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COMPARING 3D VIRTUAL LABS AND TRADITIONAL LABS: IMPACT ON TEACHER TRAINING AND STUDENT LEARNING IN PHYSICS EDUCATION

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ABSTRACT

Experiments are fundamental to physics education but are often hindered by resource constraints. This study investigates the effectiveness of teacher training using 3D Virtual Labs (3DVL) compared to Traditional Labs (TL) in teaching the electron charge-to-mass ratio (e/m). The research aimed to quantitatively compare the impact of these methods on teachers' and students' conceptual understanding, critical thinking, and experimental skills. A quasi-experimental design was employed involving 32 teachers and 131 students, utilizing a pre-test/post-test comparison structure. Teachers received training in either 3DVL or TL methods before applying the instruction in their classrooms. The results indicate that both 3DVL and TL groups improved significantly ($p < .001$) in conceptual mastery and problem-solving abilities. While no statistically significant difference was observed between the groups' overall post-test scores, TL showed a slight advantage in problem-solving, whereas 3DVL was associated with higher student confidence and perceived experimental skill improvement. These findings suggest that 3DVL is a viable, cost-effective alternative to traditional equipment. The study concludes that integrating virtual simulations can effectively overcome infrastructure limitations and enhance learning outcomes in resource-constrained settings.

Keywords: 3D virtual labs; Physics education; conceptual understanding; critical thinking; experimental skills

INTRODUCTION

Experiments are a cornerstone of physics education, essential for helping students grasp abstract concepts through practical application (Swarat et al., 2012; Roberts et al., 2018). Traditionally, hands-on experiments foster engagement and scientific literacy. However, the implementation of these laboratories often faces significant hurdles, including inadequate facilities, high equipment costs, and safety concerns, particularly in resource-constrained schools (Grivokostopoulou et al., 2020; Milner-Bolotin et al., 2021; Rodrigues & Carvalho, 2022). These limitations can hinder students from observing phenomena directly, often leaving them struggling to comprehend complex concepts—such as the electron charge-to-mass ratio (e/m)—which are mathematically intensive and counterintuitive (Niu et al., 2019; Saputra & Mustika, 2022; Otero et al., 2023). The difficulty in visualizing microscopic phenomena necessitates effective pedagogical tools to bridge the abstract-concrete gap (Argaw et al., 2017; Zhang et al., 2024)

In response to these challenges, 3D Virtual Laboratories (3DVL) have emerged as a promising alternative. Literature suggests that virtual simulations can improve accessibility and provi-

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de safe, interactive environments for students to visualize unobservable phenomena (Chen et al., 2010; Elmoazen et al., 2023; Asencios-Trujillo et al., 2024). The use of virtual experiments, including videos and simulations, provides flexibility and opportunities for repeated practice not available in traditional settings(Velentzas et al., 2024). While some studies indicate that combining real and virtual labs enhances learning outcomes (Kapici et al., 2019; Raman et al., 2022), others suggest that virtual labs alone can be as effective as traditional methods for certain learning goals(Falode & Onasanya, 2015; Ranjan, 2017; Safaryan, 2023). However, the current body of research often focuses on general outcomes, and there is debate regarding whether virtual labs can fully replace the tactile learning experience of physical equipment in developing problem-solving and experimental skills (Oser & Fraser, 2015; Ratamun & Osman, 2018).

Despite the growing adoption of virtual tools, a significant gap remains in understanding the specific efficacy of teacher training using 3DVL compared to Traditional Labs (TL). Few studies have quantitatively isolated the impact of the training method itself on teachers' conceptual mastery and the subsequent transfer of that knowledge to students, specifically for abstract topics like e/m. Furthermore, existing research often conflates critical thinking with general problem-solving, lacking precise comparisons of how 3DVL versus TL influences specific scientific process skills in resource-constrained settings.

Therefore, this study aims to: Quantitatively compare the effectiveness of teacher training using 3D Virtual Labs versus Traditional Labs in improving conceptual understanding and problem-solving skills; andAssess the impact of these distinct training methods on student engagement and perceived experimental skills.

Research Question: How does teacher training using 3D Virtual Labs compare to Traditional Labs in improving teachers' and students' conceptual understanding of the electron charge-to-mass ratio (e/m) and their problem-solving skills?

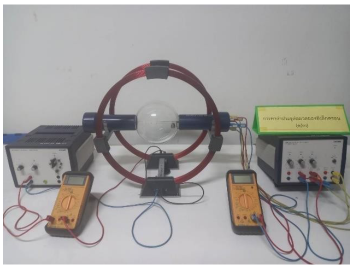
METHODS

This study utilized a quasi-experimental design employing a pre-test/post-test comparison group structure. This design was applied to evaluate the intervention's effects on both teacher and student outcomes, following established methodologies for evaluating educational interventions. The quasi-experimental design was chosen due to the practical constraints of conducting randomized controlled trials in educational settings.

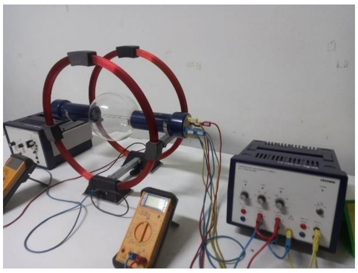
The participants included 32 physics teachers who were randomly divided into two groups: a 3D Virtual Lab (3DVL) training group and a Traditional Lab training group. Each group received a total of 4 hours of dedicated training on their respective lab format. Following the training phase, five teachers from each group voluntarily applied their newly acquired knowledge in classroom instruction, teaching 10–12 students per class to maintain a structured learning environment. A total of 131 students participated, with 67 students being taught by teachers trained in 3DVL and 64 students being taught by traditionally trained teachers (The slight numerical difference between the student groups (67 in 3DVL vs. 64 in Traditional) arose because student recruitment was based on voluntary participation within the existing school networks of the participating teachers. This approach was taken to ensure students remained within their established peer groups and typical classroom settings, thus preserving a natural and comfortable learning environment. The research team determined that this minor imbalance (a difference of only 3 students) would not introduce statistically significant bias into the study outcomes)".This study was conducted in accordance with the Declaration of Helsinki and received ethical approval from the Surindra Rajabhat University Human Research Ethics Committee (approval number HE 651004). All teachers and students provided written informed consent prior to participation, confirming their understanding of human research ethics.

The experiment was to verify the charge-mass ratio (Niu et al., 2019) of an electron which introduced participants to an image of how electrons were accelerated into the magnetic field created using a set of Helmholtz coils. The participants were observing the electrons' circular paths in a uniform magnetic field. When an electron moved in a magnetic field and a direction at right angles to the field, they were acted on by a force of magnitude F in newton's given by $F = evB$ where B is the magnetic field strength in Tesla (Webers/m^2), e is the magnitude of the charge on the electron in coulombs (C) and v is the speed of the electron in meter·second-1(m/s).

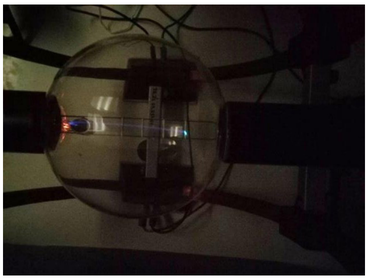
Traditional Laboratory (TL): Students interacted with physical apparatus, including a narrow beam tube, Helmholtz coils, and high-voltage power supplies. Students were required to manually connect circuits, adjust voltage to vary the electron beam radius, and use digital multimeters to record current and voltage data (Figure 1).



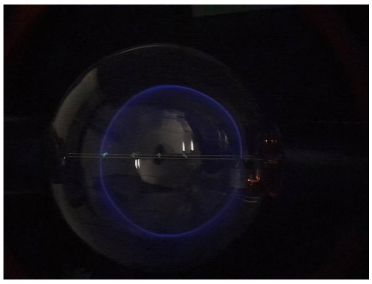
a. Specific Charge of the Electron Equipment (front view)



b. Specific Charge of the Electron Equipment (side view)



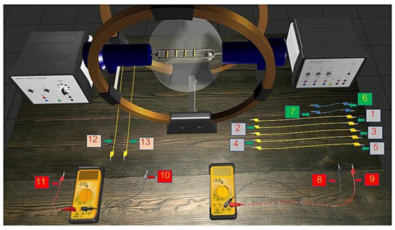
c. The Electron Beam Moving Circularly in the Magnetic Fields (top view)



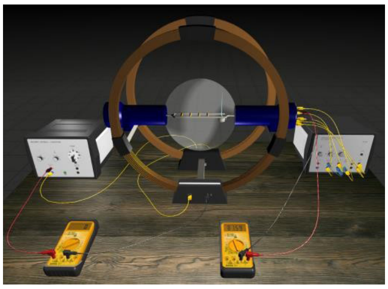
d. The Electron Beam Moving Circularly in the Magnetic Fields (side view)

Figure 1. The TL of the Specific Charge of the Electron

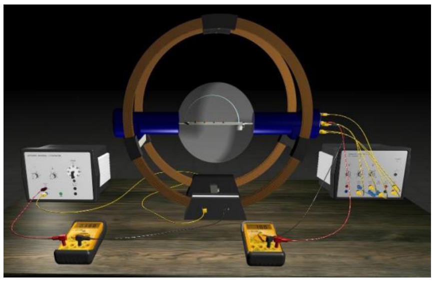
3D Virtual Laboratory (3DVL): Developed using Fusion 360, 3DMax, and ActionScript3, the 3DVL provided a high-fidelity digital twin of the traditional setup. Rather than a passive video, the 3DVL offered a fully interactive simulation where students could manipulate 3D objects, adjust virtual power supplies, and observe real-time changes in the electron beam's trajectory. The simulation was coded to replicate physical laws, ensuring that variables such as magnetic field intensity and electron deviation responded exactly as they would in the physical lab (Figure 2).



a. 3DVL of Specific Charge of the Electron Equipment (the top view)



b. The Electron Beam Moving Without the Magnetic Fields (3DVL)



c. The Electron Beam Moving Circularly in the Magnetic Fields (3DVL)

Figure 2. The 3DVL of the Specific Charge of the Electron

The study was conducted in three distinct phases as illustrated in the flowchart above (Figure 3):

1. Training Phase: Teachers were randomized into 3DVL or TL groups and underwent a 4-hour training session on the technical and pedagogical implementation of their assigned format. Both groups completed the PhyTCUT as a pre-test.

2. Implementation Phase: Selected teachers delivered the electron charge-to-mass ratio curriculum to their students over a period of 2 weeks (6 hours). This included lecture instruction followed by the designated laboratory activity (3DVL or TL).

3. Assessment and Crossover: Immediately following instruction, students completed the post-test battery (STCUT, STPSS, STEXSS, STEXST). Subsequently, a crossover phase was implemented where teachers swapped training methods. This allowed all teachers to experience both modalities, enabling a comparative evaluation for the Teacher Perception Survey.

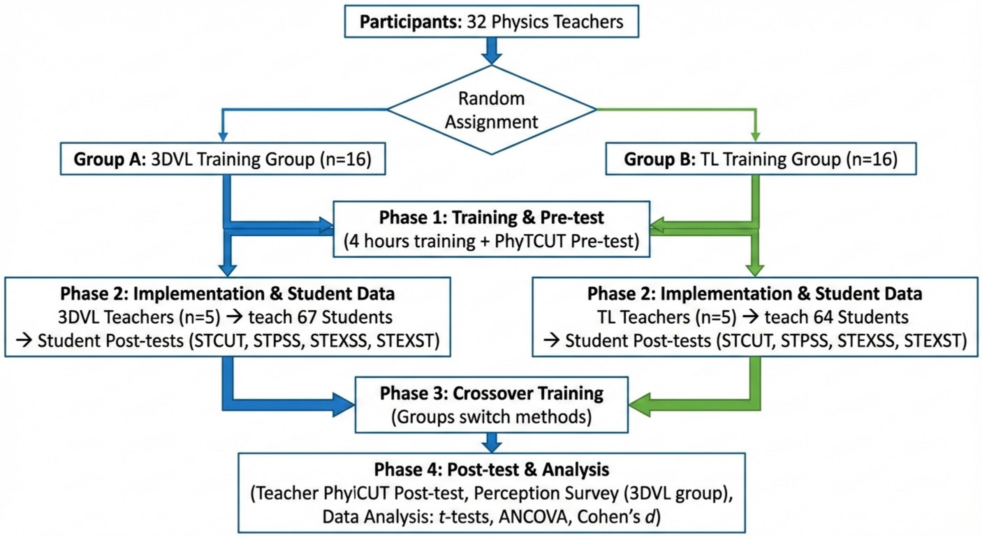


Figure 3. The Research Flowchart

To ensure robust measurement of outcomes, five validated instruments were utilized.

1). Physics Teacher Conceptual Understanding Test (PhyTCUT): A 9-item instrument (max score = 36) assessing teachers' mastery of electron dynamics and magnetic fields. Face validity was established by physics education experts. (Reliability = 0.805).

2).Student Conceptual Understanding Test (STCUT): Identical to the PhyTCUT, this tool measured student concept attainment, allowing for direct teacher-student comparison. (Reliability = 0.805).

3).Student Problem-Solving Skills Test (STPSS): A 5-item assessment (max score = 20) evaluating students' ability to apply physics principles to novel scenarios. Questions required students to identify variables, select appropriate equations, and calculate unknowns. Scoring was based on a validated rubric assessing problem identification, planning, and execution. (Reliability = 0.812).

4). Student Experiment Skills (STEXSS & STEXST):

4a. Self-Reported (STEXSS): An 11-item Likert-scale survey where students rated their confidence in skills such as equipment setup, data recording, and error analysis. (Reliability = 0.854).

4b. Teacher-Reported (STEXST): A 10-item

observational rubric where teachers objectively scored student proficiency in handling apparatus (virtual or physical) and executing experimental procedures. (Reliability = 0.899).

5).Teacher Perception Survey on 3DVL: A 10-item Likert-scale survey administered after the crossover phase to assess perceived utility, student engagement, and ease of use compared to traditional labs.

Data analysis was conducted using SPSS version 27 with a significance level of $p < .05$.

Descriptive Statistics: Means and standard deviations were calculated for all variables.

Comparative Analysis: To address the reviewer's concern regarding cluster effects and pre-existing differences, a one-way Analysis of Covariance (ANCOVA) was employed to compare student outcomes (STCUT, STPSS) between groups, using pre-test scores as the covariate.

Effect Size: To determine the magnitude of the intervention's impact, Cohen's d was calculated for all significant differences, where 0.2, 0.5, and 0.8 represent small, medium, and large effects, respectively.

Paired t-tests: Were used to analyze within-group gains (Pre-test vs. Post-test) for both teachers and students.

RESULTS AND DISCUSSION

The Paired Samples Test indicated that both the Control and Experimental groups showed significant improvements ($p < .001$) in conceptual understanding of e/m after training (Table 1).

Table 1. Paired Samples Test results of PhyTCUT,STCUT,STPSS, STEXSS and STEXST of the Specific Charge of the Electron (e/m) Between the Pre-Test and Post-Test for the Control and Experimental Groups

			Paired Differences				**t**	**df**		**Sig. (2-tailed)**
			Mean	**N**	**Std**	**95% Confidence Interval of the Difference**		**Lower**	**Up-per**	
PhyT-CUT	Con	Post	23.25	16	5.066	15.016	20.484	13.836	15	.000
		Pre	5.50	16	2.875					
	Ex	Post	22.88	16	8.024	15.141	20.984	13.177	15	.000
		Pre	4.81	16	3.291					
STCUT	Con	Pre	3.54	35	2.559	-7.621	-5.579	-13.136	34	.000
		Post	10.14	35	4.081					
	Ex	Pre	3.73	37	3.115	-7.265	-5.167	-12.020	36	.000
		Post	9.95	37	4.801					
STPSS	Con	Pre	2.16	62	2.002	5.606	7.426	14.316	61	.000
		Post	8.68	62	2.647					
	Ex	Pre	1.85	65	1.787	5.690	7.294	16.174	64	.000
		Post	8.34	65	2.819					
STEXS	Con	Pre	10.05	40	3.328					
(Self Report)		Post	18.00	40	4.255	6.665	9.235	12.511	39	.000
	Ex	Pre	9.31	54	4.193					
		Post	19.22	54	4.223	9.113	10.701	25.026	53	.000
STEXS	Ex	Post	23.60	40	6.279					
(Teacher Report)	Con	Post	24.48	40	3.328					

The Experimental group (3DVL-trained teachers) grained a slightly higher post-test mean (M = 22.88, SD = 8.024) compared to the Control group (M = 23.25, SD = 5.066), though the difference in raw scores was small. A ceiling effect was observed among teachers who had higher initial understanding, while those with lower pre-test scores benefited the most (Figure 4). To rigorously compare the effectiveness of the two interventions while controlling for initial differences in prior knowledge, ANCOVA was performed, using the pre-test score as the covariate and post-test score as the dependent variable.

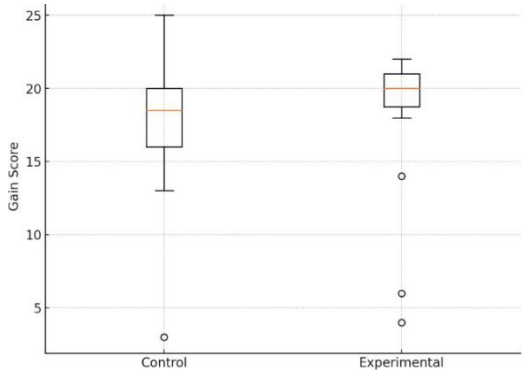


Figure 4. Gain Score of Physics Teachers' Conceptual Understanding

The ANCOVA results indicate that the difference in post-test scores between the groups was not statistically significant ($F(1, 29) = 0.094$, $p = 0.761$) (Table 2). The effect size was negligible ($d = -0.06$). This suggests that both 3D Virtual Labs and Traditional Labs were equally effective in enhancing teachers' conceptual understanding, reinforcing the idea that virtual labs can serve as an effective alternative, but not necessarily a superior replacement, for traditional hands-on training.

Table 2. Summary of Statistical Comparison Between 3DVL and Traditional Lab (TL) Groups (Post-Test)

Outcome Measure	Group Means (Post-Test)		ANCOVA/t-test Results
	3DVL	TL	$F(df, df_{error})$, p /t(df), p
PhyTCUT	M = 22.88	M = 23.25	F(1, 29) = 0.094, p = 0.761
STCUT	M = 9.95	M = 10.14	F(1, 69) = 0.325, p = 0.570
STPSS	M = 8.34	M = 8.68	F(1, 124) = 0.837, p = 0.362
STEXSS	M = 19.22	M = 18.00	F(1, 91) = 6.541, p = 0.012
STEXST	M = 23.60	M = 24.48	t(78) = **-0.884**, p = 0.380[a]

[a] Independent Samples t-test was used due to the absence of pre-test score.

The Paired Samples Test confirmed that both groups of students significantly improved in conceptual understanding ($p < .001$), with the Experimental group ($M = 9.95$, $SD = 4.801$) and Control group ($M = 10.14$, $SD = 4.081$) achieving similar raw post-test results. The box plot analysis of student conceptual understanding gain scores (Figure 5) also indicated similar median learning improvements. The ANCOVA, controlling for the pre-test score, further confirmed this finding, showing no statistically significant difference between the 3DVL and TL groups in post-test scores ($F(1, 69) = 0.325$, $p = 0.570$). The effect size was negligible ($d = -0.04$). Although both instructional methods were equally effective in improving conceptual understanding, the Experimental group exhibited more high-value outliers, suggesting that some students benefited significantly more from virtual lab instruction, possibly due to increased engagement or enhanced visualization.

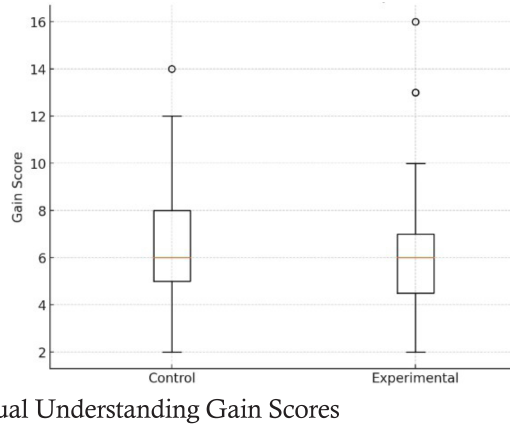


Figure 5. Student Conceptual Understanding Gain Scores

The results for student problem-solving skills (Figure 6) indicate that both groups exhibited significant improvements ($p < .001$). The Control group (M = 8.68, SD = 2.647) had a slightly higher raw post-test mean than the Experimental group (M = 8.34, SD = 2.819).The ANCOVA, controlling for pre-test scores, supports this finding of equivalence, showing no statistically significant difference in problem-solving skills between groups ($F(1, 124) = 0.837$, $p = 0.362$). The effect size was negligible ($d = -0.15$). This suggests that both instructional methods were equally effective overall, and any marginal raw score advantage for the Traditional Lab instruction in problem-solving skill development was not statistically meaningful after accounting for initial differences

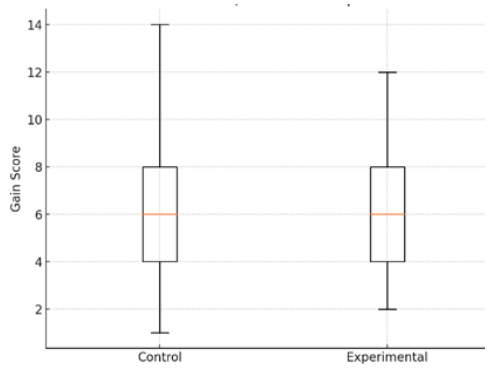


Figure 6. Student Problem-Solving Skills Gain Score

The self-reported experiment skills analysis (Figure 7) suggests that both groups achieved similar median learning improvements, with the Paired Samples Test confirming a statistically significant improvement ($p < .001$) for both. The Experimental group (M = 19.22, SD = 4.223) reported higher raw post-test scores than the Control group (M = 18.00, SD = 4.255). Importantly, ANCOVA, controlling for baseline experimental skills , revealed a statistically significant difference between the groups, favoring the 3DVL Experimental group ($F(1, 91) = 6.541$, $p = 0.012$). The effect size, though small, was positive ($d = 0.29$). This result is stronger than the previous t-test, indicating that once students' initial self-reported skills are accounted for, those trained by teachers using 3DVL perceived significantly greater improvements in their experimental skills. This perceived advantage is likely due to the enhanced visualization and interactivity of the virtual lab.

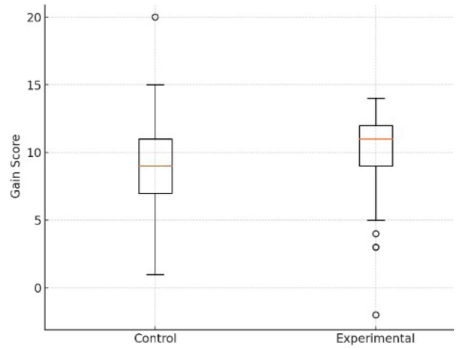


Figure 7. Students' Experiment Skills score – Self- Reported

The teacher-reported experiment skills assessment (Figure 8) reveals that both groups exhibited comparable median scores, with the Paired Samples Test showing significant improvement ($p < .001$) for both. The raw post-test means were M = 23.60 (Experimental) and M = 24.48 (Control). Because pre-test data was not available for this measure, an Independent Samples t-test was conducted on the post-test scores. The test confirmed no statistically significant difference in teacher-assessed experiment skills ($t(78) = -0.884$, $p = 0.380$). The effect size was negligible ($d = -0.20$). This suggests that while 3DVL provided a viable alternative to TL, the teachers evaluating students based on classroom observations and lab reports did not perceive a significant difference in skill development between the two methods.

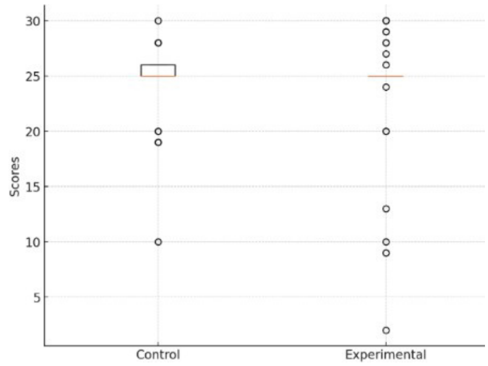


Figure.8 Students' Experiment Skills – Teacher-Reported

While statistical analysis confirms that both 3DVL and TL significantly enhance conceptual understanding and problem-solving skills, qualitative insights from teachers provide additional context regarding the effectiveness of 3DVL in classroom implementation. Teachers provided their feedback after undergoing training in both methods, ensuring their evaluations reflected direct comparisons rather than one-sided experiences. They highlighted multiple benefits of 3DVL, emphasizing its ability to enhance student engagement and motivation, improve conceptual visualization of complex topics, and provide greater accessibility, flexibility, and cost- effectiveness. These advantages suggest that 3DVL serves as an effective instructional tool in physics education by bridging theoretical knowledge with interactive learning experiences. Table 3 summarizes the key factors influencing the successful integration of 3DVL, reinforcing its role in modernizing science education while addressing practical constraints such as resource availability and cost limitations. Teachers also noted key external factors influencing the successful implementation of 3DVL, including:

Availability of high-performance computer equipment to support 3D simulations

Institutional support from school administrators and faculty

Prior foundational knowledge among students, which aids in the effective use of virtual labs

Table 3. Factors Supporting the Success of 3DVL According to Teacher Feedback

Factor	Mean	SD	Impact Level
Enhances direct experiential learning for students	4.86	0.35	Very High
Provides an innovative and engaging learning experience	4.86	0.35	Very High
Stimulates curiosity and motivation for learning	4.68	0.48	Very High
Facilitates long-term knowledge retention	4.73	0.46	Very High
Aligns with curriculum objectives and learning goals	4.68	0.57	Very High
Offers flexibility in learning (reduces time/location constraints)	4.73	0.46	Very High
Reduces costs relate d to laboratory equipment	4.59	0.67	Very High
Allows students to learn independently at their own pace	4.73	0.55	Very High
Bridges abstract concepts with real-world applications	4.73	0.46	Very High
Encourages interactive, student-led learning	4.77	0.43	Very High

The findings of the present study offer mixed, yet crucial, evidence regarding the comparative efficacy of the custom-built 3D Virtual Lab versus the Traditional Lab approach, particularly when accounting for baseline knowledge. For the three core measures of cognitive achievement—teacher conceptual understanding (PhyTCUT), student conceptual understanding (STCUT), and student problem-solving skills (STPSS)—the ANCOVA consistently showed no statistically significant differences between the 3DVL and TL groups (Table 2). The effect sizes were negligible (Cohen's d -0.15). This robust finding demonstrates that, from a cognitive achievement standpoint, the 3DVL is an effective alternative to traditional hands-on instruction, producing comparable learning gains and supporting existing research on virtual lab equivalence (Brinson, 2017; Fadda et al., 2022). Several meta-analyses confirm this equivalency across different STEM disciplines, particularly for knowledge acquisition (Liu et al., 2015; Heradio et al., 2016). .This suggests that the core principles of effective experimental pedagogy, rather than the physical medium, are the primary drivers of cognitive improvement.

The most critical finding lies in the analysis of student experimental skills, where a distinct difference emerged between student self-perception and teacher observation.

Superior Self-Efficacy with 3DVL: The ANCOVA for Student Experiment Skills – Self-Reported (STEXSS), controlling for pre-test scores, revealed a statistically significant advantage favoring the 3DVL group ($F(1, 91) = 6.541$, $p = 0.012$). With a small-to-medium positive effect size ($d = 0.29$), this result is the study's strongest evidence that the 3DVL intervention significantly enhanced students' self-efficacy and confidence in their experimental skills. This aligns with literature suggesting that virtual labs promote confidence and engagement due to their risk-free, repeatable, and visually enhanced nature (Shieh & Chang, 2014;

Smith & Holmes, 2020; Alhashem & Alfailakawi, 2023). Specifically, the sense of control and lack of real-world consequences in a virtual setting boosts self-regulation and motivation (Alnaser & Forawi, 2024; Lopes et al., 2024).

Lack of Validation in Teacher Report (STEXST): Conversely, the Teacher-Reported Experiment Skills showed no statistically significant difference between groups ($t(78) = -0.884$, $p = 0.380$), with a negligible effect size ($d = -0.20$). This discrepancy, highlighted when comparing Figure 7 (Self-Report) and Figure 8 (Teacher-Report), is central to the study's interpretation. It suggests that while the immersive environment of the 3DVL positively influenced student motivation and self-perception, these gains did not fully translate into observable, externally validated improvements in experimental competence as judged by the teachers. Possible reasons include:

Skill Transfer Deficit: The hands-on complexity of manipulating real-world equipment, which teachers observed, may not be fully replicated in the virtual environment. While virtual labs are excellent for conceptualization, the gap in psychomotor skill development remains a known challenge (Gumilar & Trisnowati, 2018; Sanzana et al., 2024). Bridging the gap between conceptual understanding fostered in simulations and practical execution in the lab is a persistent area of concern in physics education research(Smith et al., 2020)

Assessment Misalignment: Teacher-reported assessment criteria may emphasize physical dexterity or real-world problem-solving not captured by the self-report tool. The reliance on standardized rubrics in teacher assessment may not fully credit the procedural understanding gained in the virtual space (Al-Salmani & Thacker, 2021; Geschwind et al., 2024).

Self-Report Inflation: Students' confidence may be inflated due to the low-stakes, repeatable nature of the virtual lab, which is a potential side effect of virtual environments. This disconnect between perceived and actual learning outcomes is a recognized issue in studies evaluating novel educational technology (Arora & Chauhan, 2021; Williams, 2018)

While the ANCOVA strengthened the causal inference by rigorously controlling for pretest differences (thus justifying the design switch from simple t-tests), the study's cluster-randomized design warrants discussion of internal validity threats.

Firstly, the data may contain unaddressed cluster effects, as student outcomes within the same class (cluster) are not truly independent. This potentially inflates the degrees of freedom for student measures. Secondly, the influence of teacher differences cannot be fully discounted. The non-significant cognitive outcomes across groups, however, mitigate the impact of confounding variables such as general teacher quality. Finally, the potential placebo effect of the novel 3DVL—where teacher enthusiasm or student novelty preference temporarily boosts performance or self-report—must be considered. Recent studies emphasize the need to control for this Hawthorne effect, particularly in high-engagement virtual environments (Widiasih et al., 2025). The fact that the positive effects were limited to self-report (STEXSS) and did not transfer to objective cognitive measures (STCUT, STPSS) or external validation (STEXST) suggests that the novelty effect primarily impacted affective outcomes (motivation and confidence) rather than deep cognitive learning.

The evaluation of the novel, custom-built 3DVL is a key feature of this research. This tool was specifically designed to overcome practical limitations of the traditional e/m lab, such as limited equipment availability, high risk of damage, and restrictions on independent exploration. The 3DVL achieves this by allowing unlimited, risk-free repetitions of the experiment, thereby incentivizing student exploration and discovery. This ability to facilitate repetition without resource constraints is a primary benefit over traditional labs (Daineko et al., 2015; Bogusevschi & Muntean, 2020).

Qualitative feedback confirmed the value of this bespoke approach. Teachers provided strong support for the 3DVL, highlighting its ability to stimulate curiosity, motivation, and conceptual visualization (Table 3, M 4.68). Crucially, teachers noted the significant practical advantage of reducing costs and providing a viable option for schools with limited resources (M = 4.59). This overwhelmingly positive perception underscores the potential of purpose-built virtual labs to address resource constraints in science education(Nkwande et al., 2024).

The findings indicate that 3DVL offers an equivalent learning platform for core cognitive skills and a superior platform for fostering student self-efficacy in experimental skills. Therefore, 3DVL should not be considered a direct replacement, but rather an essential component of a hybrid approach (Darrah et al., 2014; Nathaniel, 2016; Brinson, 2017; Sypsas & Kalles, 2018; Sarapak, Sukman, et al., 2022; Sarapak, Surat, et al., 2022). A blended methodology is crucial for bridging the theory-practice gap and maximizing problem-solving outcomes (Hidaayatullaah et al., 2020; Pal & Rinki, 2022). A blended methodology—combining the cost-effectiveness, accessibility, and motivational power of 3DVL with the development of physical skills provided by traditional experiences—is likely to maximize student learning outcomes. This is supported by evidence that hybrid models outperform either single modality alone in complex tasks (Mahfudin et al., 2021; Usman et al., 2021). Future research should focus on developing assessment tools that bridge the gap between virtual self-efficacy and real-world performance.

CONCLUSION

This study compared the effectiveness of teacher training using 3D Virtual Labs (3DVL) versus Traditional Labs (TL) on the conceptual understanding of the electron charge-to-mass ratio (e/m). The findings indicate that while both instructional methods led to statistically significant improvements in learning outcomes ($p < .001$) compared to baseline, there was no statistically significant difference in the overall posttest scores between the two groups. This suggests that 3DVL is a pedagogically viable alternative to traditional equipment for fostering conceptual mastery in resource-constrained settings. However, nuances in the data reveal that while 3DVL excelled in building student confidence and engagement, TL retained a slight edge in developing specific psychomotor and instrumentation skills. These findings contribute empirical evidence supporting the strategic integration of virtual laboratories in physics teacher training, particularly in resource-limited educational contexts. Several limitations should be considered when interpreting these results. First, the study employed a quasi-experimental design where teachers were randomized, but students remained in their existing class cohorts, introducing potential cluster bias. Second, the assessment of problem-solving and experimental skills relied partially on self-reported data, which may be subject to social desirability bias compared to direct observational assessment. Third, the small sample size (N=131) limits the generalizability of the findings and the statistical power to detect smaller effect sizes between the interventions. Future studies should aim for larger, fully randomized samples to calculate more robust effect sizes and control for classroom-level variables. The study supports a "hybrid" or "preconditioning" model for physics education. 3DVL as Preconditioning: Educators should utilize 3D Virtual Labs as a preparatory tool to familiarize students with experimental procedures and safety protocols before they enter the physical laboratory. This maximizes the efficiency of limited hands-on time. Role of Traditional Labs: TL remains superior for developing fine motor skills and tactile familiarity with instrumentation (e.g., cabling, multimeter adjustments). Therefore, 3DVL should not entirely replace TL but rather supplement it. Schools can implement the 3DVL module described (requiring only standard PCs and no specialized physics hardware) to bridge the gap in schools where the cost of high-voltage power supplies and Helmholtz coils is prohibitive.

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