



Enhancing Students' Conceptual Understanding of Elasticity and Hooke's Law Through PhET-Supported Guided Inquiry Learning: A Constructivist and Cognitive Load Perspective

Antonius Suban Hali^{1*}, Francisca R. H. Bokilia², Vinsensius Lantik¹, Amiruddin Supu¹, Markus Simeon K. Maubuthy¹

¹Program Studi Pendidikan Fisika, Universitas Nusa Cendana, Kupang, Indonesia.

²SMA Anugerah Kasih, Lembata, Indonesia.

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Corresponding Author:

Antonius Suban Hali

antonius.hali@staf.undana.ac.id

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Abstract: The rapid transformation of science education in the digital era calls for pedagogical innovations that promote deep conceptual understanding rather than rote memorization. This study aims to investigate the effect of integrating PhET interactive simulations into a guided inquiry learning model on students' conceptual understanding of elasticity and Hooke's Law. A quasi-experimental pretest-posttest control group design was employed with 55 eleventh-grade science students at SMA Frater Don Bosco Lewoleba, Indonesia. The experimental group experienced PhET-supported guided inquiry, while the control group received guided inquiry instruction with real demonstration tools. Statistical analysis revealed that students in the experimental group achieved significantly higher posttest scores than those in the control group ($t(53) = 2.89$, $p = 0.01$), with a medium-to-high effect size (Cohen's $d = 0.67$). The findings suggest that PhET interactive simulations function as cognitive scaffolds by visualizing abstract physical phenomena, reducing extraneous cognitive load, and supporting conceptual reconstruction during inquiry activities. These results highlight the pedagogical value of embedding digital simulations within inquiry-based physics instruction to enhance students' conceptual understanding and foster meaningful learning in abstract scientific domains.

Keywords: Cognitive load theory; Conceptual understanding; Constructivist; Elasticity; Guided inquiry; Hooke's law; PhET

Introduction

The digital transformation of education in the era of Industry 4.0 demands innovative pedagogical approaches that foster student-centered, interactive, and technology-integrated learning (Tytler, 2020). Physics, as an experimental and conceptual science, requires learning experiences that bridge theoretical understanding with empirical observation (Liew & Treagust, 2022). However, limited laboratory access and inadequate facilities often hinder effective physics learning in many Indonesian schools. These constraints highlight the importance of alternative learning

environments, such as virtual laboratories, that can simulate real-world phenomena in an interactive and accessible manner.

One promising solution is the use of PhET interactive simulations, which provide dynamic visualizations of abstract scientific concepts and allow learners to manipulate variables and observe causal relationships. Previous studies have demonstrated that PhET simulations can significantly enhance students' learning outcomes, conceptual understanding, and higher-order thinking skills (Hadi et al., 2023; Khairunnastuti et al., 2026; Mahzum et al., 2024; Marwanti et al., 2024). In addition, PhET-based virtual

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laboratories have been shown to support analytical reasoning, scientific literacy, and problem-solving skills by enabling students to actively engage with complex phenomena that are otherwise difficult to observe directly (Azizaturredha et al., 2019; Sukardiyono et al., 2025; Susilawati et al., 2022). These findings suggest that digital simulations can serve as powerful tools to bridge the gap between abstract theory and concrete understanding in physics learning.

To maximize their pedagogical potential, such simulations need to be integrated within appropriate instructional models. Guided inquiry learning, rooted in constructivist theory (Vygotsky, 1978), promotes active knowledge construction through questioning, exploring, and reasoning (Bybee et al., 2006; Chen & Chen, 2025). In this approach, students act as active problem-solvers, while teachers facilitate the learning process by guiding investigation and reflection (Sam, 2024). Empirical evidence indicates that inquiry-based learning can significantly improve students' conceptual understanding, critical thinking, and scientific skills (Adaayah & Aznam, 2024; Becker et al., 2020; Kousloglou et al., 2023; Srisawasdi & Panjaburee, 2019; Tawfik et al., 2020; Wale & Bishaw, 2020; Zourmpakis et al., 2024). Furthermore, the integration of inquiry models with PhET simulations has been shown to produce more effective learning outcomes compared to conventional approaches, particularly in enhancing students' motivation and conceptual mastery (Pratiwi et al., 2025)

From a cognitive perspective, learning physics often imposes a high cognitive load due to the abstract and symbolic nature of its concepts. Cognitive Load Theory suggests that effective instructional design should minimize extraneous cognitive load while optimizing germane load to support schema construction (Mayer, 2020; Sweller, 2011, 2020). Interactive simulations such as PhET can reduce unnecessary cognitive burden by providing visual representations and immediate feedback, enabling learner to manipulate variables, thereby facilitating deeper conceptual processing (Mahzum et al., 2024; Perkins et al., 2006; Wieman et al., 2008). Such integration is particularly relevant for learning topics such as elasticity and Hooke's Law, where students often struggle to interpret the relationship between force and extension (Kurnaz & Arslan, 2021; Ma'ruf, 2024; Rafiah & Miyaqi, 2025).

Although previous studies have shown that PhET can improve students' performance in physics, limited research has examined their integration within guided inquiry learning specifically in the context of elasticity while simultaneously considering constructivist and cognitive perspectives.

This study advances the current literature by integrating three theoretical lenses, constructivism, the

inquiry learning cycle, and cognitive load theory, to explain the effect of PhET-assisted guided inquiry learning. The distinctive contribution of this study lies in explaining how digital simulations may function as cognitive scaffolds that reduce extraneous cognitive load and facilitate deeper engagement in the inquiry process. Specifically, this study investigates the extent to which PhET-assisted guided inquiry enhances students' conceptual understanding of elasticity and Hooke's Law. It also examines how constructivist and cognitive load principles may explain the observed improvement in learning outcomes.

Method

This study was conducted at SMAS Frater Don Bosco Lewoleba. The research employed a quasi-experimental nonequivalent control group pretest-posttest design (Fraenkel et al., 2012), in which intact classes were assigned as experimental and control groups. A purposive sampling technique was used based on administrative and scheduling considerations. The participants consisted of Grade 11 Natural Science 1 students (n = 28) assigned as the experimental group (EG) and Grade 11 Natural Science 2 students (n = 27) assigned as the control group (CG). The experimental group received guided inquiry supported by PhET simulations, while the control group engaged in guided inquiry through hands-on experimental activities using real laboratory apparatus.

Table 1. Research design

Pretest	Treatment	Posttest
O ₁	X _a	O ₂
O ₁	X _b	O ₂

Description:
 O₁ = Pretest
 O₂ = Posttest
 X_a = Experimental group
 X_b = Control group

The data collected consisted of quantitative data (pretest and posttest scores) and qualitative data obtained through structured classroom observation sheets. In alignment with constructivist principles, qualitative evidence of students' knowledge construction was documented through systematic observations of inquiry-based activities, analysis of students' worksheet responses, and records of their participation during PhET-mediated explorations. These observation sheets captured students' engagement in the inquiry phases without relying on numerical rating scales, allowing the analysis to focus on the nature and quality of their learning behaviors.

Students' conceptual understanding was assessed using a 14-item test on elasticity and Hooke's Law developed specifically for this study. The items consist of five indicators: concept explanation (CE), evaluates students' ability to articulate the fundamental ideas of elasticity, describe the meaning of Hooke's Law, and express the physical significance of variables; graphical interpretation (GI), assesses students' capacity to identify appropriate force-extension graphs and to interpret the slope of the graph as the spring constant; problem-solving with conceptual reasoning (PS), measures students' ability to apply conceptual knowledge to novel situations and to justify solutions through coherent reasoning rather than mere formula substitution; predictive and hypothetical reasoning (PHR), captures students' ability to anticipate how changes in system variables, such as mass, force, or spring constant, affect observable outcomes; and evidence-based explanation (EBE), examines students' ability to support their conceptual claims using data derived from PhET simulations or hands-on experimental observations. The distribution of items was as follows: CE (3 items), GI (3 items), PS (3 items), PHR (2 items), and EBE (3 items)

The instrument was validated by three physics education experts using a 4-point relevance scale, resulting in a Scale-level Content Validity Index (S-CVI) of 0.89. Reliability testing using Cronbach's Alpha yielded $\alpha = 0.82$, indicating good internal consistency.

Quantitative data were analyzed using SPSS 22. Normality (Shapiro-Wilk test) and homogeneity (Levene's test) assumptions were satisfied. Independent sample t-tests were used to examine differences between the two groups, and Cohen's d was calculated to determine effect size. Qualitative data from observation sheets and student worksheets were analyzed

descriptively to contextualize and support the quantitative findings.

Result and Discussion

Initial Conceptual Understanding Test Results

Students' initial conceptual understanding refers to their level of understanding prior to receiving instruction through the guided inquiry learning model. The comparison of each indicator is presented in Figure 1. Overall, the results indicate that the experimental group's mean pretest score ($M = 42.60$, $SD = 9.22$) was nearly identical to that of the control group ($M = 42.59$, $SD = 9.18$).

Based on the Shapiro-Wilk normality test conducted using SPSS v.25, the experimental group obtained a significance value of 0.08, while the control group obtained a significance value of 0.07. Since both p-values exceed 0.05, the pretest data for both groups can be considered normally distributed. The histogram of the normality test results is presented in Figure 2.

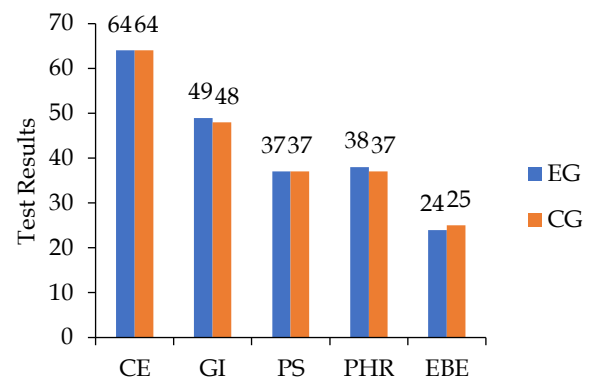
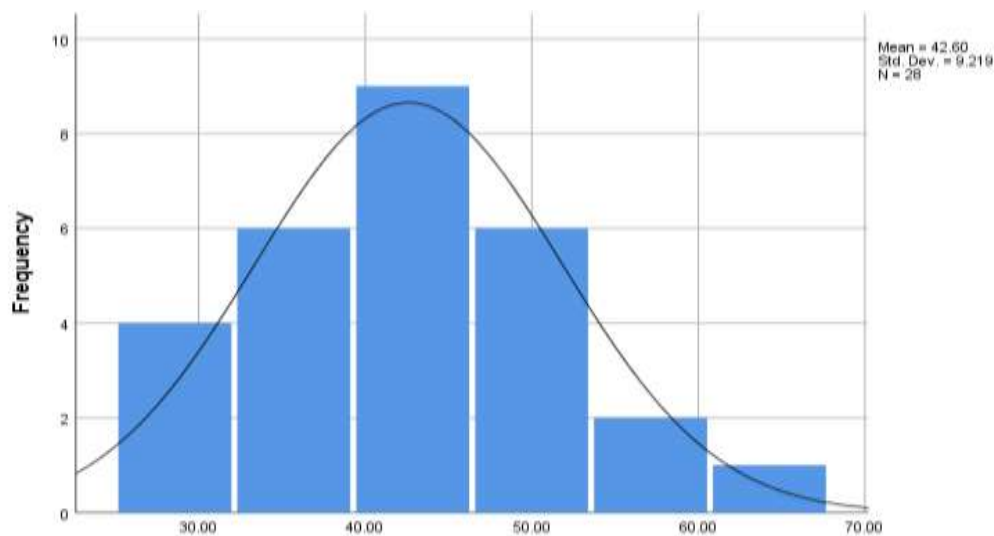


Figure 1. Average score of sample's initial conceptual understanding for each indicator



(a)

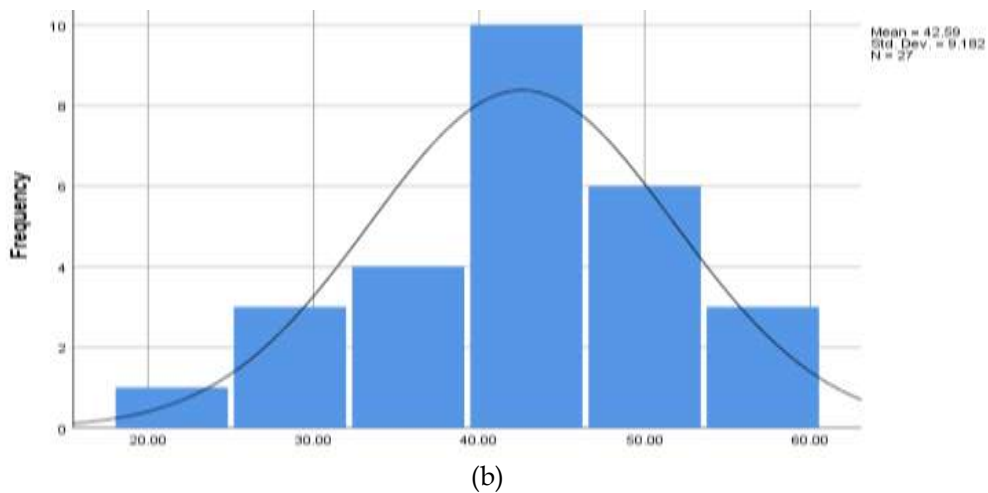


Figure 2. Histogram of the normality test results for students' initial conceptual understanding: (a) GI + PhET, (b) GI

Furthermore, the homogeneity of variance assumption was examined using Levene's Test in SPSS v.25. As presented in Table 2, the resulting p-value was greater than 0.05, indicating that the variances of the experimental and control groups were homogeneous.

Final Conceptual Understanding Test Results

The final results of students' conceptual understanding represent the outcomes obtained after the implementation of the Guided Inquiry model, with the experimental group additionally supported by PhET simulations. Following the administration of the pretest to both the experimental and control groups, each class received learning activities consistent with the guided inquiry syntax. After the instructional treatments were completed, students' conceptual understanding was assessed again through a posttest. Improvements were observed across all indicators. A comparison of the mean for each indicator is presented in Figure 3.

Descriptive statistics showed that the experimental group's mean posttest score (M = 80.36, SD = 9.45) exceeded that of the control group (M = 73.02, SD = 9.36).

Based on the Shapiro-Wilk normality test conducted using SPSS v.25, the experimental group obtained a significance value of 0.14, while the control group obtained a significance value of 0.07. Since both p-values exceed 0.05, the pretest data for both groups can be considered normally distributed. The histogram of the normality test results is presented in Figure 4.

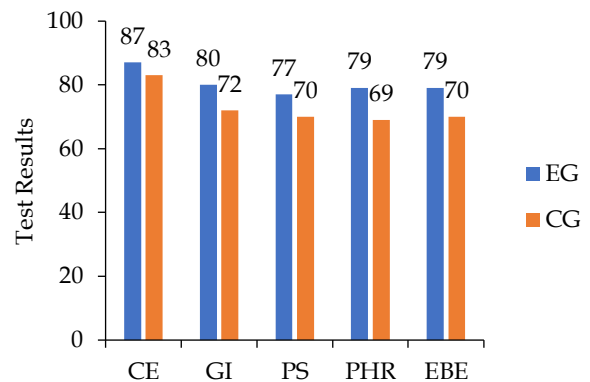
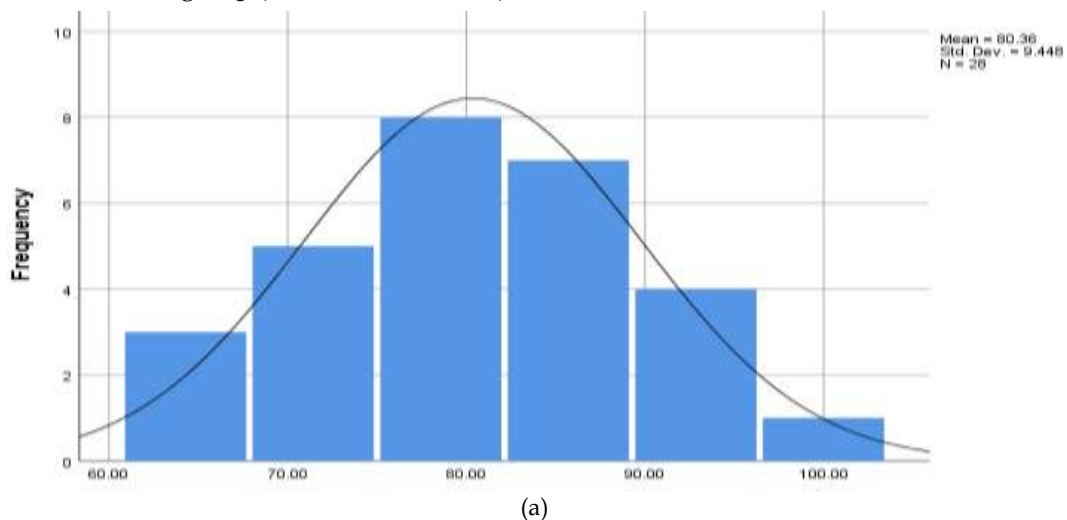


Figure 3. Average score of sample's final conceptual understanding for each indicator



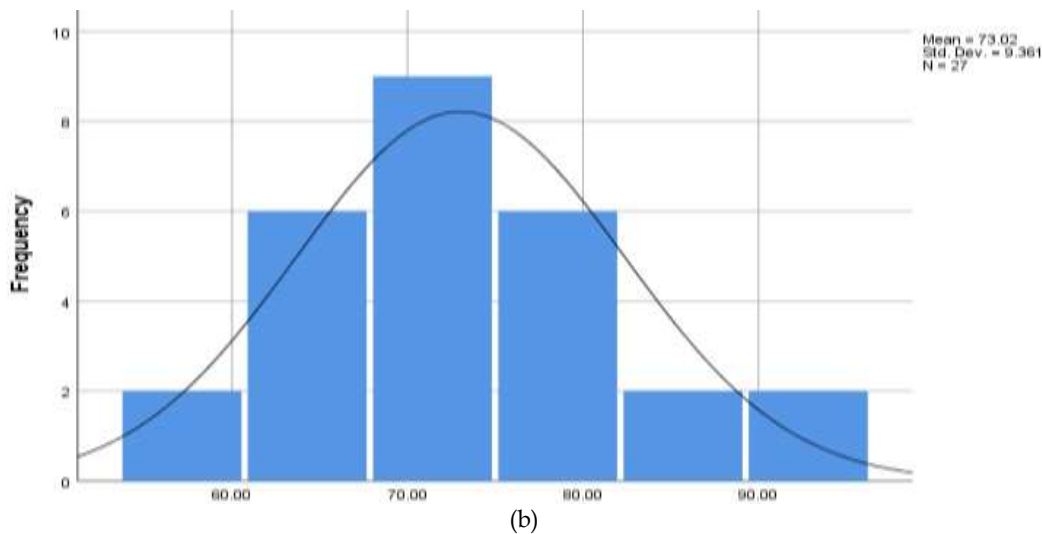


Figure 4. Histogram of the normality test results for students' final conceptual understanding: (a) GI + PhET, (b) GI

Furthermore, the homogeneity of variance assumption was examined using Levene's Test in SPSS v.25. As presented in Table 3, the resulting p-value was

greater than 0.05, indicating that the variances of the experimental and control groups were homogeneous.

Table 2. Homogeneity test results of students' initial conceptual understanding

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Students' initial conceptual understanding	Based on Mean	.03	1	53	.87
	Based on Median	.02	1	53	.88
	Based on Median and with adjusted df	.02	1	52.55	.88
	Based on trimmed mean	.01	1	53	.91

Table 3. Homogeneity test results of students' final conceptual understanding

Test of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
Students' conceptual understanding	Based on Mean	.06	1	53	.81
	Based on Median	.09	1	53	.76
	Based on Median and with adjusted df	.09	1	52.75	.76
	Based on trimmed mean	.07	1	53	.79

The t-test indicated a statistically significant difference, $t(53) = 2.89$, $p = 0.01 < 0.05$, with a medium-to-high effect size ($d = 0.67$). These findings demonstrate that PhET-assisted guided inquiry leads to higher learning gains in elasticity and Hooke's Law.

Discussion

The results of this study show that students who learned through PhET-supported guided inquiry achieved substantially higher conceptual understanding than those who learned through guided inquiry alone. These result are consistent with meta-analysis by Fadillah et al. (2026), which highlights that PhET simulations can be a powerful instructional tool in physics education when carefully integrated with consideration of instructional context. The medium-to-large effect size ($d = 0.67$) indicates a meaningful

influence of the intervention, and the consistency between the quantitative results and qualitative observations strengthens the internal validity of these findings.

Differences in Learning Processes Reflected in LKPD Work

The learning process in this study followed the guided inquiry stages proposed by Sanjaya (2006), which consist of orientation, problem formulation, hypothesis formulation, data collection, hypothesis testing, and drawing conclusions. In the context of guided inquiry, the teacher retains partial responsibility for defining the problem and outlining the investigative procedures, thereby ensuring that students remain focused on the essential conceptual goals while still engaging actively in the scientific process. Students, however, are required to generate hypotheses, gather

and analyze data, and formulate evidence-based conclusions. This balance of teacher scaffolding and student autonomy supports meaningful knowledge construction and aligns with the constructivist underpinnings of the inquiry model.

An examination of students' worksheet (LKPD) responses reveals clear differences in how the two groups engaged with the inquiry process. Elasticity and Hooke's Law represent abstract and mathematically intensive topics that many students struggle to visualize, particularly when the relationship between force, extension, and spring constant is presented purely symbolically. PhET simulations allowed students to manipulate masses, springs, and forces in real time, providing immediate visual feedback that supported their exploration of variable relationships. In the experimental group, students' responses demonstrated more accurate identification of variable relationships, clearer representation of force, extension patterns, and more coherent explanation of their findings. Many students generated multiple trials, compared conditions, and used simulation data as evidence when justifying their conclusions. This pattern reflects a deeper engagement with exploratory behaviors and iterative reasoning, characteristics central to constructivist learning.

By contrast, LKPD responses in the control group tended to be more procedural. Students focused primarily on recording measurements, completing tables, and performing calculations without exploring alternative scenarios. Limitations in equipment and time also restricted the number of trials they could conduct, resulting in narrower data sets and more limited opportunities for hypothesis revision. Consequently, students' explanations tended to be descriptive rather than analytical, and evidence-based reasoning was less frequently observed.

Improvement Across Conceptual Understanding Indicators

A comparison of pretest and posttest scores for each indicator further illustrates the impact of the intervention. For Concept Explanation (CE), Both groups started with identical CE mean scores. After instruction, the experimental group achieved 87, slightly higher than the control group (83). This suggests that both forms of guided inquiry can support conceptual explanation, but PhET enhances clarity through visualization of force, extension, and the spring constant, making conceptual relationships easier to articulate. A similar pattern appeared in Graphical Interpretation (GI), where both groups started at comparable levels, but the experimental group achieved a markedly higher posttest score compared to the control group. The dynamic graphing features in PhET likely helped

students visualize linear relationships more clearly and understand the slope as the spring constant, supporting more accurate graph interpretation.

For Problem-Solving with Conceptual Reasoning (PS), the initial scores were identical, yet the experimental group again outperformed the control group in the posttest. This suggests that exposure to multiple simulated scenarios strengthened students' ability to transfer conceptual knowledge to unfamiliar contexts. Students using PhET were able to simulate unfamiliar conditions, strengthening their ability to transfer concepts to novel contexts, an essential feature of conceptual reasoning.

The largest initial discrepancy emerged in Predictive and Hypothetical Reasoning (PHR), where the experimental group began at 38 and the control group at 37. After instruction, these scores increased to 79 and 69, respectively, with the experimental group showing a substantially greater improvement. This difference can be attributed to the nature of the learning environments. In the PhET-supported inquiry class, students were able to manipulate variables such as mass, spring constant, and applied force instantly and repeatedly, allowing them to observe outcomes in real time and revise their hypotheses whenever inconsistencies arose. This rapid feedback loop supported iterative prediction-making, a core component of hypothetical reasoning. In contrast, hands-on activities in the control group required students to physically adjust apparatus, wait for the system to stabilize, and address measurement challenges such as parallax error and inconsistent spring behavior. These procedural demands limited the number of trials students could conduct and reduced opportunities for hypothesis revision. As a result, students in the control group tended to base predictions on intuition or single observations rather than systematic exploration. This contrast suggests that PhET's efficiency and visual immediacy created a learning environment more conducive to developing strong predictive and hypothetical reasoning skills.

Finally, both groups began with low performance in Evidence-Based Explanation (EBE), yet the experimental group showed a substantial increase, surpassing the control group. Students in the experimental group made frequent use of simulation-generated numerical and visual evidence when explaining phenomena, while the control group's hands-on experience, limited by fewer trials and real-world measurement inconsistencies, provided a narrower basis for evidence-based reasoning.

Overall, the experimental group's consistently higher posttest performance across all indicators demonstrates that PhET-supported inquiry strengthens

students' representational fluency, conceptual transfer, predictive reasoning, and evidence-based explanation, competencies essential for meaningful conceptual understanding in physics.

Theoretical Interpretation Through Constructivism and CLT

Although hands-on laboratory work has traditionally been regarded as a central component of physics learning, the findings of this study demonstrate that PhET-supported guided inquiry yielded substantially higher conceptual gains than the hands-on activities conducted in the control group. This result reinforces emerging evidence that virtual simulations, when integrated within structured pedagogical models, can outperform conventional laboratory approaches in fostering conceptual understanding (Fadillah et al., 2026; Hadi et al., 2023; Pranata, 2024; Sukardiyono et al., 2025; Willard, 2021).

This difference can be understood through the combined lenses of constructivist learning and Cognitive Load Theory (CLT), both of which clarify the cognitive and epistemic advantages afforded by virtual experimentation. From a constructivist standpoint, PhET simulations function as mediating tools that externalize abstract physical phenomena and support the iterative construction of mental models. Observation sheets and worksheet analyses showed that students in the experimental group engaged more frequently in generating hypotheses, exploring relationships among variables, interpreting evidence, and articulating causal explanations, behavior indicative of active participation in the inquiry cycle. These findings are consistent with prior research indicating that inquiry-based learning environments promote active knowledge construction and deeper conceptual engagement (Adayah & Aznam, 2024; Espinoza, 2020). The simulation environment provided a broader and more flexible exploratory space, allowing students to manipulate variables, observe outcomes instantly, and refine their conceptual models through rapid cycles of testing and revision, thereby strengthening the connection between theoretical constructs and observable outcomes, which is critical for meaningful learning in physics.

In contrast, hands-on activities imposed procedural constraints that interrupted the flow of conceptual reasoning and reduced opportunities for iterative inquiry and conceptual exploration. As a result, students conducted fewer trials, encountered greater variability in their data, and relied more heavily on descriptive rather than analytical explanations. This limitation has also been observed in previous studies comparing traditional and virtual laboratories, where physical experimentation was found to be less efficient in supporting conceptual exploration due to practical

constraints (Darwis & Hardiansyah, 2023). The higher frequency of causal reasoning, accurate data interpretation, and metacognitive regulation observed in the PhET group thus reflects the more cognitively efficient and conceptually supportive environment enabled by virtual experimentation.

The results also align strongly with Cognitive Load Theory (Mayer, 2020; Ouwehand et al., 2025; Sweller, 2011), which provides a clear explanation for why students in the PhET group achieved higher conceptual gains. Elasticity and Hooke's Law impose considerable intrinsic cognitive load due to their abstract and quantitative nature. In hands-on settings, this intrinsic load is compounded by extraneous cognitive demands that arise from procedural complexities, for example, aligning measurement tools accurately, correcting parallax errors, stabilizing oscillating springs, and dealing with inconsistent spring behavior. These non-instructional tasks require substantial working memory yet contribute little to conceptual understanding (Sweller, 2020, 2024). PhET simulations eliminate these procedural burdens entirely. By allowing students to observe force-extension relationships through coherent, dynamic, and error-free visualizations, the simulation reduces extraneous load and frees cognitive resources for germane processing. Students no longer need to mentally imagine how a spring stretches under varying forces, they can observe it directly. This reallocation enables more efficient schema construction, clearer relational reasoning, and more consistent interpretation of physical patterns, which together offer a compelling theoretical explanation for the superior conceptual gains observed in the experimental group (Sweller, 2020). This aligns with empirical findings that digital simulations enhance conceptual understanding by simplifying complex representations and allowing students to focus on underlying principles (Becker et al., 2020; Fadillah et al., 2026; Mahzum et al., 2024; Villaruel, 2025).

Beyond cognitive efficiency, the synergy between inquiry-based learning and simulation media created a learning environment that strongly supported metacognitive regulation. As students manipulated variables in the PhET environment, they received immediate feedback that enabled them to revise hypotheses, correct misconceptions, and monitor their reasoning processes. This finding is consistent with recent studies (Hendratmoko et al., 2023; Pratiwi et al., 2025; Putri et al., 2021; Pyatt & Sims, 2012; Susilawati et al., 2022), which indicate that virtual experiments, when meaningfully integrated within inquiry frameworks, support students' epistemic engagement and scientific reasoning.

Compared with earlier studies (Azizaturredha et al., 2019; Umiliya et al., 2023), which primarily reported

learning gains without unpacking the underlying cognitive mechanisms, this research provides a deeper theoretical rationale. The improvement in students' conceptual understanding can be attributed to three interrelated mechanisms in guided inquiry learning, namely reduced cognitive overload through visual simulations, increased inquiry engagement enabled by interactive experimentation, and stronger representational mapping between theoretical constructs and observable phenomena (Kurnaz & Arslan, 2021). Qualitative observations further revealed heightened motivation, curiosity, and persistence in the PhET group, suggesting that PhET-supported guided inquiry learning also enhances affective drivers of long-term conceptual retention (Tytler, 2020).

Additionally, the temporal efficiency of PhET-enabled inquiry allowed students to explore a wider range of conditions, such as varying spring constants and series-parallel configurations, than what the hands-on group could feasibly attempt within the same instructional period. This breadth of exploration supported deeper conceptual elaboration, particularly during the Explain and Elaborate phases of the inquiry cycle. Hands-on settings, by contrast, were constrained by equipment limitations and time-consuming setup procedures, resulting in narrower inquiry experiences.

Taken together, these findings suggest that virtual experimentation does not merely substitute physical laboratory work but enhances the inquiry process by optimizing cognitive resources and enabling richer, more iterative cycles of conceptual exploration. While hands-on laboratories remain essential for developing procedural competencies and real-world measurement skills, PhET simulations appear to be more effective for fostering conceptual understanding in topics involving abstract quantitative relationships such as elasticity and Hooke's Law. This view is consistent with previous work by Maubuthy et al. (2025), integrating multimedia-based student worksheets to guide hands-on laboratory activities in dynamic electricity experiments. In their approach, digital media provided structured procedural guidance and animations illustrating electron motion, phenomena that cannot be directly observed in real laboratory settings, while the experimental implementation itself relied on physical equipment. Although that study primarily demonstrated improvements in students' laboratory skills rather than conceptual understanding, it highlights the pedagogical potential of combining digital media with hands-on activities. Accordingly, future instructional designs may benefit from strategically integrating virtual simulations to build robust conceptual foundations before or alongside hands-on experimentation to strengthen both conceptual understanding and practical proficiency.

Conclusion

This study provides empirical evidence that guided inquiry supported by PhET simulations results in significantly higher conceptual understanding of elasticity and Hooke's Law compared to guided inquiry using hands-on activities. The experimental group achieved higher posttest scores than the control group ($M = 80.82$ vs. 73.81), with a statistically significant difference ($t(53) = 2.89$, $p = 0.01$) and a medium-to-high effect size ($d = 0.67$). Improvements were consistently observed across all indicators of conceptual understanding. These findings highlight the distinctive contribution of integrating PhET simulations within a guided inquiry framework, particularly in facilitating the learning of abstract physics concepts that are difficult to visualize through conventional experimental approaches. The results suggest that virtual simulations provide a more efficient and supportive environment for conceptual learning than hands-on activities alone. These gains are consistent with Constructivist Learning Theory, which emphasizes active knowledge construction, and Cognitive Load Theory, which explains how PhET reduces extraneous cognitive demands by eliminating procedural complexities inherent in hands-on experiments. Future research is recommended to explore the combined use of virtual simulations and hands-on experiments, as well as to examine their effects across different physics topics and educational contexts to further validate and extend these findings.

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Author Contributions

Conceptualization, methodology, validation, investigation, A.S.H., F.R.H.B., V.L., and A.S.; data curation, formal analysis, writing—original draft preparation, M.S.K.M.; writing—review and editing, A.S.H., F.R.H.B., V.L., A.S., and M.S.K.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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