = 0.05$) warrants further investigation, as it hints at a possible trend [34] that could be more apparent with a larger sample.

Table 6. Analysis of background characteristics by instructional format.

Variable	**χ^2 (Statistic)**	**DF**	**p**
Gender	0.096	1	0.75
Age Group	4.533	2	0.6
Computer Game Experience	9.073	4	0.05
3D Virtual Environment Experience	7.545	4	0.11

Accordingly, Mann–Whitney *U* tests (Table 7) were conducted to compare participants' perceptions of the perceived quality and learning effectiveness of the intervention across the different instructional formats.

The analysis revealed a significant difference in how learners perceived the relevance of the educational content (U = 158.5, z = −2.48, $p = 0.01$) with participants in the face-to-face format rating the content as more 'relevant' and 'accurate' than those in the online format, thus highlighting the influence of instructional delivery on learners' perceptions. This observation aligns with the existing literature suggesting that face-to-face interactions can foster greater engagement and knowledge retention, likely due to increased opportunities for real-time feedback and clarification [35].

Table 7. Comparison of perceived quality and learning effectiveness.

Variable	U	Z	p
Q1. Content Relevance	158.5	−2.48	0.01 *
Q2. Visual Quality	211.5	−1.26	0.2
Q3. Animation Quality	262	−0.05	0.96
Q4. Material Quality	198	−1.64	0.1
Q5. Text Quality	234.5	−0.74	0.46
Q6. Topic Comprehension	189.5	−1.69	0.09
Q7. Transversal Skill Development	225	−0.98	0.32
Q8. Overall Impression	165	−2.33	0.02*
Q9. Interest Level	243.5	−0.5	0.62
Q10. Teacher Necessity	244	−0.5	0.61
Q11. Future Use	252.5	−0.28	0.77
Q12. Recommendation	236.5	−0.71	0.47

* $p < 0.05$.

In contrast, we found no significant differences between the two formats in learners' perceptions of learning material quality (U = 198, z = −1.64, p = 0.1), including aspects such as visuals (U = 211.5, z = −1.26, p = 0.2), animations (U = 262, z = −0.05, p = 0.96), and text clarity (U = 234.5, z = −0.74, p = 0.46). On these grounds, it can be suggested that developers may have flexibility in how they prioritize these aspects across delivery methods. Similarly, we found no significant differences between formats in learners' perceptions of the 3DVLE's effectiveness in aiding topic comprehension (U = 189.5, z = −1.69, p = 0.09), skill development (U = 225, z = −0.98, p = 0.32), or stimulating learners' interest in the subject matter (U = 243.5, z = −0.50, p = 0.62). We, therefore, hypothesize that the 3DVLE's design and features, rather than the delivery mode, may be the primary factors influencing learners' engagement and perceptions of its educational value.

Interestingly, participants in the face-to-face format reported a significantly more positive overall impression of their learning experience within the 3D virtual environment (U = 165, z = −2.33, p = 0.02) implying that, while the virtual environment itself is effective, the social context of face-to-face learning may contribute to a more positive and enriching overall experience. Lastly, we observed no significant differences between the groups in their perceptions regarding the necessity of teacher presence (U = 244, z = −0.50, p = 0.61), willingness to use a similar environment in the future (U = 252.5, z = −0.28, p = 0.77), or likelihood of recommending the approach to others (U = 236.5, z = −0.71, p = 0.47). This consistency across formats points to a general acceptance and potential for broader adoption of 3DVLEs in education by underscoring their versatility and potential to complement various instructional approaches.

3.2.3. Factors Influencing Learners' Attitude toward VR-Based Simulations

The correlation analysis (Table 8) indicated that several factors significantly influence learners' intention to adopt VR-based training simulations in forensic molecular biology courses. Notably, demographic factors did not show significant correlations with the key outcomes, implying that perceptions of VR learning effectiveness are relatively independent of these variables.

However, content relevance emerged as a critical factor, showing strong correlations with visual quality (r = 0.31, p < 0.05, R^2 = 0.116), comprehension (r = 0.46, p < 0.01, R^2 = 0.199), overall impression of learning in a 3D virtual environment (r = 0.56, p < 0.01, R^2 = 0.292), overall immersive learning experience (r = 0.50, p < 0.01, R^2 = 0.244), and future use (r = 0.30, p < 0.05, R^2 = 0.079). This underscores the importance of relevant content in shaping learners' overall perceptions and intentions regarding VR training.

Table 8. Associations between participant characteristics and perceptions toward the learning experience.

	Age	Exp. Games	Exp. 3D Env.	Content Rel.	Visual Qual.	Anim. Real.	Learn. Mat. Qual.	Text Clar.	Comp.	Skill Dev.	Imp.	Experience	Teacher Pres.	Future Use	Recommend
Age	1														
Experience with Games	−0.21	1													
Experience with 3D Environments	−0.18	0.16													
Content Realism	0.02	0.53 **	−0.11	1											
Visual Quality	−0.08	0.31 *	0.07	0.31 *	1										
Animation Realism	−0.05	0.12	−0.07	0.36 *	0.30 *	1									
Learning Material Quality	0.06	0.26	0.22	0.33 *	0.47 **	0.39 **	1								
Text Clarity	0	0.15	−0.2	0.33 *	0.33 *	0.44 **	0.26	1							
Comprehension	−0.13	0.33 *	−0.09	0.46 **	0.30 *	0.21	0.30 *	0.13	1						
Transversal Skill Dev.	0.13	0.25	−0.15	0.32 *	0.27	0.37 *	0.2	0.23	0.41 **	1					
Impression	0.05	0.30 *	−0.17	0.56 **	0.53 **	0.31 *	0.44 **	0.2	0.45 **	0.49 **	1				
Immersive Learning Experience	−0.04	0.27	−0.13	0.50 **	0.18	0.06	0.29 *	−0.03	0.56 **	0.22	0.51 **	1			
Teacher Pres.	0.31 *	0	−0.05	0.17	0.38 **	−0.02	0.39 **	0.16	0.07	0.27	0.28	0.11	1		
Future Use	0.21	0.19	−0.04	0.30 *	0.18	0.14	0.27	−0.03	0.44 **	0.33 *	0.36 *	0.41 **	0.30 *	1	
Recommend	−0.05	0.22	−0.09	0.17	0.27	0.17	0.42 **	0.17	0.47 **	0.45 **	0.39 **	0.26	0.15	0.43 **	1

* $p < 0.05$, ** $p < 0.01$.

Similarly, visual quality was positively correlated with the smoothness and realism of animations ($r = 0.30$, $p < 0.05$, $R^2 = 0.102$), overall quality of learning materials ($r = 0.47$, $p < 0.01$, $R^2 = 0.221$), and comprehension ($r = 0.30$, $p < 0.05$, $R^2 = 0.087$), highlighting the role of high visual standards in enhancing the perceived realism and quality of learning materials. Animation realism also demonstrated significant correlations with the overall quality of learning materials ($r = 0.32$, $p < 0.05$, $R^2 = 0.164$), overall impression of learning in a 3D virtual environment ($r = 0.45$, $p < 0.01$, $\mathrm{R}^2 = 0.097$), overall learning experience ($r = 0.56$, $p < 0.01$, $R^2 = 0.004$), and future use ($r = 0.44$, $p < 0.01$, $R^2 = 0.023$), suggesting that realistic animations are pivotal in fostering positive learner impressions and experiences, which in turn promote future use of VR training simulations.

Furthermore, the overall quality of learning materials was significantly correlated with the clarity and readability of texts ($r = 0.33$, $p < 0.05$, $R^2 = 0.054$), overall impression ($r = 0.49$, $p < 0.01$, $R^2 = 0.188$), and future use ($r = 0.36$, $p < 0.05$, $R^2 = 0.078$), indicating that high-quality learning materials enhance learners' perceptions and their intention to reuse VR simulations. Text clarity also showed significant correlations with overall impression ($r = 0.20$, $p < 0.05$, $R^2 = 0.043$), development of new transversal skills ($r = 0.33$, $p < 0.05$, $R^2 = 0.009$), and future use ($r = 0.33$, $p < 0.05$, $R^2 = 0.003$), highlighting the importance of clear and concise text in improving learner understanding and positively impacting their overall impression and intention to continue using VR applications.

Additionally, the development of new transversal skills was strongly related to overall impression ($r = 0.49$, $p < 0.01$, $R^2 = 0.193$), overall experience ($r = 0.51$, $p < 0.01$, $R^2 = 0.317$), and future use ($r = 0.41$, $p < 0.01$, $R^2 = 0.204$), emphasizing that horizontal skill development through VR interventions such as problem-solving and cooperation significantly influences the likelihood of continued use. Both overall impression and immersive learning experience were critical, with overall impression strongly correlated with future use ($r = 0.36$, $p < 0.05$, $R^2 = 0.128$) and recommendation to other students ($r = 0.43$, $p < 0.01$, $R^2 = 0.160$), while the overall immersive learning experience was correlated with future use ($r = 0.41$, $p < 0.01$, $R^2 = 0.175$) and recommendation to other students ($r = 0.47$, $p < 0.01$, $R^2 = 0.081$). This indicates that positive learner impressions and experiences are essential in promoting future engagement and recommendations.

Finally, although teacher presence showed a positive correlation with future use ($r = 0.30$, $p = 0.05$), it was not statistically significant, suggesting a potential trend where effective teacher presence may contribute to the intention to use VR training, though further research is needed.

4. Discussion and Conclusions

This research work has proposed a development approach for an immersive simulation module and investigated the use of the 3DVLE in forensic molecular biology course. The developed scenario for VR/3D forensic module enabled students to move as avatars, explore and navigate inside a 3D crime scene with guidance from their teachers inside the simulated environment, collect evidence, perform analysis inside the virtual molecular biology lab, view learning resources, and answer quizzes as assessment tool inside the virtual world.

The findings confirm the transformative potential of 3DVLEs in forensic molecular biology education by echoing recent research that highlights the efficacy of VR in various scientific disciplines [36]. Our findings demonstrate that both online and face-to-face VR-based instruction can effectively convey core concepts, thus challenging the traditional notion that face-to-face interaction is inherently superior; an outcome which is also in agreement with [37]. On these grounds it can be suggested that, with careful design and consideration of pedagogical principles, VR-based training can provide comparable educational benefits and may even surpass traditional methods in certain scientific contexts and subjects that are difficult or dangerous to replicate in physical classrooms.

The study also emphasizes the critical role of high-fidelity virtual environments in shaping learners' perceptions towards VR-based learning. Specifically, content relevance, visual quality, and animation realism were identified as the most influential factors in learners' overall experience and intention to reuse VR for training purposes. The aforementioned outcomes align with existing research that underscores the importance of multimedia elements in immersive experiences as a means of enhancing sense of presence [38]. Collectively, such attributes contribute to VR's ability to foster motivation and engagement which, in turn, lead to improved performance on complex tasks and greater enjoyment of the learning process [39–41].

Furthermore, the experiential nature of VR facilitated the practical application of learned concepts and provided learners with opportunities to experiment and develop new horizontal skills. This aligns with the broader pedagogical shift towards active learning and experiential education [42], which prioritizes the provision of authentic contexts and encourages the development of transversal skills through simulated experiences that closely mimic the real-world conditions requiring collaboration to address complex problems [12,43].

Finally, although our study did not demonstrate a statistically significant effect of teacher presence on learners' perceptions of VR, an emerging trend suggests that instructor–learner interaction might influence learners' willingness to utilize VR in the future [44]. This observation requires further investigation to identify the optimal balance between independent exploration and guided instruction within VR environments [45,46].

The implications of the study extend beyond forensic molecular biology to the broader educational landscape. Firstly, the success of VR across both online and face-to-face modes underscores its potential to supplement or even substitute traditional teaching methods, particularly for complex subjects. This opens new avenues for learners who may encounter obstacles accessing or feel uncomfortable in physical labs or classrooms. Secondly, the study emphasizes the importance of incorporating high-quality visuals and animations in VR learning. Prioritizing these elements not only enhances immediate engagement but also fosters sustained interest in technology and its educational advantages. Thirdly, VR's potential to facilitate skill development, by allowing learners to actively apply scientific concepts in the virtual environment, is crucial for both conceptual understanding and retention of complex information [47]. Lastly, while the expected impact of instructor presence was not confirmed, the observed trend suggests a promising avenue for future innovation. Integrating features like Intelligent Pedagogical Agents (IPAs) that offer personalized guidance could further elevate the VR educational experience [48].

5. Limitations and Future Work Recommendations

The study provides several insights but also comes with certain limitations. The sample size was relatively small, from two higher education institutions, and focused on a specific field, thus limiting the generalizability of the findings. Future research should involve larger, more diverse participant groups across different scientific disciplines to validate and extend these results. Another suggested research direction would be comparing the effects of an online immersive CSI module with a respective attendance-based lesson or unit. Additionally, the study did not assess the short- and long-term effects of VR training on knowledge retention and skill transfer. Longitudinal studies are needed to evaluate how well learning outcomes are maintained over time and to determine the ideal frequency and duration of VR training for lasting educational benefits. Further research could also explore (a) the effectiveness of VR in other scientific fields, such as chemistry, physics, and environmental science, as well as (b) the perceptions of teachers who use 3VLEs systematically for teaching and learning. To this end, personalizing the instructional approach to match individual learners' needs and preferences should also be a focus for future investigations. Finally, future research could examine the sustainability of 3DVLEs in terms of their reusability and adaptability with easy-to-use authoring tools for updating the simulation with different scenarios and learning materials.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14177513/s1, Table S1: Full dataset.

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Appendix A. Data Collection Instrument

Category	Item/Description	Measurement	Responses/Coding
Instructional Group	1. In which format was your training course delivered?	Dichotomous	1: Face-to-Face, 2: Online
Background information	Please indicate your gender.	Nominal	1: Male, 2: Female, 3: Prefer not to answer
Background information	Please indicate your age group.	Ordinal	1: 18–20 years old, 2: 21–23 years old, 3: 24 years old and above
Background information	How would you rate your experience with computer-based games?	Likert scale	1: No experience, 2: Beginner, 3: Intermediate, 4: Advanced, 5: Expert
Background information	How would you rate your experience with 3D virtual environments?	Likert scale	1: No experience, 2: Beginner, 3: Intermediate, 4: Advanced, 5: Expert
Perceived Quality of the Virtual Environment	Q1. How would you rate the content of the scenario in terms of relevance and accuracy?	Likert scale	1: Very Poor, 2: Poor, 3: Fair, 4: Good, 5: Excellent
Perceived Quality of the Virtual Environment	Q2. How would you rate the visual quality of the 3D objects in the scenario?	Likert scale	1: Very Poor, 2: Poor, 3: Fair, 4: Good, 5: Excellent
Perceived Quality of the Virtual Environment	Q3. How would you rate the smoothness and realism of the animations in the scenario?	Likert scale	1: Very Poor, 2: Poor, 3: Fair, 4: Good, 5: Excellent
Perceived Quality of the Virtual Environment	Q4. How would you rate the overall quality of the learning materials in the scenario?	Likert scale	1: Very Poor, 2: Poor, 3: Fair, 4: Good, 5: Excellent
Perceived Quality of the Virtual Environment	Q5. How would you rate the clarity and readability of the texts in the scenario?	Likert scale	1: Very Poor, 2: Poor, 3: Fair, 4: Good, 5: Excellent
Perceived Quality of the Virtual Environment	Q6. To what extent did your activities in the 3D virtual environment help you understand the presented topics?	Likert scale	1: Not at all, 2: Very little, 3: Somewhat, 4: To a great extent

Category	Item/Description	Measurement	Responses/Coding
Perceived Quality of the Virtual Environment	Q7. Do you feel that this tool positively impacted your learning by helping you develop new transversal skills such as collaboration and problem-solving?	Likert scale	1: No, not really, 2: Neutral, 3: Yes, definitely
Perceived Quality of the Virtual Environment	Q8. What is your overall impression of learning in a 3D virtual environment?	Likert scale	1: Very negative, 2: Negative, 3: Neutral, 4: Positive, 5: Very positive
Perceived Quality of the Virtual Environment	Q9. How would you rate your overall immersive learning experience in the virtual environment?	Likert scale	1: Very uninteresting, 2: Uninteresting, 3: Neutral, 4: Interesting, 5: Very interesting
Adoption Perception	Q10. To what extent do you believe teacher's presence is necessary when undertaking learning activities in a virtual environment?	Likert scale	1: Not necessary at all, 2: Somewhat necessary, 3: Absolutely necessary
Adoption Perception	Q11. Would you consider using a similar educational 3D Virtual Environment for future training?	Likert scale	1: No, not really, 2: Maybe, 3: Yes, definitely
Adoption Perception	Q12. How likely are you to recommend this learning approach to other students?	Likert scale	1: Not likely at all, 2: Somewhat likely, 3: Very likely

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