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Research Article

Beyond the Physical Laboratory: Evaluating PhET Interactive Simulations for Physics Concept Learning Among STEM Students

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ABSTRACT

Laboratory experiences hold an important place in science education, playing the part of a bridge between abstract scientific concepts and observations and experiments. However, the lack of laboratory facilities, equipment, and resources restricts the opportunity to carry out worthwhile learning. The objective of this research was to find out if Physics Education Technology (PhET) Interactive Simulations are effective as an auxiliary tool for science laboratory activities for Grade 12 STEM students. The research employed a quasi-experimental pre-test-posttest control group design, which included 60 participants from 2 intact classes: 30 for control and 30 for experimental groups respectively. Participants were chosen purposefully and matched in their age, gender, and General Physics 2 grades. A validated 40-question achievement test was utilized with the Cronbach's alpha coefficient at the level of 0.8784. The control group used standard laboratory experiences while the experimental group was engaged with PhET Interactive Simulations. The main findings showed no significant difference between the groups at the pretest stage ($M=20.30$ and 21.00 ; $t=0.550$). Both groups improved significantly upon finishing the instruction: however, the experimental group achieved a far greater posttest mean ($M=33.70$, $SD=2.91$) than the control group ($M=29.67$, $SD=2.89$). Furthermore, 80% of the participants from the experimental group achieved Very Good performance, while only 33.33% did in the control group. The results of the research suggest that laboratory instruction supported by PhET is effective in students' education.

Keywords: *Conceptual Understanding, General Physics 2, Phet Interactive Simulations, STEM Education, Virtual Laboratory*

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Introduction

Laboratory work connects abstract scientific concepts with observation, experimentation, and evidence. Gericke et al. (2023) reviewed laboratory work in secondary school science education, providing a relevant foundation for examining laboratory instruction among Grade 12 STEM students. In the present study, conceptual understanding refers specifically to achievement on selected General Physics 2 concepts.

Laboratory activities can provide opportunities to manipulate variables, examine relationships, and revise explanations. These opportunities underpin the study's use of constructivist and inquiry-based principles: learners actively test ideas and interpret feedback rather than only receive information.

Physical laboratories require equipment, consumables, space, and safety provisions. Insufficient resources may restrict opportunities for hands-on investigation. Reviews of virtual laboratories discuss their potential as complementary learning environments, although findings from undergraduate science and chemistry contexts require careful application to senior high school physics (Chan et al., 2021; Reeves & Crippen, 2021).

Virtual laboratories and digital simulations offer opportunities to manipulate variables and observe processes. Zhang et al. (2021) reviewed virtual physiology laboratories, while Chan et al. (2021) examined virtual chemical laboratories. These reviews inform the broader rationale for virtual experimentation, but neither directly establishes effectiveness for Grade 12 General Physics 2 learners.

PhET Interactive Simulations allow learners to explore representations of physical phenomena and receive immediate feedback. Within the study's constructivist and inquiry-based rationale, variable manipulation and interpretation of simulation outcomes may help students revise their conceptual explanations. Banda and Nzabahimana (2021) reviewed literature on PhET and physics conceptual understanding; their work is a literature review, rather than a single qualitative experiment. Kefalis et al. (2025) synthesized recent empirical research on digital simulations in STEM education and identified inquiry-based learning

as a common instructional approach. Together, these sources support investigating guided simulation activities while recognizing that outcomes depend on instructional design and context.

Evidence of conceptual learning does not establish that simulations develop practical laboratory skills equally well. Reviews identify limitations in the evidence on skill-based outcomes and emphasize instructional support (Chan et al., 2021; Reeves & Crippen, 2021; Zhang et al., 2021). Harahap et al. (2025) provide a bibliometric analysis of PhET research; this maps research activity and should not be treated as direct evidence of an intervention's causal effectiveness. Gan et al. (2026), in a systematic review of rural STEM interventions, offer broader context on technology and access, rather than a direct test of PhET in this urban senior high school. These recent syntheses inform the study's rationale while preserving the distinction between research trends, empirical learning outcomes, and the local intervention evaluated here.

Although prior studies examine simulations across different disciplines and educational levels, context-specific evidence is needed for Grade 12 STEM students studying General Physics 2. The present study compares PhET-supported laboratory instruction with conventional laboratory activities in two intact senior high school classes at the University of Cebu Main Campus. The comparison concerns conceptual achievement on selected topics; it does not directly assess practical laboratory competence.

This need is especially urgent for the present educational context that has noted the opportunities provided by technology for work in a laboratory without the need to use real materials and deal with scheduling constraints in laboratory work. Hence, the question is not whether technology can replace real physical laboratories completely, but how effective computer-based learning sources can be in implementing the goals of lab-oriented scientific learning. By establishing such evidence, it is expected that this may influence science teachers to make better decisions in terms of the correct application of virtual experimentation in laboratory learning and provide schools with the

option of giving students an opportunity to learn about scientific concepts if there are not enough laboratory facilities available.

The study aimed to evaluate PhET Interactive Simulations as a support for laboratory instruction among Grade 12 STEM students at the University of Cebu Main Campus Senior High School Department. It compared pretest and posttest achievement in control and experimental groups using a quasi-experimental design. The study examined whether posttest performance differed between the groups, while recognizing the limits of causal inference from intact classes.

Methodology

Research Design

The study used a quasi-experimental pretest-posttest control group design involving intact Grade 12 STEM classes. Students were not randomly assigned to instructional conditions. This design permits comparisons in an existing classroom setting, but matching on observed characteristics does not eliminate unmeasured differences between classes. El Khammari and Hasnaoui (2025) provide broader context on evaluating educational programs in secondary schools.

The participants of the study included a total of 60 Grade 12 STEM students studying at the University of Cebu Main Campus Senior High School Department in Cebu City, Philippines, where 30 students from Grade 12 STEM 4P formed the experimental group and another 30 students from Grade 12 STEM 1A comprised the control group. The students were purposely chosen and matched based on age, gender, and third quarter grades in General Physics 2 so as to ensure the baseline comparability of the two groups under study.

A researcher-made 40 item multiple-choice achievement test on electric charge, Coulomb law, electric field, and electric flux was used as pretest and posttest. The instrument was made to be in line with the K-12 General Physics 2 competencies through the Table of Specifications for the instrument to be validated by the General Physics teachers. Pilot testing was done on students outside the groups under study and yielded a Cronbach alpha of 0.8784 which indicates satisfactory internal

consistency. Cronbach's alpha provides an estimate of internal consistency for multi-item instruments (Tavakol & Dennick, 2011).

Data Collection Procedures

Before collecting the data, permission to conduct the study was secured from the University of Cebu Main Campus Senior High School Department. The achievement test was pilot tested first on the students from one STEM section that was not part of the study. After establishing the reliability of the instrument, the researchers matched the grades, age and gender for the participants. The same 40 item pretest was used for both groups so as to ensure the baseline performance of both groups studied.

The instruction received by the two groups was the same in terms of the General Physics 2 topics taught but differed in laboratory teaching methods. The control group conducted its laboratory activities through the use of available materials and equipment. The experimental group, however, used the PhET Interactive Simulations using laptops to engage with concepts such as electric charges, movement of various particles and forces of either attraction or repulsion. According to Banda and Nzabahimana (2021), PhET simulation provided interactive representations for manipulation of different variables to observe the relationships among concepts in physics. After the intervention has taken place, the same test was used as a posttest for both groups, where the scores from the tests were verified and prepared for analysis.

Data Analysis and Interpretation

Data collected from the pretest and posttest scores were analyzed using different statistical procedures including the use of frequency, percentage, mean, and standard deviation in order to find the performance of both the groups. The interpretation also involved the classification of scores as very good (31-40), good (21-30), fair (11-20), and poor (0-10).

Frequencies, percentages, means, and standard deviations summarized performance. Independent-samples t-tests compared the groups at pretest and posttest; paired-samples t-tests evaluated pretest-to-posttest change

within each group. The significance level was $\alpha = .05$. The paired tests do not test a between-group difference in gains, and the posttest comparison does not constitute a baseline-adjusted treatment-effect estimate. No difference-in-differences or analysis of covariance result is reported.

Effect of the Intervention

Table 1. Pretest Results of Control and Experimental Groups

Score Range	Description	Control f	Control %	Experimental f	Experimental %
31 – 40	Very Good	0	0.00	0	0.00
21 – 30	Good	13	43.33	14	46.67
11 – 20	Fair	17	36.67	16	33.33
1 – 10	Poor	0	0.00	0	0.00
Total		30	100.00	30	100.00
Mean		20.30		21.00	
SD		4.82		3.04	

As shown in Table 1, both groups have performed similarly before the implementation of the program. In the control group, 56.67% have achieved Fair and 43.33% have got good grades and in the experimental group, 53.33% have got Fair and 46.67% Good grades. Both groups had no students who achieved Excellent or Poor score. As for the mean score, it was 20.30 (SD = 4.82) for the control group and 21.00 (SD = 5.04) for the experimental group.

This shows that the two groups commenced the program with roughly similar knowledge of Physics concepts covered in the current research. The fact that we got the baseline results

Results and Discussion

This section examines the findings on the use of PhET Interactive Simulations in science laboratory activities for students in Grade 12 STEM. The data has been presented according to the questions asked in the study and analyzed accordingly.

is particularly significant from the point of view of quasi-experimental studies since it gives a starting point for later comparisons. The fact that both groups have achieved quite similar results makes the comparison more meaningful.

The groups had similar observed pretest performance on the assessed General Physics 2 concepts. These baseline scores provide a starting point for interpreting subsequent achievement, although they do not demonstrate equivalence on unmeasured characteristics (Kusuma & Redhana, 2025; Zhang et al., 2021).

Results of Study Group After the Intervention

Table 2. Posttest Performance of the Control and Experimental Groups

Score Range	Description	Control f	Control %	Experimental f	Experimental %
31 – 40	Very Good	10	33.33	24	80.00
21 – 30	Good	20	66.67	6	20.00
11 – 20	Fair	0	0.00	0	0.00
1 – 10	Poor	0	0.00	0	0.00
Total		30	100	30	100.00
Mean		29.67		33.70	
SD		2.89		2.91	

As indicated in Table 2, both groups performed better after training. More precisely, the distribution of the ratings was different. For example, only 33.33% of participants from the control group achieved a Very Good score,

while 80% of the participants from the experimental group met this requirement. Furthermore, the experimental group had higher mean scores than the control group (M = 33.70, SD = 2.91 vs. M = 29.67, SD = 2.89, respectively).

It can be noted that both conventional laboratory instructions and PhET-supported instructions resulted in the students learning something about the subject. Nevertheless, students in the experimental group gained more knowledge than the others. Probably, this benefit is connected to the fact that those who were provided with PhET had opportunities to conduct experiments using simulations and be in control of the changes in the variables, as well as observe the results of their actions. Banda and Nzabahimana (2021) confirmed that PhET-supported instruction can improve the students' conceptual understanding of physics.

This conclusion aligns with other studies related to virtual laboratories. Specifically, Chan et al. (2021) showed that virtual laboratories give the results like real laboratories, if specific conditions are met. Zhang et al. (2021) also reviewed evidence on learning with virtual laboratories. This finding shows that PhET can provide an effective technology-supported environment for learning scientific concepts better. Nevertheless, it should be noted that the results of the post-testing should be regarded as obtaining knowledge regarding the items on a 40-item test.

Baseline Comparison Among the Study Groups

Table 3. Comparison of Pretest Outcomes of the Experimental Groups and Control Groups

Group	Mean	t-Computed	t-Critical	Decision on H_0	Interpretation
Control	20.30	0.550	2.002	Fail to Reject H_0	Not Significant
Experimental	21.00				

According to the information in Table 3, the mean pretest score of the control group is 20.30, and the mean pretest score of the experimental group is 21.00. The calculated value of $t=0.550$ is less than t critical = 2.002. Thus, the null hypothesis is retained, meaning that pretest performances of both groups do not differ significantly. The finding supports the statistical description derived from Table 2 and confirms that both groups are similar in terms of their achievements measured at baseline. The significant absence of the difference before the experiment brings the probability of the influence of one group on the results of the posttest

lower. The significance of establishing the similarity of the groups at the beginning of the study increases the plausibility of conclusions made based on the differences found at later stages of the research (Shaluhayah et al., 2025).

However, achieving the baseline equivalence in achievement should not be considered the proof of the complete equivalence between the groups. The formation of existing class groups may mean that there are other qualities of the students obtained through their training and education that can vary from one group to another.

Changes in Performance Following the Intervention

Table 4. Differences Between the Pretest and Posttest Performance of the Control and Experimental Groups

Group	Test	Mean	t-Computed	t-Critical	Decision on H_0	Interpretation
Control	Pretest	20.30	12.469	2.045	Reject H_0	Significant
	Posttest	29.67				
Experimental	Pretest	21.00	18.017	2.045	Reject H_0	Significant
	Posttest	33.70				

Table 4 provides information on how the control and experimental groups performed before and after the intervention. The table indicates improvement in both groups. In the control group, the mean score increased from 20.30 in the pretest to 29.67 in the posttest (t -

computed = 12.469 > t -critical = 2.045). Similarly, the experimental group also showed improvement, as the mean score increased from 21.00 to 33.70 (t -computed = 18.017 > t -critical = 2.045). Thus, H_0 was rejected in both cases.

These findings show that both methods of instruction had a strong effect on performance. The fact that there was an increase in the control group means that standard lab activities were effective in helping learners. On the other hand, the experimental group increased its raw mean score by 12.70, while the raw mean score in the control group increased only by 9.37. This means that PhET is much more effective.

The pattern is consistent with the literature reviewed by Banda and Nzabahimana (2021) on PhET and physics conceptual understanding. Reviews of virtual laboratory research also inform possible opportunities for repeated

experimentation and variable manipulation (Chan et al., 2021; Wang et al., 2025). These proposed mechanisms were not separately measured in the present study.

However, it is important to note that higher raw score of the experimental group cannot be interpreted as a statistical difference between the two groups, as the paired t-tests used in the table are meant to check if the groups improved separately, but not whether improvement was statistically different in both groups. A better comparison for the PhET group will be provided by the posttest comparison presented in Table 5.

Post Intervention Comparison Between the Study Group

Table 5. Difference in the Posttest Performance of the Control and Experimental Groups

Group	Mean	t-Computed	t-Critical	Decision on H_0	Interpretation
Control	29.67	5.380	2.002	Reject H_0	Significant
Experimental	33.70				

Table 5 presents the key data comparing the effectiveness of the usage of PhET-supported teaching methods. The experimental group resulted in the average posttest score of 33.70, while the control group gained 29.67. The computed t-value of 5.380 is greater than the critical value of 2.002 meaning the null hypothesis should be rejected. Therefore, there is a statistically significant difference in the posttest results between the two groups.

The finding is consistent with the literature review by Banda and Nzabahimana (2021) and the broader systematic review of digital simulations by Kefalis et al. (2025). Reviews in chemistry and physiology provide additional context for virtual experimentation, but their disciplinary settings differ from the present physics intervention (Chan et al., 2021; Zhang et al., 2021).

The obtained results correspond to the findings of Banda and Nzabahimana (2021). Their meta-analysis of numerous studies has provided supporting evidence that PhET simulations support conceptual understanding of Physics (Alhusni et al., 2025). The results also correspond to the previous studies that state the use of virtual laboratories helps students gain conceptual understanding by manipulating the variable and conducting experiments (Winkelmann et al., 2021; Zhang et al., 2021).

However, still, the finding can be interpreted in a way that takes into consideration the fact that the study was quasi-experimental. Since the entire classes were involved in the study, rather than letting some participants be selected at random, then those results provide sufficient evidence that PhET as a method is effective in teaching, but further studies are needed to identify all causal connections between the use of PhET-supported method and the effect it had.

Combining the data one can see the same pattern of using PhET Interactive Simulations in laboratory teaching. It can be stated that the groups had almost the same pretest performance but ended up showing the same tendency for the strong posttest performance. However, the results in terms of the experimental group were higher since 80.00% of its members were at least Very Good in their performance in the posttest compared to only one-third of participants in the control group. This explanation correlates with structural evidence that favors simulation-based discovery (Banda & Nzabahimana, 2021; Winkelmann et al., 2021; Zhang et al., 2021). Therefore, it can be argued that PhET Interactive Simulations are a successful way to support students' understanding of General Physics 2 topics. Nevertheless, further studies are necessary to address

the issues of developing laboratory skills, motivational attitudes, scientific views, and knowledge retention because the instruments measuring such concepts do not exist (Gan et al., 2026; Meronda et al., 2025).

Conclusion

The purpose of this research was to investigate the utility of PhET Interactive Simulations as a technology-based technique for science laboratory work among Grade 12 STEM learners. The researchers applied a quasi-experimental pretest-posttest control group scheme which contrasted the results of students taking part in regular laboratory work with those receiving PhET-assisted laboratory instruction for selected concepts in General Physics 2.

Both groups improved in achievement, and the experimental group obtained a significantly higher reported posttest mean than the control group. The findings are consistent with a benefit of PhET-supported instruction for the selected General Physics 2 concepts. Similar observed pretest performance strengthens the comparison, but nonrandom assignment and intact-class differences prevent attributing the entire posttest gap solely to PhET.

The results lead to the conclusion that PhET Interactive Simulations may be regarded as a useful addition to teachers' arsenal while having to teach General Physics 2. The fact that the simulations facilitate interaction, variable manipulation, practice of several experiments, and direct observation of the interrelations make them indispensable where delivering abstract messages is quite difficult or where access to laboratory supplies is limited. The results do not give any evidence supporting the idea that PhET should substitute regular laboratory work since the simulations should be used as additional material to supplement laboratory instruction.

Teachers may consider integrating PhET simulations with guided laboratory instruction for relevant General Physics 2 topics. The study is limited to a 40-item achievement test administered to 60 Grade 12 STEM students in two intact classes at one institution. Potential selection bias, selection-maturation interactions, diffusion of treatment, testing effects, and classroom clustering constrain causal

inference and generalizability. Larger studies involving multiple classes, stronger allocation procedures, and baseline-adjusted analyses are needed to estimate the contribution of PhET more precisely.

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