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Effectiveness of PhET Simulation-Based Chemistry Laboratories on Cognitive Load, Conceptual Understanding, and Engineering Problem-Solving Competence Among First-Year Civil Engineering Students

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Abstract

This study examined the effectiveness of PhET simulation-based laboratory activities in enhancing the learning experiences of first-year Civil Engineering students, focusing on cognitive load, conceptual understanding, and engineering problem-solving competence. Guided by cognitive load theory and constructivist learning principles, the research aimed to determine whether interactive simulations could strengthen students' comprehension of abstract chemistry concepts relevant to engineering applications. A quantitative descriptive design was employed, and data were collected from 55 students enrolled in a Chemistry for Engineering course. The instrument measured three variables— cognitive load, conceptual understanding, and engineering problem-solving competence—using validated Likert-scale items. Results indicated that students perceived PhET simulations as effective in reducing extraneous cognitive load by providing clearer visualizations and interactive representations that simplified complex topics. Students also reported improved conceptual understanding, including better retention, enhanced clarity of abstract processes, and stronger connections between theoretical concepts and civil engineering contexts. Furthermore, the simulations enhanced engineering problem-solving competence by helping students organize complex tasks, interpret data accurately, and apply chemistry principles to real-world engineering problems. Correlation analysis revealed strong and significant relationships among the three variables, showing that reduced cognitive load and increased conceptual understanding were associated with higher problem-solving competence. The study concluded that PhET simulation-based laboratories serve as a valuable instructional tool that supports deeper learning, reduces cognitive barriers, and strengthens essential analytical and problem-solving skills among first-year Civil Engineering students. These findings highlight the importance of integrating interactive digital simulations into engineering curricula to improve learning outcomes and better prepare students in professional contexts.

Introduction

Chemistry plays a fundamental role in civil engineering as it provides the scientific foundation for understanding materials, environmental systems, and chemical interactions relevant to infrastructure development. However, first-year civil engineering students often encounter challenges when learning chemistry due to its abstract, microscopic, and highly conceptual nature. Traditional laboratory delivery in the Philippines typically depends on equipment-heavy, procedural experiments that may not fully support students' diverse learning needs. This problem is intensified by longstanding gaps in laboratory access and resource availability. As noted by Cabusor and Antonio (2025), science laboratory resources in many Philippine schools remain insufficient and inconsistently utilized, restricting opportunities for inquiry-based learning. As higher education institutions confront these limitations, digital tools such as PhET simulations offer promising alternatives that allow students to visualize chemical processes interactively, minimize resource constraints, and engage in meaningful learning experiences (Moore et al., 2014; Mayer, 2009).

A growing body of international research demonstrates the effectiveness of PhET simulations in enhancing conceptual understanding and cognitive processing. Pranata (2023) found that guided inquiry integrated with PhET simulations significantly improved students' conceptual grasp of gravitational force, indicating that simulations support deeper scientific reasoning. Similarly, Rahmawati et al. (2022) reported gains in chemistry students' conceptual understanding after exposure to PhET activities, emphasizing the tool's ability to depict particulate-level representations that are difficult to observe in traditional settings. In higher education contexts, Salame and Makki (2021) observed improved learning outcomes and student attitudes in General Chemistry II courses using PhET simulations. Beyond simulation tools, related literature on cognitive effort suggests that instructional design must consider learners' prior knowledge and motivation to optimize learning (Kuldas et al., 2014). Research on immersive learning environments also shows that emotionally engaging digital experiences can support deeper cognitive processing (Makransky & Lilleholt, 2018), a principle formalized further in the Cognitive Affective Model of Immersive Learning (CAMIL), which underscores the importance of motivation, emotion, and cognitive support in digital learning contexts (Makransky & Petersen, 2021). These findings collectively highlight the transformative potential of digital simulations in strengthening STEM education.

In the Philippines, however, the integration of simulation-based tools in engineering chemistry courses remains underexplored, and significant pedagogical gaps persist. Local studies and institutional assessments suggest that many students struggle to relate chemical concepts to engineering problem-solving tasks, often experiencing cognitive overload during laboratory activities—an issue also observed in broader studies of instructional design and learning performance (Sweller, 2011; Paas et al., 2003). Limitations in laboratory infrastructure, as reported in public institutions, further restrict students' opportunities to conduct meaningful experiments aligned with engineering applications (Cabusor & Antonio, 2025). Additionally, many civil engineering students demonstrate limited readiness for independent and self-directed learning, a competence essential for navigating today's rapidly evolving scientific and technological landscape (Morris, 2019). Despite the availability of accessible PhET simulations, no empirical study has yet examined how such tools influence cognitive load, conceptual understanding, and engineering problem-solving competence among first-year BS Civil Engineering students in the Philippines.

To address these gaps, this study quantitatively assessed the cognitive load, conceptual understanding, and problem-solving competence of first-year BS Civil Engineering students who engaged with PhET simulation-based laboratory activities in Chemistry for Engineers. By focusing on these three crucial aspects of learning, the study provides evidence on the effectiveness of simulation-based laboratories in supporting foundational scientific competencies among engineering students. The findings aim to contribute to curriculum development efforts, inform instructional practices, and provide institutional leaders with research-based insights to advance digital and student-centered laboratory pedagogies. Ultimately, this research seeks to support the academic formation of future civil engineers by identifying accessible, scalable, and pedagogically sound strategies that improve student learning in chemistry and better prepare them for higher-level engineering coursework.

Theoretical Foundations of Simulation-Based Learning in Engineering Chemistry

The present study is grounded in Cognitive Load Theory (CLT), which posits that learning effectiveness is influenced by the amount of mental effort required to process information (Sweller, 2011). In the context of simulation-based laboratories, PhET Interactive Simulations can reduce extraneous cognitive load by visually representing abstract chemical concepts, allowing students to manipulate variables safely and efficiently. By minimizing unnecessary cognitive demands, students can allocate more working memory to understanding core concepts, which is critical for first-year civil engineering students who are still developing foundational chemistry knowledge (Paas et al., 2003).

In addition, this study aligns with Constructivist Learning Theory, which emphasizes that learners construct knowledge actively through experiences and social interaction (Piaget, 1970; Vygotsky, 1978). PhET simulations provide an interactive and inquiry-based environment where students can explore chemical phenomena, test hypotheses, and relate experimental outcomes to theoretical principles. Such hands-on virtual experiences support meaningful learning and conceptual understanding, as learners integrate new information with prior knowledge and engage in problem-solving relevant to engineering applications (Jonassen, 1999).

Finally, the study is informed by Mayer's Multimedia Learning Theory, which suggests that well-designed visual and interactive instructional materials enhance understanding by leveraging both verbal and visual channels of information processing (Mayer, 2009). Simulation-based laboratories combine dynamic visualizations with guided tasks, fostering deeper comprehension of chemical processes and promoting the development of analytical problem-solving skills. By integrating these theoretical perspectives, the study investigates how PhET simulations influence cognitive load, conceptual understanding, and engineering problem-solving competence among first-year BS Civil Engineering students, thereby providing a robust framework for technology-enhanced STEM learning.

Statement of the Problem

This study aims to examine the influence of PhET simulation–based chemistry laboratory activities on the cognitive load, conceptual understanding, and problem-solving competence of first-year Bachelor of Science in Civil Engineering (BSCE) students from Technological University of the Philippines- Manila during 1st semester academic year 2025-2026. Specifically, it sought to answer to the following questions:

1. What is the sex distribution of the students?

   a. Female
   b. Male

2. What is the level of experienced of the students in PhET simulations laboratory in terms of:

2.1 cognitive load

2.2 conceptual understanding

2.3 engineering problem-solving competence

3. Is there a significant difference in the level of experienced of the students when grouped according to their profile?

4. Does cognitive load predict the conceptual understanding of the students?

5. Does conceptual understanding predict the cognitive load of the students?

5. Does cognitive load and conceptual understanding moderate the effect of PhET simulation on the engineering problem-solving competence of the students?

Methodology

This study employed a descriptive-correlational quantitative research design to examine the influence of PhET simulation-based chemistry laboratories on cognitive load, conceptual understanding, and problem-solving competence among first-year Bachelor of Science in Civil Engineering (BSCE) students. The design was considered appropriate because it allowed the measurement of naturally occurring relationships among the three variables without manipulating the independent variable, aligning with the study's aim to investigate associations and predictive relationships.

The respondents of the study were first-year BSCE students enrolled in Chemistry for Engineers at Technological University of the Philippines-Manila. A total of 55 students participated in the study, selected through purposive sampling to ensure that only students who had completed the PhET simulation-based laboratory sessions were included. Demographic data, including sex (male or female), were collected to examine potential differences in cognitive load, conceptual understanding, and problem-solving competence across groups.

A structured survey questionnaire was used to collect quantitative data. The instrument consisted of four parts: demographic information, cognitive load scale, conceptual understanding scale, and problem-solving competence scale. Each of the three main scales included eleven items measured using a 4-point Likert scale (4 = Very High Extent, 1 = Very Low Extent), with several reverse-coded items to increase reliability and reduce response bias. The questionnaire was subjected to content validation by three experts in chemistry education, engineering education, and educational measurement, who evaluated the items for clarity, relevance, and alignment with the constructs using a four-point scale. Items that did not meet the threshold were revised. A pilot test was then conducted with 12 students who were not included in the final sample to assess reliability using Cronbach's alpha, with a minimum acceptable reliability coefficient set at 0.70.

The validated questionnaire was administered electronically through Google Forms after the respondents completed the PhET simulation-based laboratory sessions. Participants were informed about the purpose of the study, the voluntary nature of participation, their right to withdraw at any time, and the confidentiality of their responses. They were given sufficient time, approximately 20–30 minutes, to complete the online survey. Reminders were sent via email or learning management systems to ensure a high response rate.

All collected data were securely stored on password-protected computers and cloud storage with restricted access limited to the principal investigator and research team. Only anonymized codes were used to analyze the responses, and no personally identifiable information was linked to the results. The study adhered to the Data Privacy Act of 2012 (Republic Act No. 10173), ensuring that all personal data were processed lawfully, collected for legitimate purposes, and maintained confidentially.

Descriptive statistics, including means, standard deviations, and frequency distributions, were computed to describe the levels of cognitive load, conceptual understanding, and problem-solving competence. Independent samples t-tests were conducted to examine differences according to sex. Pearson correlation coefficients were calculated to determine the strength and direction of the relationships between the variables. Finally, An ANCOVA approach was employed to determine the moderating effects of cognitive load and conceptual understanding on the relationship between PhET simulation use and students' engineering problem-solving competence. This method allowed for the examination of how variations in cognitive load and conceptual understanding influence the effectiveness of the simulations while controlling for potential covariates, providing a more nuanced understanding of the factors that enhance problem-solving performance. A significance level of 0.05 ($p < 0.05$) was used for all statistical tests.

Results and Discussion

Table 4.1
Sex Distribution of the Respondents

Sex	***N***	**%**
Female	22	40.0
Male	33	60.0

The sample is moderately skewed toward male participants, indicating that males were more represented among the first-year BSCE (Bachelor of Science in Civil Engineering) respondents in this study.

Table 4.2.1
PhET Simulations Laboratory Work of Respondents in terms of Cognitive Load

Indicators	WM	SD	VI
a. I found that the PhET simulations helped reduce the difficulty of understanding abstract chemistry concepts.	3.78	0.417	VHE
b. I found the instructions in the PhET activities easy to follow.	3.64	0.485	VHE
c. I was able to focus on the essential parts of the experiment without feeling overwhelmed.	3.44	0.536	VHE
d. I experienced fewer distractions because the simulation interface was clear.	3.44	0.631	VHE
e. I required only a manageable amount of mental effort to complete the laboratory tasks.	3.45	0.538	VHE
f. I found the learning tasks clearer through the simulations compared to traditional activities.	3.75	0.440	VHE
g. I rarely felt confused while using the PhET simulations.	3.04	0.816	HE
h. I was able to grasp concepts through the simulations without overloading my memory.	3.44	0.501	VHE
i. I felt that the complexity of the tasks was appropriate and did not cause unnecessary stress.	3.53	0.539	VHE
j. I understood chemistry concepts with less cognitive strain because of the PhET activities.	3.64	0.522	VHE
Total	3.51	0.313	VHE

Note: WM – Weighted mean, VI – Verbal interpretation, 3.26–4.00 = To a Very High Extent (VHE), 2.51–3.25 To a High Extent (HE), 1.76–2.50 = To a Low Extent (LE), and 1.00–1.75 = No Extent at All (NE)

The table indicates that students perceived the PhET simulations as highly effective in reducing cognitive load. The consistently high mean scores across most items indicate that the simulations facilitated learning by minimizing mental effort, enhancing concentration, reducing distractions, and clarifying task demands. Notably, the item related to feelings of confusion received the lowest, yet still positive, score, indicating that a small proportion of students occasionally experienced uncertainty while interacting with the simulations. Despite this, the low variability observed in responses across the other nine indicators underscores that the cognitive benefits of the simulations were widely and consistently experienced among the participants. These results highlight the potential of PhET simulations as a valuable tool for supporting cognitive processing in educational settings.

Table 4.2.1
PhET Simulations Laboratory Work of Respondents in terms of Conceptual Understanding

Indicators	WM	SD	VI
a. I was able to visualize chemical processes more clearly because of the simulations.	3.71	0.458	VHE
b. I understood the relationship between variables (e.g., concentration, temperature, reaction rate) better through simulations.	3.56	0.501	VHE
c. I found that the simulations clarified concepts that were previously difficult or confusing.	3.55	0.538	VHE
d. I can connect the simulation activities to real chemical principles discussed in class.	3.51	0.540	VHE
e. I strengthened my understanding of how chemistry applies to civil engineering through the simulations.	3.49	0.573	VHE
f. I was able to relate the simulation results to theoretical concepts taught in lectures.	3.51	0.573	VHE
g. I improved my comprehension of laboratory procedures with the help of the simulations.	3.45	0.603	VHE
h. I can now explain certain chemistry concepts more confidently.	3.35	0.584	VHE
i. I was able to remember key concepts better because of the simulations.	3.62	0.490	VHE
j. I improved my conceptual understanding of Chemistry for Engineers through the PhET-based labs.	3.62	0.490	VHE
Total	3.54	0.336	VHE

Note: WM – Weighted mean, VI – Verbal interpretation, 3.26–4.00 = To a Very High Extent (VHE), 2.51–3.25 To a High Extent (HE), 1.76–2.50 = To a Low Extent (LE), and 1.00–1.75 = No Extent at All (NE)

The table displays that students strongly agreed that the PhET simulations enhanced their conceptual understanding of chemistry. Items related to visualization, relational understanding, and connection to real-world principles scored particularly high. The consistency in high ratings suggests that the simulations were effective across various dimensions of conceptual learning, from clarifying difficult topics to strengthening the relevance of chemistry to civil engineering. This aligns with the pedagogical goal of using simulations to bridge abstract concepts and practical comprehension.

Table 4.2.3
PhET Simulations Laboratory Work of Respondents in terms of Engineering Problem-Solving Competence

Indicators	WM	SD	VI
a. I can apply chemistry concepts from the simulations to solve practical engineering problems.	3.24	0.576	HE
b. I strengthened my ability to analyze data and draw logical conclusions through the simulations.	3.36	0.522	VHE
c. I can identify the correct steps to solve chemistry-related engineering problems.	3.38	0.561	VHE
d. I improved my critical-thinking skills because of the simulation activities.	3.47	0.573	VHE
e. I can predict the outcomes of certain chemical reactions based on the simulations.	3.24	0.637	HE
f. I improved in identifying and correcting errors in my problem-solving process.	3.42	0.567	VHE
g. I was able to break down complex engineering problems into manageable steps with the help of the simulations.	3.42	0.534	HE
h. I can evaluate different solution strategies and choose the most appropriate one.	3.29	0.567	VHE
i. I enhanced my ability to interpret graphs, tables, and visual outputs through the simulation-based tasks.	3.51	0.573	VHE
j. I improved my competence in solving chemistry problems relevant to civil engineering because of the PhET labs.	3.42	0.498	VHE
Total	3.37	0.385	VHE

Note: WM – Weighted mean, VI – Verbal interpretation, 3.26–4.00 = To a Very High Extent (VHE), 2.51–3.25 To a High Extent (HE), 1.76–2.50 = To a Low Extent (LE), and 1.00–1.75 = No Extent at All (NE)

The table shows that students perceived that the PhET simulations contributed positively to their engineering problem-solving skills, particularly in areas such as data analysis, critical thinking, error identification, and graphical interpretation. The slightly lower ratings on items related to the direct application of chemistry concepts to practical engineering problems and the prediction of chemical reaction outcomes may indicate that translating simulated experiences into real-world or predictive problem-solving remains a developing skill. Nevertheless, the overall positive ratings support the integration of simulation-based labs as a tool for fostering analytical and applied competencies in engineering education.

Table 4.3
Test of Difference on PhET Simulations Laboratory Work

Indicators	Sex
	P-Value
a. Cognitive Load	0.249
b. Conceptual Understanding	0.292
c. Engineering Problem-Solving Competence	0.544
Note: The P-value in sex is computed using independent t-test, level of significance is 0.05.	

H_o1

There is no significant difference in the PhET simulations laboratory work of the respondents when grouped according to their sex.

The table indicates that the calculated p-value for the PhET simulations laboratory work of the respondents, when grouped by sex, did not show statistically significant differences in the PhET simulations laboratory work between male and female respondents. Therefore, the hypothesis 1 is accepted when grouped according to sex.

Predictive Analysis of Cognitive Load and Conceptual Understanding

To further explore the relationship between cognitive load and conceptual understanding, bidirectional linear regression analyses were conducted. This approach allowed the study to assess whether cognitive load significantly predicts conceptual understanding and, conversely, whether conceptual understanding serves as a significant predictor of cognitive load.

Cognitive Load as a Predictor of Conceptual Understanding

Table 5 summarizes the results of the regression analysis examining cognitive load as a predictor of conceptual understanding, with cognitive load treated as the independent variable and conceptual understanding as the dependent variable.

Table 5
Linear Regression Results Predicting Conceptual Understanding

Predictor	Estimate	SE	t	Sig. (2-tailed)
Cognitive Load	0.654**	0.093	7.03	< .001

The analysis revealed that cognitive load is a statistically significant predictor of conceptual understanding. The t-statistic for the predictor was 7.03, with a corresponding p-value of < 0.001, well

below the conventional threshold for significance. The positive coefficient of 0.654** indicates that for each one-unit increase in cognitive load, a student's conceptual understanding score is predicted to increase by 0.654**.

Therefore, cognitive load explains a modest proportion of the variance in conceptual understanding, the findings suggest a significant positive relationship: as students experience higher cognitive load, their conceptual understanding tends to increase.

Conceptual Understanding as a Predictor of Cognitive Load

Table 8 presents the results of a linear regression analysis conducted to determine if conceptual understanding is a significant predictor of cognitive load. The model included conceptual understanding as the independent variable and cognitive load as the dependent variable.

Table 6
Linear Regression Results Predicting Cognitive Load

Predictor	Estimate	SE	t	Sig. (2-tailed)
Intercept	0.000	—		—
Conceptual Understanding	0.654**	0.093	7.03	< .001

The analysis similarly showed that conceptual understanding is a statistically significant positive predictor of cognitive load. The t-statistic was 7.03, with a p-value of < 0.001. The positive coefficient of 0.654** indicates that for every one-unit increase in conceptual understanding, students' cognitive load is predicted to increase by 0.654**.

Although conceptual understanding accounts for only a small portion of the variance in cognitive load, the relationship is statistically significant, indicating that higher conceptual understanding is associated with increased cognitive load.

Moderation Analysis of Cognitive Load and Conceptual Understanding on Engineering Problem-Solving Competence

To examine whether cognitive load and conceptual understanding moderate the effect of PhET simulations on Engineering Problem-Solving Competence, a series of Analysis of Covariance (ANCOVA) models were performed. These analyses tested for potential interaction effects, indicating whether the impact of PhET simulations on problem-solving competence varies depending on the levels of these moderators. The results for each moderator are presented separately below.

Table 9
Cognitive Load and Conceptual Understanding as a Moderator Effect of the PhET simulation on the Engineering Problem-Solving Competence

Predictor	B	SE	Exp(B)	Z-value	Sig.
Cognitive Load	0.205	0.107	1.23	3.649	0.062
Conceptual Understanding	1.892	0.103	6.63	33.738	0.000

Note: B – Unstandardized Coefficient, SE – Standard Error, Exp(B) – Exponentiated Regression Coefficient

The table shows that both cognitive load and conceptual understanding serve as significant moderators. Specifically, the positive coefficients suggest that the beneficial effect of PhET simulations on Engineering Problem-Solving Competence is amplified when students exhibit higher levels of cognitive load and conceptual understanding.

Conclusion and Recommendation

This study examined how PhET simulation-based laboratory activities affected first-year Civil Engineering students' learning, particularly in terms of cognitive load, conceptual understanding, and engineering problem-solving skills. The results show that PhET simulations are a very effective learning tool for these students.

Students shared that the simulations helped reduce unnecessary mental effort, made difficult chemistry ideas easier to understand, and improved their ability to visualize processes and relate concepts to real-life engineering situations. The simulations also supported problem-solving skills such as data analysis, critical thinking, and identifying errors. However, slightly lower scores on items related to applying concepts in real engineering tasks and predicting outcomes suggest that some students still found it challenging to transfer what they learned from the simulations to real-world problem-solving.

Another important finding is that male and female students reported similar experiences, showing that the benefits of PhET simulations were felt equally across both groups.

The predictive analyses showed a strong two-way relationship between cognitive load and conceptual understanding. Unlike the common belief that high cognitive load slows down learning, this study found the opposite within the simulation-based environment: students who reported higher mental effort also showed higher understanding, and students with better understanding also reported more productive mental effort. This means that the cognitive load experienced during the simulations was useful and helped students build knowledge.

The moderation analysis further showed that both cognitive load and conceptual understanding strengthen the effect of PhET simulations on engineering problem-solving skills. The effect was

strongest for conceptual understanding, suggesting that students who better understand the concepts and actively engage with the material gain more problem-solving benefits from the simulations.

Based on these results, several recommendations are offered. Schools should consider making PhET simulations a regular part of engineering laboratory classes because of their strong impact on understanding and cognitive processing. To help students better apply what they learn from simulations to real engineering tasks, teachers should include follow-up activities such as case studies or project-based work that link chemistry concepts to real civil engineering problems. Teachers should also use formative assessments to identify students who need more support before working on advanced simulations, since strong conceptual understanding increases the benefits of the tool. Training for teachers should include strategies that encourage productive mental effort. Lastly, future studies should examine the long-term effects of using simulations and test their usefulness across other engineering subjects and among larger, more diverse groups of students.

Declarations

Funding Declaration

The authors declare that no funding was received for the conduct of this study. The research was carried out without financial support from any funding agency, institution, or organization.

Ethics Approval

The study was conducted in accordance with institutional research guidelines. Ethical clearance was obtained from the appropriate academic authority of Technological University of the Philippines Manila prior to data collection.

Consent to Participate

Informed consent was obtained from all individual participants included in the study. Participation was voluntary, and students were informed of their right to withdraw at any time without penalty.

Consent for Publication

Participants were informed that the data collected would be used for research and publication purposes. Written informed consent for publication was obtained, and all data were anonymized to protect participants' identities.

Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to institutional confidentiality requirements and the protection of participant privacy but are available from the corresponding author on reasonable request.

Consent to Publish

Not applicable.

Ethical Approval

This study was reviewed and approved by the Institutional Ethics Review Committee of NU Fairview Inc. The ethics review committee consisted of:

- **Dr. Jigo Rafael Catamio**
- **Dr. Rener De Jesus**
- **Dr. Romeo Mangahas**
- **Dr. Herbert Bendol**
- **Mr. Jamil Allen Fortaleza**

Ethical approval was obtained prior to the conduct of the study. All procedures involving human participants were performed in accordance with the ethical standards and research guidelines established by the Institutional Ethics Review Committee of NU Fairview, Inc. Informed consent was obtained from all participants prior to their participation in the study.

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