Jurnal Pendidikan MIPA
e-ISSN: 2685-5488 | p-ISSN: 1411-2531
URL: https://jpmipa.fkip.unila.ac.id/index.php/jpmipa
Jounal's DOI: http://doi.org/10.23960/jpmipa

Vol. 27, No. 1, 2026
Article ID: 1242
Pages: 587-609

Enhancing High School Spectroscopy Education: The Efficacy of a Virtual Reality Laboratory for Hydrogen Emission Experiments

Melani Putria Dewi Sari, Hartono Bancong*, & Rahmawati
Department of Physics Education, Universitas Muhammadiyah Makassar, Indonesia

*Corresponding email: hartono.b.b@unismuh.ac.id

Received: 24 January 2026 *Accepted: 07 March 2026* *Published: 07 April 2026*

Abstract: Many high schools struggle to conduct a hydrogen emission spectrum experiment because they lack sufficient, up-to-date, and easy-to-use optical equipment. As a result, students often miss opportunities to observe diffraction patterns and to connect their analyses to atomic transitions. This study developed a virtual-reality-based laboratory for a hydrogen emission spectrum experiment to measure the spectrum across different diffraction orders and to improve students' learning outcomes. The ADDIE framework was used for the research and development process. It included analysis, design, development, implementation, and evaluation. Four physics teachers were interviewed to identify classroom problems and users' needs. The virtual reality-based laboratory made a hydrogen light source, a spectrometer, and a diffraction grating that users could interact with to align and measure angles for data collection. Three experts used a Likert-scale tool to rate its validity with respect to scientific accuracy, instructional design, and ease of use. Used Aiken's V to check for validity. The simulations showed that the diffraction patterns were always the same. The average angle changed from violet to red, and the second-order angle was always higher than the first-order angle for the same color. The first- and second-order wavelength estimates were very close to each other (3.80×10{ w –6.20×10{ w m), and 97–98% of the colors measured were the same in all orders. The values we found for the constants were very close to the known values (Rydberg constant 1.096×10w m{ ^{1}, error 0.09%; Planck constant 6.663×10{ ^{3}t J s, error 0.56%). Validator coefficients (0.80–0.90) helped improve things, such as a phased rollout, a zoomable angular scale, feedback on alignment, and smoother interactions with the controller. The learning outcomes improvement, measured using the normalized gain index (N-Gain), was N-Gain = 0.83 (83.11%). This shows that the development of media has improved students' learning outcomes. Virtual reality laboratories are more accessible and help students learn more about spectroscopy.

Keywords: diffraction grating simulation; hydrogen emission spectrum; physics education; spectroscopy experiment; virtual reality laboratory.

Article's DOI: https://doi.org/10.23960/jpmipa.v27i1.pp587-609

INTRODUCTION

Ideally, physics education should not only convey theory but also provide learning experiences through experiments, as these can connect observations with the theories being studied. Students can use experiments to test theories they have learned, prove existing ones, identify what does not fit, or even develop new ones (Canright & Brahmia, 2021; Omar, 2023). Students learn to think critically and solve problems scientifically through lab experiments. This helps them learn how to plan experiments, analyze experimental data, make sense of it, and connect theory with what they see in the real world (Dekhkonova & Yakubova, 2025; Vlachos et al., 2024). Experiments are generally conducted in groups, thereby enhancing communication and collaboration, as well as mutual support in problem solving (Ibirinde et al., 2024; Vlachos et al., 2024). Students can also learn new skills, work together, and think more critically when doing experiments (Menchafou et al., 2023). Engaging in scientific activities such as experiments can foster scientific attitudes, perseverance, precision, and intellectualism in students. Observations in schools also show that students are more motivated to learn when they can see real phenomena being studied through experiments (Girwidz et al., 2021).

Experimentation is especially useful for teaching when high school curricula begin to cover small, abstract, and counterintuitive phenomena such as the hydrogen emission spectrum experiment. Hydrogen is the simplest atomic system, and its discrete spectral lines are associated with quantized energy levels and electronic transitions (Halliday & Resnick, 1970). This is a great way to learn about spectroscopy and atomic structure. In school physics, spectral series such as the Lyman and Balmer series are a useful way to begin discussing quantization, photon emission, and the relationship between wavelength and energy. These ideas are often framed in terms of the Bohr model and its concepts of stationary orbits and energy-level transitions (Kamajaya, 2007; Hanam et al., 2024). However, students frequently find it difficult to connect symbolic equations and diagrams to the idea that a transition between levels produces a specific spectral line, especially when the lesson relies on static visuals rather than hands-on exploration (Girwidz et al., 2021). In many classrooms, students see formulas for energy differences and wavelength relationships. However, they do not see how a measured line position, a scale reading, or a calculated wavelength connects observation to the transition model. The hydrogen emission spectrum experiment topic benefits from activities in which students observe lines, compare them across series, and practice linking their observations to the reasoning that each line must have a discrete transition underlying it. When the learning sequence includes measurement and interpretation, students can view the spectrum as data that must be read, recorded, and explained rather than merely as a picture in a book.

Many schools also have difficulty conducting laboratory activities at the appropriate level because they lack appropriate equipment, must pay substantial costs to maintain it, and receive insufficient support for teachers to use specialized tools (Alves & Santos, 2021; Menchafou et al., 2023). If there is not enough equipment, teachers may have to cut back on the number of inquiry steps, give students fewer projects, or prioritize finishing work over investigation. In many cases, the teacher may only show how to do something without any hands-on work. Students find it more difficult to change variables and connect theory to data when this happens. Because students primarily rely on verbal or symbolic explanations rather than the hands-on learning that practical inquiry provides, these systemic problems have been linked to poorer educational outcomes (Sibomana et al., 2021). The hydrogen emission spectrum experiment is much more difficult because it usually requires a working discharge source, optical components, and a spectrometer setup to identify emission lines and connect them to atomic transitions (Halliday & Resnick, 1970; Kamajaya, 2007). In resource-limited settings, equipment may be unavailable, malfunction, or difficult to maintain. Because people lack real-world experience with it, the hydrogen emission spectrum experiment may seem like a purely theoretical idea unrelated to what can be seen. This situation makes it urgent for schools to find realistic alternatives so inquiry-based learning on the hydrogen emission spectrum experiment can continue even when laboratory equipment is unavailable. The VR-based laboratory is positioned as a shared learning resource. The intended users are (1) schools that do not have spectroscopy/optics equipment but can access VR devices through sharing schemes (school clusters, district resource centers, university partners, or government/CSR programs) and/or (2) schools that can adopt VR in a phased implementation (a small number of headsets used in rotation for group inquiry, while other students observe via a casting display). VR is used to replace the hard-to-maintain optical instruments with a stable, repeatable environment where students can still practice key inquiry steps, aligning components, reading angles, recording data, and interpreting spectral lines, so the learning goals remain achievable even when physical labs are constrained.

Digital simulations and virtual labs are effective ways to address resource constraints in hands-on science classes. They require no physical equipment; students can practice as much as they want without worrying about wear and tear or safety, and they can be used at any time and from any place (Bartošoviè, 2022; Wang et al., 2025). Students can easily reset and repeat virtual experiments when they have little time in the lab. This helps them go over the steps and look at the results of different trials. Students have been shown to learn concepts more effectively when they use interactive platforms such as PhET in inquiry-based lessons (Serevina & Kirana, 2021). However, two-dimensional and screen-based simulations do not always show how things are set up in space, how to move them around, or how real labs work. This may pose difficulties for students, necessitating the alignment of optical components, the coordination of instruments, or the interpretation of results using diverse methodologies (Anselmo et al., 2024). These problems are especially important in optics because the way experiments are set up, how students observe them, and how they use tools for measurement rather than just as props all affect how well they learn. Recent research indicates that we need to develop educational materials that provide more interactive and immersive experiences to help students understand difficult topics and remain engaged (Asiksoy, 2023; Tatira & Mshanelo, 2024; Triejunita et al., 2021). suggest that creating more interactive, immersive educational materials can help students learn hard subjects and maintain their interest.

Virtual reality is a good option because it can create three-dimensional environments that students can interact with and receive instant feedback. Presence and embodied interaction are prevalent characteristics of educational virtual reality. They let students move around in a virtual world and use tools in ways that differ from those in traditional screen-based media (Chandra et al., 2022; Xi, 2024). Many people think of VR as a way to help students learn about topics that are hard to understand, or that are too risky, too expensive, or too dangerous to do in school labs (Shepa et al., 2021). Several studies have demonstrated that VR-based learning enhances student engagement, facilitates comprehension of the material, and sustains motivation. This is because VR has interactive experiences and moving images that make it feel real (Mowbray, 2020; Rosmaria & Heryani, 2024). VR labs can also help people learn outside of school more flexibly, making them useful in a wider range of situations (Vergara et al., 2020; Sümer & Vanìèek, 2022). From a research perspective, VR can monitor key aspects of experiments, such as setting parameters, aligning instruments, reading scales, and tracking results. This lets students practice a measurement workflow and see how spectral observations relate to changes. This is how VR can help small labs and make it easy for students to follow along with an inquiry in class.

Recent research has concentrated on virtual reality as a medium for simulating physics experiments, highlighting the accuracy of these environments in depicting scientific principles while promoting substantial learning. Students could change the positions of the mirrors and lasers in a VR simulation of the Michelson–Morley experiment and see how the interference patterns changed. Experts said this was scientifically sound and fit with what students were learning (Alka et al., 2024). Students could examine and adjust key variables in a virtual reality (VR) prototype of the photoelectric effect.

This was similar to how they would do experiments in real life. People said that this prototype was both scientifically sound and good for teaching because it was engaging and easy to see (Bancong & Nanda, 2025). Also, studies of VR-based learning media for electromagnetic radiation show that immersive visual experiences can help people better understand abstract physical phenomena, especially those that are difficult to grasp with static images or traditional explanations (Shepa et al., 2021). On a larger scale, VR tools for K–12 science education based on the metaverse demonstrate how these technologies can be used in the classroom. The way they work, however, depends heavily on how they are made and where they are used (Wang, 2025; Huan & Sanmugam, 2024; Gavin Lai et al., 2021). Studies that preceded this one have shown VR works for education. The ease of use, adherence to scientific principles, and alignment with educational objectives determine learning outcomes. All of these things need to be tested systematically (Dodevska et al., 2025). Even with these changes, most studies that have been proven true about VR-based physics education still focus on topics such as the photoelectric effect, interferometry, and electromagnetic radiation. The hydrogen emission spectrum experiment is a powerful bridge between the Bohr model and real measurements because students can produce spectral lines, measure diffraction angles, and explain how each line is linked to a specific electronic transition (Halliday & Resnick, 1970; Kamajaya, 2007; Hanam et al., 2024). The contribution is not limited to moving a familiar activity into VR. The student's experience is organized around a measurement-centered inquiry path that makes the link transition, photon wavelength, and measurable angle concrete. Students align the setup, take angle readings, estimate wavelengths, and interpret the result in terms of spectral series and atomic transitions. The environment also supports how measurements are carried out in spectroscopy activities, including alignment guidance, a zoomable angular scale for careful readings, and a repeat-and-compare workflow across trials and diffraction orders. Scientific coherence is treated as part of the learning design; diffraction patterns remain consistent across orders; wavelength estimates agree between first and second orders; and derived constants can be checked against established values within the reported errors. These elements help distinguish the work from many VR-based laboratory studies that focus mainly on immersion or usability but provide less emphasis on a spectroscopy-specific, measurement-driven inquiry model supported by physics-consistency evidence and learning outcome reporting. This shows there is a need for more research and development of VR learning tools for the hydrogen emission spectrum experiment, especially for high school students. Because in the learning process, there are not enough lab resources, and two-dimensional representations do not always show how experiments work well (Anselmo et al., 2024; Alves & Santos, 2021).

Therefore, his study aims to develop a VR-based laboratory for high school students to conduct the hydrogen emission spectrum experiment. The VR environment simulates the operations of a real optics laboratory, allowing students to use a hydrogen light source, a spectrometer, and a diffraction grating, observe characteristic emission lines, and relate measurements to spectral series and electron transitions. Three main questions guide the research: (1) Do the virtual reality-based digital learning media developed in high school physics labs meet the validity criteria? (2) To what extent do the measurement results in VR show coherent diffraction patterns and estimates of the wavelength between orders? (3) Do the virtual reality-based digital learning media developed in high school physics practicums meet the criteria for effectiveness? This study aims to enhance the development of contemporary physics educational resources tailored to laboratory constraints and the needs of 21st-century learners. Furthermore, the findings of this study can provide an empirical foundation for integrating VR technology secondary school science education.

■ METHOD

Participants

The subjects in the research and development of the VR-based laboratory for hydrogen emission spectrum experiments were four physics teachers, who were interviewed to determine how the labs were set up and whether they had the appropriate equipment for the experiments. Three validators, who were physics education lecturers at different universities, also participated in this study. One validator had conducted research and published on digital learning media, and the other had professionally developed a VR-based laboratory. This study also included 36 grade XII students from SMA Negeri 1 Gowa who participated in a limited trial to evaluate the learning media. The participants were selected using purposive sampling. This sample was chosen because it met specific criteria relevant to the research objectives, including (1) access and permission to research, (2) having facilities to support VR implementation, and (3) matching the curriculum topic for grade XII. The students served as the research participants in both the small-scale. The purposive sampling technique was therefore appropriate for evaluating improvements in student learning outcomes in the developed VR-based laboratory within a specific and relevant learning context.

Research Design and Procedures

Development model (ADDIE)

This study utilizes a research and development (R&D) methodology, specifically the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) model, to develop a VR-based laboratory for a high school hydrogen emission spectrum experiment (Branch, 2010). A one-group pretest-posttest design was employed as a preliminary effectiveness check. In a well-developed VR-based laboratory, a trial group conducted a hydrogen emission spectrum experiment. Pre- and post-test assessments were then used to systematically compare the student learning outcomes. This study clarifies how the treatment of the developed learning media can improve student learning outcomes (Creswell & Creswell, 2018; Bogusevschi et al., 2020).

Figure 1. ADDIE stages

Analysis

This study conducted a needs assessment during the analysis phase to determine the school's requirements for conducting physics experiments. Interviews were conducted with several physics teachers to assess the condition of the school laboratory and the experimental equipment available there. Then, a first draft of a virtual lab design was created that meets acceptable visual standards and facilitates the collection of accurate experimental data. It was carefully planned so that each part of the VR-based laboratory would improve the accuracy and precision of physics experiments.

Design

The design phase begins after the needs analysis phase. At this point, an application storyboard is a useful way to generate new ideas and plan how the components and functions of the virtual lab will fit together. Input received from several physics teachers was adapted to the design to be built in the VR environment. It is hoped that the resulting laboratory will adhere to scientific principles, both visually and functionally. The features in this VR laboratory are designed to serve as an alternative to real-life physics experiments conducted in a laboratory.

Development

The VR-based learning media were made to show what the setup for measuring the hydrogen emission spectrum experiment would look like. This included a hydrogen cylinder as a light source, an optical spectrometer, a diffraction grating, and the emission lines produced by the hydrogen cylinder. In Blender, three-dimensional models of the lab equipment and environment were created to provide realistic, detailed representations of the objects. Unity 3D is used to integrate 3D models with objects into an interactive VR world, manage user navigation and interaction, and run simulations to make the experience feel more realistic.

Experimental objects can be added to the simulation, spectral lines selected for each order, and the angle of deviation of each line measured relative to the color-indicating thread on the optical spectrometer. Afterward, the wavelength, Rydberg constant, and Planck constant can be calculated from the angles obtained in the VR-based laboratory. The application built using Unity 3D is also compatible with HMDs and Meta Quest devices, which can make the experiment more realistic and allow for a more realistic laboratory experience. This simulation is based on the physics of the hydrogen emission spectrum experiment. The experiments conducted in this VR-based laboratory are validated to ensure that the measurement data is not too biased and can be tested both theoretically and practically.

Before the validators began, they were given a brief overview of the development goals, the steps for the simulation experiments, the steps for taking measurements, the locations of the visual experimental tools, and the angle readings from an optical spectrometer. During the practicum, the validators used the Meta Oculus Quest 3 device to gather data and check the accuracy, media functionality, and consistency of the data-collection methods. This small-scale trial was used to determine the extent to which the VR lab could represent the experimental procedure, the extent to which the measurement results in VR showed coherent diffraction patterns and inter-order wavelength estimates if the experiment was carried out independently by the students, and the extent to which the developed VR lab was effective for use in learning.

Implementation

The implementation phase involves using VR-based laboratories for hydrogen emission spectrum experiments in schools, particularly in grade XII, to measure the effectiveness of the developed media as an alternative to real laboratories. A small-scale trial was conducted to assess potential problems with using a VR-based laboratory for a hydrogen emission spectrum experiment in the classroom to improve student learning outcomes. The limited trial of the learning took place over four weeks, with two sessions per week, each approximately 90 minutes. During the trial, teachers followed established implementation procedures, which included (1) explaining the learning objectives and (2) assisting students in using the VR-based hydrogen emission spectrum experiment during the learning. The trial was first conducted on a small scale to identify any problems that might arise when using the VR-based hydrogen emission spectrum experiment in the classroom. After several revisions and improvements, the VR-based laboratory was used to measure the extent to which VR-based experiments improved student learning outcomes.

Instrument

The data collection instruments in this study consisted of two main components. First, the validity of VR-based laboratory in hydrogen emission spectrum experiment material (conceptual coherence, design quality, and technical performance) was assessed using three instruments: a content material validity sheet, completed by material experts, with 20 items evaluating consistency, relevance, relationship between theory, tools, and practical (e.g., correctness of hydrogen spectral-series concepts; correctness of the diffraction-order logic; consistency between the experiment flow and spectroscopy principles; appropriateness of explanations and symbols), a learning media design validity sheet, completed by media experts, with 20 items measuring interface, visual and functional for learning (e.g., clarity of learning objectives; inquiry flow clarity; quality of visual layout; readability of scales and labels; suitability of interaction prompts for grade XII student's), and the last a technical use of tools validity sheet, completed by IT experts, with 20 items measuring application, compatibility and safety technical system (e.g., navigation and controller responsiveness; interaction stability; compatibility/performance; comfort/safety consideration; ease of deployment in classroom setting). These indicators were formulated by adapting common criteria used in educational media evaluation and science learning media validation, and then contextualizing them to a measurement-centered VR spectroscopy activity. Content validity was quantified using Aiken's V to reflect agreement among validators for each indicator (Aiken, 1980; Azwar, 20212; Retnawati, 2016). Indicators that did not meet the target criterion were revised based on the validators' qualitative notes.

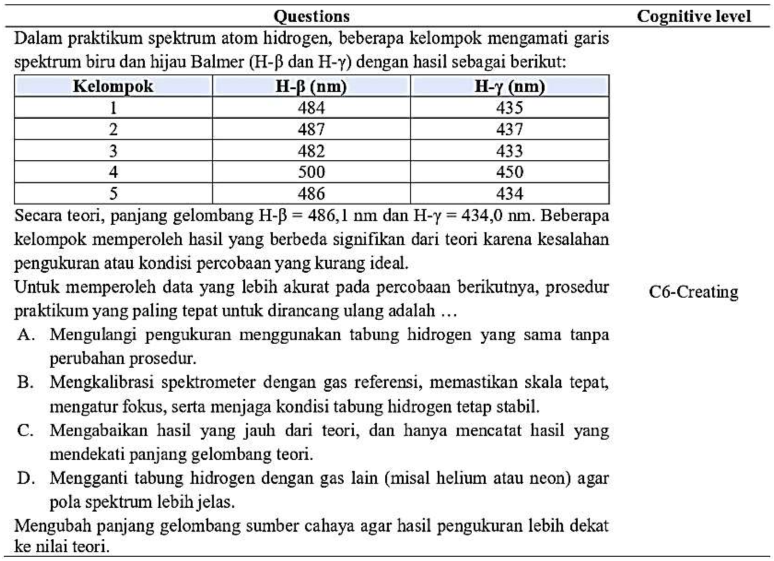
Second, the effectiveness of the VR-based laboratory for the hydrogen emission spectrum experiment was evaluated through a learning outcome test question. The students' question consists of 30 items, covering 6 cognitive levels in Bloom's taxonomy (C1-C6). Multiple-choice test questions with varying levels of difficulty according to cognitive level (Bloom, 2014). Before the main trial, the items were checked for clarity and feasibility through a limited trial with students with characteristics similar to those of the target participants. Responses from the try-out were used to conduct basic item analysis, including item difficulty and item discrimination, and to identify distractors that were not functioning as intended. Items with unclear wording or weak performance were revised prior to use in the pre-test and post-test.

The instrument's validity was assessed using the point-biserial correlation method. Questions were declared valid if the calculated r-value (Pearson Correlation) > r_{table} at a significance level of 0.05 (Waworuntu, 2024). Meanwhile, the instrument's reliability was assessed using Kuder-Richardson (KR-20). Questions were considered reliable (consistent) if the KR-20 value was e• 0.70 (Arikunto, 2012). Meanwhile, the test, administered as a pre-test and a post-test, measured improvements in students' learning outcomes. Instrument testing was conducted using a pretest and posttest, with indicators listed in Table 1 (Bloom, 2014).

Table 1. Learning outcomes test indicators

No	Indicator	Cognitive level
1	Students can recall the basic concepts of the hydrogen emission spectrum.	C1-Remembering
2	Students can understand the relationship between electron transitions and spectral series.	C2-Understanding
3	Students can apply physical formulas to calculate spectral quantities.	C3-Applying
4	Students can analyze spectral data from practical results.	C4-Analizing
5	Students can evaluate the accuracy of calculation results and the practical procedures.	C5-Evaluating
6	Students can develop further interpretations, hypotheses, or new solutions based on laboratory data.	C6-Creating

Based on the indicators listed in Table 1, representative multiple-choice items for the cognitive level are presented in Figure 2. These sample items were used to ensure that the VR-laboratory was conceptually, pedagogically, and technically sound before the final implementation.



Questions | **Cognitive level**

Dalam praktikum spektrum atom hidrogen, beberapa kelompok mengamati garis spektrum biru dan hijau Balmer (H-β dan H-γ) dengan hasil sebagai berikut:

Kelompok	H-β (nm)	H-γ (nm)
1	484	435
2	487	437
3	482	433
4	500	450
5	486	434

Secara teori, panjang gelombang H-β = 486,1 nm dan H-γ = 434,0 nm. Beberapa kelompok memperoleh hasil yang berbeda signifikan dari teori karena kesalahan pengukuran atau kondisi percobaan yang kurang ideal.

Untuk memperoleh data yang lebih akurat pada percobaan berikutnya, prosedur praktikum yang paling tepat untuk dirancang ulang adalah …

A. Mengulangi pengukuran menggunakan tabung hidrogen yang sama tanpa perubahan prosedur.

B. Mengkalibrasi spektrometer dengan gas referensi, memastikan skala tepat, mengatur fokus, serta menjaga kondisi tabung hidrogen tetap stabil.

C. Mengabaikan hasil yang jauh dari teori, dan hanya mencatat hasil yang mendekati panjang gelombang teori.

D. Mengganti tabung hidrogen dengan gas lain (misal helium atau neon) agar pola spektrum lebih jelas.

Mengubah panjang gelombang sumber cahaya agar hasil pengukuran lebih dekat ke nilai teori.

C6-Creating

Figure 2. Examples of learning outcome test instruments

Data Analysis

Quantitative analysis of validation data was conducted using Aiken's V-coefficient to assess the validity of VR-based learning media in terms of content validity, learning media design, and technical usability. Expert validators used a Likert-type scale to assess each item in the validity assessment indicators.

The Aiken's V values found were between 0 and 1 and were based on preset validity standards. In this study, a cutoff value of V e" 0.80 was used to determine whether an item was valid. This is standard practice when making instruments and learning media. Aiken's V values of 0.80 or higher indicate a high level of expert agreement and strong content validity (Aiken, 1980; Azwar, 2012; Retnawati, 2016). Values below this threshold were considered in need of change, and the mean Aiken's V for all items in each validation aspect was calculated to assess the overall validity of the media.

Table 2. Interpretation criteria for aiken's V coefficient

Score	Criteria
$0.80 < V \leq 1.00$	Very valid
$0.60 < V \leq 0.80$	Valid
$0.40 < V \leq 0.60$	Moderately valid
$0.20 < V \leq 0.40$	Invalid
$0.00 < V \leq 0.20$	Strongly invalid

The validity of the learning outcome test instrument was assessed using the point-biserial correlation in SPSS 30. Meanwhile, the instrument's reliability was analyzed using the following Kuder Richardson-20 (KR-20) . The results obtained will then be defined according to the reliability interpretation criteria in Table 3 below (Riduwan, 2010):

Table 3. Interpretation criteria for a reliability instrument

Score	Criteria
0.80 - 1.00	Very high
0.60 - 0.80	High
0.40 - 0.60	Medium
0.20 - 0.40	Low
0.00 - 0.20	Very low

The efficacy of the VR-based laboratory for the hydrogen emission spectrum experiment in enhancing learning outcomes was assessed by comparing pre- and post-test scores. Used the pre-test results to determine what students' initial abilities were before the experiment. After a VR-based laboratory for the hydrogen emission spectrum experiment was conducted, the post-test results were expected to improve student learning outcomes. Used N-Gain analysis to objectively quantify the extent to which students' learning outcomes improved. Used both a significance test and effect sizes to determine the magnitude of the treatment's effect on student learning outcomes. The N-Gain score was calculated by comparing the difference between pre-test and post-test scores with the maximum achievable score in SPSS version 30. This calculation formula is based on the equation created by Hake (Ferawati et al., 2025), which lets the analysis results show how improving student learning outcomes by putting them into one of three groups: low, medium, or high, based on the criteria that apply.

Table 4. N-Gain score criteria

Score	Criteria
$g \geq 0.7$	High
$0.3 \leq g \leq 0.7$	Medium
$g < 0.3$	Low

■ RESULT AND DISCUSSION

The Development of a VR-based Laboratory fr Hydrogen Emission Spectrum Experiment

Analysis

At the school, it was clear that conducting a hydrogen emission spectrum experiment was not possible because the laboratory facilities were not adequate. The physics lab lacked a spectrometer, the hydrogen gas cylinder was broken, and only a few sets of optical equipment were available. Additionally, many of the parts were rusted and in poor condition, which made their use in experiments even more difficult. Physics experiments have recently stopped entirely because the lab equipment keeps deteriorating.

For the hydrogen emission spectrum experiment, students needed to connect abstract concepts such as energy levels, electron transitions, and spectral series to real-world examples, including measured wavelengths and discrete emission lines, even though adequate equipment was very limited in schools. Interviews with teachers further highlighted the difficulties in teaching this abstract material. It was hard for physics teachers to explain the hydrogen emission spectrum experiment without pictures. In interviews, most students reported experiencing difficulties with spectral series, electron transitions, and energy levels. These results demonstrate the importance of easy-to-use alternative media that enable procedure-based, visually supported experiments, as schools lack adequate physical laboratory resources.

Design

The study moved from the analysis phase to the design phase after determining the schools' needs. At this stage, a storyboard was used to illustrate the experimental workflow and interface architecture, resulting in the first media design. The VR-based media for the hydrogen emission spectrum experiment were created using Universal Design for Learning (UDL) principles to help students with diverse abilities perform scientific tasks in a virtual setting. The design in Figure 3 laid the groundwork for determining how the features would be structured and what they would do. The goal of each feature was to make the virtual world feel more real and to get people more involved.

Figure 3 shows how the application works in the lab, from the opening screen to the instructions for use, intended to help both teachers and students. As part of the design process, a media expert reviewed the content and advised on its appropriateness and the media's visual and functional features. We used this feedback to improve the prototype design in the next step.

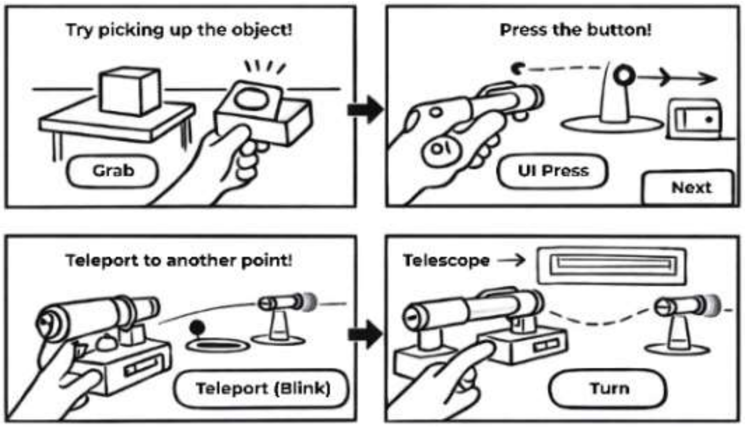


Figure 3. Storyboard hydrogen emission spectrum experiment

Development

The initial design of the VR-based laboratory for the hydrogen emission spectrum experiment was transformed into an immersive virtual reality app during development. This phase began with three-dimensional modeling of various objects in Blender 4.5. The goal was to make it easier to interact with and observe things in a virtual world. Upon completion of all 3D models, the objects were incorporated into Unity Engine version 6000.0.53f1 as the principal platform for application development. The integration enabled viewing and control of the virtual environment and experimental equipment via the Meta Oculus VR device. After that, internal testing was done in stages to check the app's stability and functionality. This included testing the teleportation system for area navigation and how well each object responded the Meta Oculus VR controller.

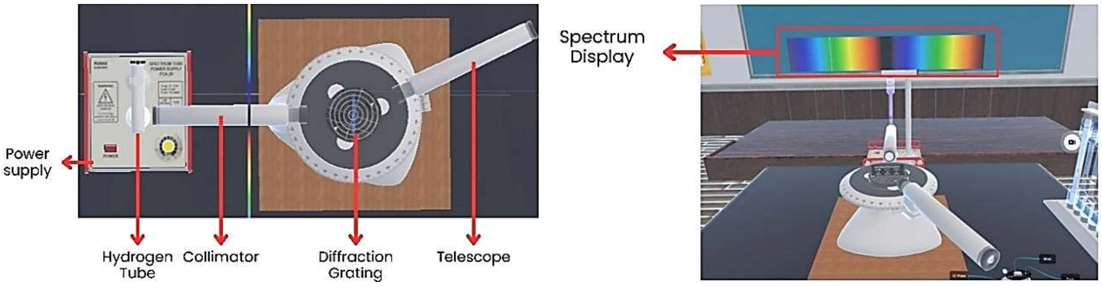


Figure 4. Display of the VR-based laboratory for the hydrogen emission spectrum experiment

Figure 4 illustrates the preliminary interface for a VR-based laboratory experiment on the hydrogen emission spectrum. This interface is supposed to look and feel like a real physics lab. This interface includes all the basic components needed for a hydrogen emission spectrum experiment. Users can move freely within the virtual laboratory and use various tools to perform scientific tasks during experiments. The immersive design makes interactions feel more real than other types of screen-based media. The goal of this experimental application is to make the experience of a real laboratory environment.

Validity of the VR-based Laboratory for the Hydrogen Emission Spectrum Experiment

This phase is all about determining whether the VR-based lab designed for the hydrogen emission spectrum experiment is useful. Three physics lecturers from different universities who were experts in both physics and the development of digital learning media took part in the validation process. The validators' feedback informed the evaluation, which found that the media met the standards and could be used instead of visiting physical labs. A five-point Likert scale questionnaire, from 1 (strongly disagree) to 5 (strongly agree), was used to gather expert opinions on content, learning media design, and the technical use of tools. To make the scores easier to understand, they were averaged, normalized to 0-1, and shown as percentages. Using established criteria, the validity level was checked, and a threshold of 0.80 or higher was used to determine if the media was valid.

Table 5. Content validation (Aiken's V) of the VR-based laboratory for the hydrogen spectrum experiment.

Indicator	V	Category
Content material		
Consistency of the hydrogen emission spectrum concept	0.9	Very valid
Relevance of material to practical work and learning outcomes	0.8	Valid
Relationship between theory, tools, and optical phenomena	0.9	Very valid
Clarity of presentation, depth, and language	0.9	Very valid
Learning media design		
Interface display clarity and navigation	0.9	Very valid
Visual quality, graphics, and representational suitability	0.8	Valid
Functionality and support for learning	0.9	Very valid
Technical use of tools		
Application stability and technical performance	0.8	Valid
Compatibility, tracking, and interaction	0.9	Very valid
Safety, security, and supporting technical systems	0.9	Very valid

Table 5 presents the results of Aiken's V test for content material, learning media design, and the technical use of tools in validating the VR-based laboratory hydrogen emission spectrum experiment. Most of the indicators got the "Very Valid" rating (V = 0.9), which means that they were very feasible with established hydrogen emission spectrum experiment concepts, that theory, experimental apparatus, and optical phenomena were clearly integrated, and that the interface, navigation, functionality, and user interaction were all clear and easy to use. Several indicators were considered "Valid" (V = 0.8), including their relationship to learning outcomes, their visual representation, and the application's stability. This means the quality is valid for use, but could be improved, especially in terms of appearance and performance. On the other hand, validation results show that the hydrogen emission spectrum experiment meets feasibility requirements. As a result, th VR-based laboratory can be used in high school physics classes.

Table 6. Pilot usability of the VR-based laboratory for the hydrogen emission spectrum

Pilot Usability Aspect	**Evaluated Indicator**	**Evaluation Description**	**Data Collection Method**	**Success Criteria**
Ease of Navigation	Teleportation system and area-to-area movement	Users can move between areas of the virtual laboratory without confusion or navigation errors.	Direct observation and internal testing notes	≥80% of users can navigate independently.
Ease of Interaction	Object responsiveness to Oculus controllers	Experimental objects respond to controller inputs accurately and consistently.	Functional testing and interaction logging	No critical errors occur during manipulation.
Interface Clarity	Room layout and object visibility	The spatial layout resembles a real laboratory and is easily understood by first-time users.	Observation and usability checklist	Key objects are readily identifiable from the outset.
Instruction Clarity	Experiment step workflow	Users understand the experiment sequence without additional instructions from the researchers.	Observation of user behavior	≥ 80% of steps are completed in the correct order.
User Comfort	Cognitive and physical load	Use does not cause disorientation, dizziness, or excessive fatigue during operation.	Brief post-test interviews	The majority of users report being comfortable.
Initial System Stability	Application performance during execution	The application runs stably without crashes throughout the testing session.	Repeated internal testing	No crashes occur during the session.
User Engagement	User responsiveness and focus	Users show interest and active engagement during exploration.	Observation and user reflection	Users actively try the available features.

Table 6 shows that the VR-based laboratory for the hydrogen emission spectrum experiment meets key usability standards for improving user learning. The evaluation assessed how easy it was to navigate, how clear the instructions were, how comfortable the user felt, how stable the system was, and how engaged the user was. Most people had no trouble getting around in the virtual world, knew what to do, and used the Oculus Quest 3 controllers well. The system worked well and gave everyone an immersive experience without making anyone feel bad.

Next, validity and reliability testing were conducted for the learning outcomes test instrument to ensure its appropriateness for measuring improvements in students' achievement. The empirical validity test using the Pearson product–moment correlation indicated that all 30 items were valid at the 0.05 significance level, as each item's *r* value exceeded the critical value (r_{table} = 0.339) for N = 34. Reliability analysis using the Kuder–Richardson Formula 20 (KR-20) yielded a coefficient of 0.96, indicating "very high" internal consistency.

Table 7. Results of the reliability test of the learning outcome test instrument

Analysis Component	Value
Number of questions	30
Total score variance	91.32
KR-20 Reliability Coefficient	0.96

Coherence of VR Diffraction Patterns and Inter-Order Wavelength Estimation

Following development, the research advanced to the pilot phase, wherein the VR experiment was assessed by collecting data on the hydrogen emission spectrum. Students could link the measured wavelengths to quantized electron transitions by looking at spectral lines and measuring diffraction angles. This supported the Bohr model and the visible-light spectral series (Halliday & Resnick, 1970; Kamajaya, 2007; Hanam et al., 2024). Initial empirical results consist of diffraction deviation angles (è) for each color in the visible spectrum at the first (n = 1) and second (n = 2) diffraction orders. Diffraction angles are read to the right and left of the first and second-order axes, then averaged to obtain representative angles for each color at each order.

Table 8. Experimental observation results: diffraction angles (right, left, and average) for visible spectrum colors at the first and second orders

Spectrum order (n)	Spectrum Color	*θ* Right (°)	*θ* Left (°)	*θ* Average (°)
1	Purple	2.15	2.20	2.17
	Indigo	2.55	2.60	2.58
	Blue	2.70	2.70	2.70
	Green	2.80	2.85	2.83
	Yellow	3.25	3.30	3.27
	Orange	3.35	3.40	3.38
	Red	3.55	3.55	3.55
2	Purple	4.35	4.40	4.38
	Indigo	5.15	5.20	5.18
	Blue	5.40	5.40	5.40
	Green	5.70	5.70	5.70
	Yellow	6.55	6.55	6.55
	Orange	6.75	6.80	6.78
	Red	7.10	7.15	7.13

Experimental results show that the average angle increases from violet to red for both diffraction orders, ranging from approximately 2.17° to 3.55° for the first order and 4.38° to 7.13° for the second order. This increase is consistent with the principle that longer wavelengths produce larger diffraction angles with a fixed diffraction grating, so that the color sequence appears as a measurable pattern. In addition, the angles at the second order are systematically larger than the angles at the first order for the same color.

Figure 5. Average diffraction angle (è)

Using the mean diffraction angles in Table 8, the wavelength of each visible color was calculated using the diffraction-grating relation $\lambda = \frac{d\sin\theta}{n}$, where d is the grating spacing, 0 is the diffraction angle, and n is the diffraction order. Operationally, the measured θ values obtained through VR scale readings were substituted into $\sin\theta$ and normalized by the order , producing wavelength estimates for the first order (λ_2) and the second order (λ_2) that could be directly compared. Employing two diffraction orders provides an internal-consistency check: for the same spectral line, λ_1 and $\lambda_1$should be close if angle readings are stable and the VR diffraction model conforms to optical principles (Halliday & Resnick, 1970).

Table 9. Analysis of wavelength observations, including first- and second-order wavelength estimates, mean wavelength, reference wavelength range, and agreement classification

Colour	$\lambda_1 \pm \Delta\lambda_1$ (10^{-7} m)	$\lambda_2 \pm \Delta\lambda_2$ (10^{-7} m)	$\bar{\lambda} \pm \Delta\lambda$ (10^{-7} m)	Reference λ (nm)	K (%)	Remark
Purple	3.79 ± 0.17	3.82 ± 0.08	3.80 ± 0.13	380–450	97	Consistent
Indigo	4.50 ± 0.17	4.51 ± 0.08	4.51 ± 0.13	450–470	97	Consistent
Blue	4.71 ± 0.17	4.71 ± 0.08	4.71 ± 0.13	470–495	97	Consistent
Green	4.94 ± 0.17	4.97 ± 0.08	4.95 ± 0.13	495–570	97	Consistent
Yellow	5.70 ± 0.17	5.70 ± 0.08	5.70 ± 0.13	570–590	98	Consistent
Orange	5.90 ± 0.17	5.90 ± 0.08	5.90 ± 0.13	590–620	98	Consistent
Red	6.19 ± 0.17	6.21 ± 0.08	6.20 ± 0.13	620–750	98	Consistent

The analysis results in Table 9 show an increase in the average wavelength from violet to red, with $\bar{\lambda}$ ranging from 3.80×10{ w m to 6.20×10{ w m. These are in good agreement with the visible spectrum order theory. The experimental results for λ_1 and λ_2, for each color are very similar, with only slight differences across the entire visible range. The "Consistent" classification for all colors, with K values of 97–98%, shows that the measurements are very accurate across all diffraction orders. The K value is a measure of measurement accuracy.

It is important to clarify the meaning of the uncertainty terms in the table. The values $\Delta\lambda_1 = \pm0.17\times10^{-7}$ m and $\Delta\lambda_2 = \pm0.08\times10^{-7}$ m are not intended to represent color-by-color variability (e.g., standard deviation from repeated readings). Instead, they represent the fixed-resolution/least-count uncertainty implied by the VR angle-reading interface and by the same measurement procedure applied to all colors within a given order. In real experiments, uncertainties can vary across lines due to intensity, line width, and observer judgment; such variation is expected when uncertainty is estimated from repeated observations.

In addition to conducting wavelength analysis, this experiment can determine the Rydberg constant (R) from the observed hydrogen emission spectrum. This research examines the correlation between the wavelengths of the hydrogen spectrum experiment and the principal quantum numbers that characterize electron behavior in the atomic model. This explains why there are discrete emission lines, which arise from energy differences that occur only in certain amounts (Halliday & Resnick, 1970; Kamajaya, 2007; Hanam et al., 2024).

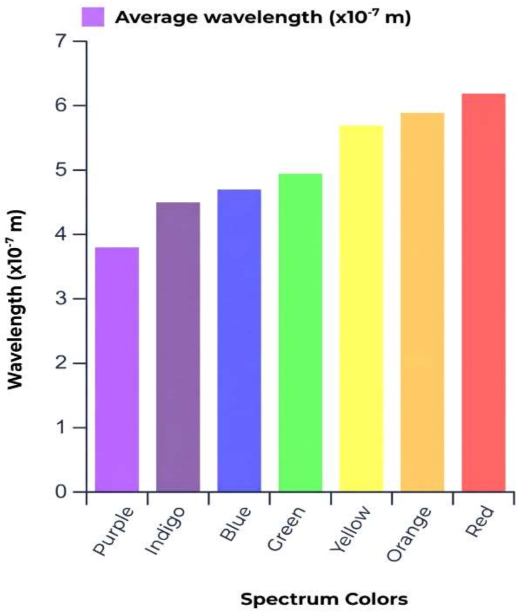


Figure 6. Wavelength (λ) per color

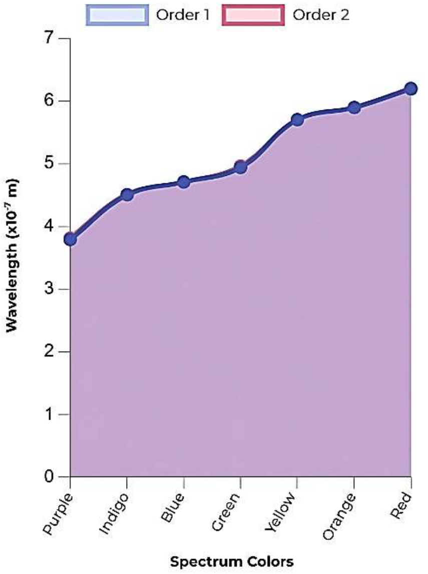


Figure 7. Comparison of first-order vs second-order

The Rydberg constant is calculated using , $R = \frac{1}{\lambda}\left|\frac{n_A^2 \times n_B^2}{n_B^2 - n_A^2}\right|$ where n_A and n_B represent the energy levels involved in the transition for the analyzed line. The visible hydrogen line spectrum is a Balmer series, so the experimentally generated ë becomes the basis for determining the R value.

In Table 10, R_1 and R_2 indicate the Rydberg constant values obtained from first-order and second-order data, respectively. These values

Table 10. Analysis of the Rydberg constant (R) derived from hydrogen spectrum observations

$R_1 \pm \Delta R_1$ (10^7 m^{-1})	$R_2 \pm \Delta R_2$ (10^7 m^{-1})	$\bar{R} \pm \Delta R$ (10^7 m^{-1})	K (%)	H (%)
1.099 ± 0.050	1.093 ± 0.025	1.096 ± 0.037	96.60	99.93

average $^{l}R = 1.096 \text{ x } 10^7 m^{-1}$with an uncertainty of 0.037×10w m{ ¹. Here, K is defined as the measurement precision (i.e., the consistency of the value across orders). At the same time, H represents the measurement accuracy relative to the reference value through the percentage error. With a reported percentage error of 0.09 for Rydberg, the very high H value (99.93%) indicates that the obtained R is in excellent agreement with accepted theory. The results presented in this experiment demonstrate that VR-based measurements not only produce a suitable spectral pattern but also a value for the Rydberg constant that is very close to theory.

The different uncertainties between orders ($\Delta R_1 > \Delta R_2$) follow directly from the wavelength-reading uncertainty in Table 9. In this VR workflow, the angle-reading interface has a fixed resolution for each diffraction order; the first-order wavelength estimate has a larger least-count uncertainty ($\Delta\lambda_1$) than the second-order estimate ($\Delta\lambda_2$) Because R is calculated from wavelength, the uncertainty propagates into R, leading to a larger ÄR for first order than for second order. This does not indicate "inconsistent precision" across constants; it reflects the same order-dependent measurement resolution being carried forward through the calculations.

The next step in the analysis is to derive the Planck constant (h) from observations of the hydrogen emission spectrum experiment. The calculations use the relation $h = \frac{2\pi^2 k^2 m_e e^4}{c \cdot R}$ which relates h to the estimated Rydberg constant, the speed of light c, and other physical constants. The R value is crucial to determining the Planck constant in this analysis. For grade XII students, this step is intended to be conceptual rather than merely computational. After the wavelength has been estimated from a scale reading, the calculation shows a clear chain of meaning, measured angles, wavelength, energy of the emitted photon, and a constant that links energy and frequency. In this way, h is presented as a bridge between what is seen in the spectrometer (line positions) and what is explained in the atomic model (quantized transitions).

To keep the task understandable at the high-school level, the workflow is structured as short, guided steps: identify a spectral line, read the deviation angle, calculate ë with the grating equation, and then use the provided relation to obtain h from the estimated R value and known constants (e.g., c). The emphasis is on interpreting whether the result is reasonable (order-to-order consistency and closeness to the reference value) rather than on algebraic manipulation. Following the approach used in the Rydberg analysis, the values of h_1 and h_2 presented in Table 11 correspond to the Planck constant values obtained from first- and second-order diffraction data, respectively.

Table 11. Analysis of Planck's constant (h) derived from hydrogen spectrum observations

$h_1 \pm \Delta h_1$ (10^{-34} J·s)	$h_2 \pm \Delta h_2$ (10^{-34} J·s)	$\bar{h} \pm \Delta h$ (10^{-34} J·s)	K (%)	H (%)
6.656 ± 0.098	6.669 ± 0.049	6.663 ± 0.073	98.90	99.45

Table 11 demonstrates that the Planck constant values for both orders are approximately identical, resulting in an average value of $\bar{h} = 6.663 \times 10^{-34} J/s$ with an uncertainty of 0.073×10{ ³t J·s. The K value of 98.90% indicates very high precision, and the H value of 99.45% indicates high accuracy relative to the reference value, with a reported error of 0.56% for Planck's constant. The results show that measurements of Rydberg constants, Planck's constant, deviation angles, and wavelengths are all consistent with a single experimental method.

Implementation

Effectiveness Based on Learning Outcomes

The implementation phase began after the development phase was over. In this stage, the VR-based hydrogen emission spectrum experiment was conducted in the trial group over four lessons. The trial assessed students' performance on the experiment, their understanding of the material, and the extent to which the experimental activity helped them learn, with a focus on the hydrogen emission spectrum experiment.

Figure 8. The use of the VR-based laboratory for the hydrogen emission spectrum experiment

Figure 8 presents the implementation of the hydrogen emission spectrum experiment within the educational context. Students were told to ensure that the experimental procedures, data collection, and spectrometer measurements were correct during the lesson.

The effectiveness of the VR-based laboratory for the hydrogen emission spectrum experiment was evaluated using pretest and posttest data. The pretest was administered prior to the learning activity, and the posttest was administered after the media was implemented. Learning improvement was summarized using the normalized gain (N-gain), calculated for each indicator of the hydrogen emission spectrum experiment material.

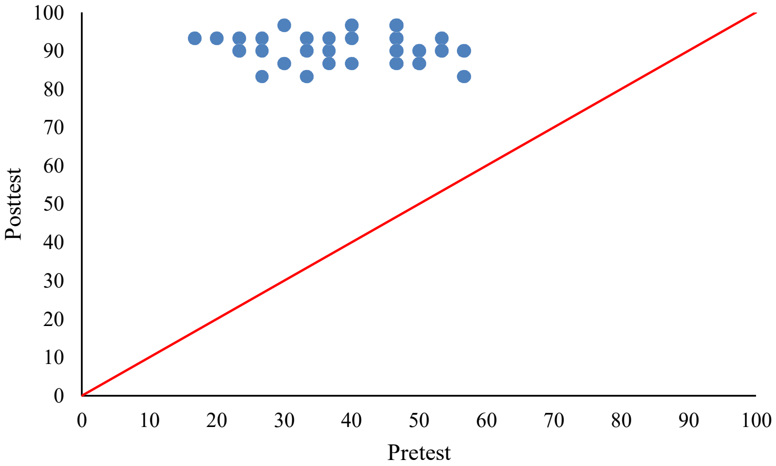


Figure 9. Scatter plot of individual student pretest and posttest scores

Figure 9 shows the relationship between students' pretest and posttest scores as a scatter plot, with each point representing an individual student. A diagonal reference line (y = x) is included to facilitate interpretation of score changes. Points above the diagonal indicate students whose posttest scores exceeded their pretest scores (improvement); points on the line indicate no change; and points below the line indicate a decrease in performance.

As shown in Figure 9, all data points are positioned above the diagonal line, indicating that all students experienced score improvement. This visual pattern supports the quantitative result of a normalized gain (N-Gain = 0.8311 or 83.11%), which falls into the "high" category and indicates substantial improvement in learning outcomes after using the developed media.

To test whether the improvement was statistically significant, the normality of the difference score was assessed. Based on the Shapiro-Wilk normality test for the difference scores (= posttest – pretest), the significance value was $p = 0.379$ ($n = 36$). Because $p > 0.05$, the diffeΔence scores can be considered normally distributed, satisfying the normality assumption for a paired-samples t-test. Therefore, a paired-samples t-test was performed to examine whether there was a significant change in students' learning outcome scores from pretest to posttest. The paired-samples t-test results in Table 12 show a statistically significant difference between pretest and posttest scores.

Table 12. Paired sample test results for learning outcomes

				95% Confidence Interval of the Difference				**Sig.**
	Mean	**Std. Deviation**	**Std. Error Mean**	**Lower**	**Upper**	**t**	**df**	**One-Sided p**
Pretest-Posttest	-51.29583	12.47875	2.07979	-55.51803	-47.07363	-24.664	35	<.001

This increase occurred because the VR media combined several features that support student learning. First, students can interact directly with the virtual experiment (e.g., placing/adjusting components and moving/rotating the telescope to find spectral lines). This direct interaction aligns with constructivist learning, where students build understanding through active exploration and evidence-based explanations. Second, VR provides integrated 3D visualization of the equipment and the resulting spectra, allowing students to see spatial relationships and changes in real time. From a multimedia learning (CTML) perspective, this can reduce unnecessary cognitive load because students do not need to manually combine 2D diagrams and text; key elements and results are connected in a single view. Third, this media allows repeated experiments with immediate feedback, which supports experiential learning (Kolb, 1984) through a cycle of doing, observing, reflecting, and trying again (e.g., comparing first- and second-order spectra and checking for conformance to reference ranges). Finally, the use of hand/controller actions can strengthen embodied cognition, making the procedural-spatial aspects of spectroscopy (finding lines, aligning displays, reading scales) feel more intuitive, which helps students understand abstract topics such as the hydrogen emission spectrum experiment. These results indicate an increase in student learning outcomes after implementing the developed media in the learning process.

Beyond improving test scores, this VR-based laboratory supports physics learning more broadly by bringing back an authentic "doing an experiment" mindset to a topic often taught as formulas to memorize. In many schools, hydrogen spectroscopy is introduced through pictures, brief demonstrations, or simplified simulations because the real equipment is limited, sensitive, and takes time to set up. The VR setting, however, keeps the essential habits of experimental physics within reach: setting up the instrument, taking measurements, repeating trials, and checking whether the results remain consistent under stable, easily repeatable conditions. This is a clear advantage over common alternatives. A traditional hydrogen tube-and-spectrometer setup feels very real. However, it is hard to run as a student-centered inquiry in large classes due to cost, maintenance, safety issues, and limited access. Video demonstrations are easy to use, yet they tend to make students spectators rather than investigators. Many 2D virtual labs explain ideas efficiently, but they often focus on "seeing the spectrum" rather than "producing evidence," so practical and spatial skills, alignment, angle reading, and comparison of diffraction orders remain weak. Low-cost or smartphone spectrometers improve access, but the results can vary widely with lighting, camera differences, and alignment quality, which can push class time toward troubleshooting rather than building concepts. The VR laboratory helps fill these gaps by pairing an inquiry workflow with consistent measurement conditions and immediate feedback, so students can focus on what the data means: how line positions connect to wavelength, how wavelength connects to transition energy, and why checking agreement across diffraction orders strengthens confidence in the conclusion. In this way, the tool is not presented as technology for its own sake, but as an instructional bridge that brings experimental reasoning and model-evidence connections back into modern physics learning when laboratory conditions are constrained.

Limitations of the Research and Practical Implications

There are several limitations to this study that need to be noted. First, the sample size was relatively small, and the participants were drawn from a single school using purposive sampling, the findings should be interpreted as preliminary and may not generalize to other schools with different student characteristics, infrastructure, or teaching practices. Future studies are recommended to use larger, more diverse samples, ideally involving multiple schools (urban-rural, differing resource levels) and probability-based or stratified sampling to strengthen external validity and the generalizability of the results. Second, this study measures changes before and after VR use in one group; because no control or comparison group was included, the observed score changes cannot be attributed solely to the VR intervention (e.g., history, maturation, and testing effects remain possible). Future studies should employ a quasi-experimental or experimental design with a conventional-learning control group (ideally randomized or matched) to support stronger causal claims. Third, technical limitations, including the number of devices and reliable internet connectivity, pose challenges to the deployment of VR-based laboratories in the field. The results of this study provide actionable insights for educational practice. Teachers can use a VR-based laboratory of the hydrogen emission spectrum experiment as an alternative to a physics lab to improve students' learning outcomes.

■ CONCLUSION

This study made a VR-based laboratory that has been tested and works well for simulating a hydrogen emission spectrum experiment. The diffraction values were the same for both first- and second-order observations in the VR environment. The diffraction angle steadily rose from violet to red, and the observed wavelengths were as expected. This simulation enables quantitative scientific analysis, unlike a purely visual demonstration, because the average wavelength values align with the known visible spectrum range. The VR-based laboratory has the potential to improve experimental methods in physics education, owing to its accuracy and close agreement between the calculated values of the Rydberg and Planck constants and established theoretical values.

The VR-based hydrogen emission spectrum experiment is a great way to learn, and studies have shown that it significantly improves students' learning outcomes. The study has some flaws, however. For example, the sample size is small, and only one group is used. This makes it inhibiting to use the results in other kinds of learning materials or situations. Future research should broaden this study by incorporating additional materials and schools to evaluate their impact on students' comprehension of concepts, inquiry skills, and engagement, and by contrasting these with conventional laboratory activities and two-dimensional simulations.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the writing of this manuscript, the authors employed ChatGPT to assist with to enhance the clarity of the writing. The authors have reviewed and edited the content generated by this tool and assume full responsibility for the content of the published article.

■ REFERENCES

Aiken, L. R. (1980). Three coefficients for analyzing the reliability and validity of ratings. *Educational and Psychological Measurement, 45*(1), 131–142. http://doi.org/10.1177/0013164485451012

Alka, M., Akib, I., & Bancong, H. (2024). Developing a virtual reality simulation of the Michelson–Morley experiment for physics education: Design, validation, and educational impact. *International Journal of Learning, Teaching and Educational Research, 23*(11), 254–267. https://doi.org/10.26803/ijlter.23.11.13

Alves, E. G., & Santos, A. L. M. (2021). Photoelectric effect: Development of a quantitative experiment. *Revista Brasileira de Ensino de Física, 43*, 1–9. https://doi.org/10.1590/1806-9126-RBEF-2021-0146

Anselmo, C. T., Prudente, M. S., Aquino, J. L. R., Dumelod, D. A., & Cabrera, F. R. (2024). A systematic review of the effectiveness of mobile learning tools in enhancing physics education. *International Journal of Learning, Teaching and Educational Research, 23*(12), 237–257. https://doi.org/10.26803/ijlter.23.12.13

Arikunto, S. (2012). *Dasar-dasar evaluasi pendidikan* (Edisi ke-2). Bumi Aksara.

Asiksoy, G. (2023). Effects of virtual lab experiences on students' achievement and perceptions of learning physics. *International Journal of Online and Biomedical Engineering, 19*(11), 31–41. https://doi.org/10.3991/ijoe.v19i11.39049

Azwar, S. (2012). *Reliabilitas dan validitas* (Edisi ke-4). Pustaka Pelajar.

Bancong, H., & Nanda, A. R. (2025). Designing and validating a virtual reality prototype for photoelectric effect experiments. *Physics Education, 60*(2), 1–13. https://doi.org/10.1088/1361-6552/adb08a

Bartošoviè, L. (2022). Virtual laboratory exercise as one of the forms of distance education at science universities. *AIP Conference Proceedings, 2458*(1). https://doi.org/10.1063/5.0078278

Bloom, B. S. (2014). *Taxonomy of educational objectives*. Longman.

Bogusevschi, D., Muntean, C. H., & Muntean, G. M. (2020). Teaching and learning physics using 3D virtual learning environment: A case study of combined virtual reality and virtual laboratory in secondary school. *Journal of Computers in Mathematics and Science Teaching, 39*(1), 5–18. https://doi.org/10.70725/297454nsjryb

Branch, R. M. (2010). *Instructional Design: The ADDIE Approach*. https://doi.org/10.1007/978-0-387-09506-6

Canright, J. P., & Brahmia, S. W. (2021). Developing expertlike epistemologies about physics empirical discovery using virtual reality. *Physics Education Research Conference Proceedings,* 75–80. https://doi.org/10.1119/perc.2021.pr.Canright

Chandra, A. Y., Prasetyaningrum, P. T., Suria, O., Santosa, P. I., Nugroho, L. E., & Pratama, I. (2022). Evaluation user acceptance of mobile virtual reality application for English learning. *Proceedings of the 2022 1st International Conference on Information System and Information Technology (ICISIT)*, 283–288. https://doi.org/10.1109/ICISIT54091.2022.9872873

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative, and mixed methods approaches* (5th ed.). SAGE Publications.

Cunayah, C., & Irawan, E. I. (2018). *1700 plus bank soal fisika SMA/MA*. Yrama Widya.

Dekhkonova, O., & Yakubova, S. (2025). The role of virtual demonstration experiments in teaching the ideal gas law. *AIP Conference Proceedings*, *3268*(1). https://doi.org/10.1063/5.0258185

Dodevska, M., Zdravevski, E., Chorbev, I., Kostoska, M., Branco, F., Coelho, P. J., Pires, I. M., & Lameski, P. (2025). Virtual reality as a learning tool: Evaluating the use and effectiveness of simulation laboratories in educational settings. *Social Sciences & Humanities Open, 12*, 1–11. https://doi.org/10.1016/j.ssaho.2025.101742

Ferawati, F., Saputri, F. H., Stianingsih, L., Putri, E. U., Sofia, D., & Hanafri, M. I. (2024). Augmented reality game based learning: enhancing basic mathematics abilities for students with special needs. *Jurnal Pendidikan MIPA, 25*(3), 1378–1396. https://doi.org/10.23960/jpmipa/v25i3.pp1378-1396

Gavin Lai, N. Y., Wei, S., Halim, D., Fow, K.-L., Kang, H. S., & Yu, L. J. (2021). Why not more virtual reality in higher ed teaching and learning?. *Proceedings of the IEEE International Conference on Engineering, Technology and Education (TALE 2021)*, 248–254. https://doi.org/10.1109/TALE52509.2021.9678523

Girwidz, R., Theyßen, H., & Widenhorn, R. (2021). Experiments in physics teaching. *Challenges in physics education*, 269–296. https://doi.org/10.1007/978-3-030-87391-2_10

Halliday, D., & Resnick, R. (1970). *Fundamentals of physics*. John Wiley & Sons.

Hanam, E. S., Harling, V. N. V., Agustina, E. B., Budirohmi, A., Rismawati, E., Pada, S. S., Agustine, D., Afrida, J., Irvani, A. I., Arifuddin, W., Wijaya, D. E., Syarifuddin, S., & Puspitasari, N. S. (2024). *Elektron dalam Atom*. CV Mega Press Nusantara.

Huan, M., & Sanmugam, M. (2024). Unveiling the educational potential of virtual reality (VR) technology. *Integrating cutting-edge technology into the classroom,* 347–361. https://doi.org/10.4018/979-8-3693-3124-8.ch017

Ibirinde, T. O., Abiodun, P. O., Olude, A. I., Owolabi, O. A., & Koissi, N. (2024). Enhancing chemistry undergraduates' peer learning collaboration and curiosity through hands-on pedagogy. *ASEE Annual Conference and Exposition, Conference Proceedings*. https://doi.org/10.18260/1-2—47301

Kamajaya. (2007). *Cerdas belajar fisika untuk kelas XII Sekolah Menengah Atas/ Madrasah Aliyah*. Grafindo Media Pratama.

Kolb, D. A. (1984). *Experiential learning: Experience as the source of learning and development*. Prentice Hall.

Menchafou, Y., Aaboud, M., & Chekour, M. (2023). Effectiveness of real and computer-assisted experimental activities in Moroccan secondary school physics education. *International Journal of Interactive Mobile Technologies, 17*(16), 16–29. https://doi.org/10.3991/ijim.v17i16.39267

Mowbray, T. (2020). From virtual to reality: A practical guide to creating educational virtual reality content. *Tertiary online teaching and learning: TOTAL perspectives and resources for digital education,* 87–10. https://doi.org/10.1007/978-981-15-8928-7_8

Omar, M. A. (2023). The epistemological limitations of scientific inquiry: Crucial experiments revisited. *Research Journal in Advanced Humanities, 4*(3), 489–502. https://doi.org/10.58256/rjah.v4i3.1188

Retnawati, H. (2016). *Analisis kuantitatif instrumen penelitian*. Parama Publishing.

Riduwan. (2010). *Belajar mudah penelitian untuk guru, karyawan, dan peneliti pemula*. Alfabeta.

Rosmaria, R., & Heryani, N. (2024). Development of multimedia learning based on digital virtual reality to improve students' skills in delivery service. *Health Education and Health Promotion, 12*(2), 189–195. https://hehp.modares.ac.ir/browse.php?a_id=72945&sid=5&slc_lang=en&html=1

Serevina, V., & Kirana, D. (2021). The development of virtual laboratory assisted by flash and PhET to support distance learning. *Journal of Physics: Conference Series, 2019*(1), 1–5. https://doi.org/10.1088/1742-6596/2019/1/012030

Shepa, M. J., Serevina, V., & Astra, I. M. (2021). Development of virtual reality-based learning media on electromagnetic wave radiation material. *Journal of Physics: Conference Series, 1876*(1), 1–10. https://doi.org/10.1088/1742-6596/1876/1/012088

Sibomana, A., Nicol, C. B., Nzabalirwa, W., Nsanganwimana, F., Karegeya, C., & Sentongo, J. (2021). Factors affecting the achievement of twelve-year basic students in mathematics and science in Rwanda. *International Journal of Learning, Teaching and Educational Research, 20*(7), 61–84. https://doi.org/10.26803/IJLTER.20.7.4

Sümer, M., & Vanìèek, D. (2022). What previous research says about virtual and augmented reality in higher education. *Proceedings of the European Conference on e-Learning (ECEL 2022), 21*(1), 406-409. https://doi.org/10.34190/ecel.21.1.884

Tatira, B., & Mshanelo, T. (2024). The impact of virtual laboratories on the academic performance of grade 12 learners in impulse and momentum. *Edelweiss Applied Science and Technology, 8*(6), 4150–4157. https://doi.org/10.55214/25768484.v8i6.2909

Triejunita, C. N., Putri, A., & Rosmansyah, Y. (2021). A systematic literature review on virtual laboratory for learning. *Proceedings of the 2021 International Conference on Data and Software Engineering (ICoDSE, 2021),* 1–6. https://doi.org/10.1109/ICoDSE53690.2021.9648451

Vergara, D., Extremera, J., Rubio, M. P., & Dávila, L. P. (2020). The proliferation of virtual laboratories in educational fields. *Advances in Distributed Computing and Artificial Intelligence Journal, 9*(1), 85–97. https://doi.org/10.14201/ADCAIJ2020918597

Vlachos, I., Stylos, G., & Kotsis, K. T. (2024). Primary school teachers' attitudes towards experimentation in physics teaching. *European Journal of Science and Mathematics Education, 12*(1), 60–70. https://doi.org/10.30935/scimath/13830

Wang, C. H. (2025). Education in the metaverse: Developing virtual reality teaching materials for K–12 natural science. *Education and Information Technologies, 30*(7), 8637–8658. https://doi.org/10.1007/s10639-024-13156-2

Wang, Y., Zhang, L., & Pang, M. (2025). Virtual experiments in physics education: A systematic literature review. *Research in Science and Technological Education, 43*(2), 633–655. https://doi.org/10.1080/02635143.2024.2327995

Waworuntu, F., Tuerah, J. M., Saiya, S. M. T. A., Paat, V., & Rumengan, S. (2024). Uji validitas sebagai penentuan kualitas butir soal pilihan ganda "Pacu Kimia" FMIPAK Unima. *Oxygenius: Journal of Chemistry Education, 6*(1), 29–38. https://doi.org/10.37033/ojce.v6i1.680

Xi, W. (2024). Virtual reality integration in teaching practices for enhanced learning experiences. *Proceedings of the 2024 IEEE 4th International Conference on Electronic Communications, Internet of Things and Big Data (ICEIB 2024),* 650–653. https://doi.org/10.1109/ICEIB61477.2024.10602565