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Using PhET Simulations-Integrated Metacognitive Argument-Driven Inquiry to Improve Students' Learning Outcomes in Physics

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This study investigated the integration of technology, particularly Physics Education Technology (PhET) simulations, into the Metacognitive Argument-Driven Inquiry (MADI) approach to improve students' conceptual understanding, science process skills, and attitudes toward learning Physics. Employing a one-group pretest-posttest design within the framework of pedagogical action research, the study utilized both quantitative and qualitative data. The participants were 26 Grade 9 students enrolled in a science class at a state university in Central Luzon, Philippines. Over a six-week period, students engaged in scientific inquiry and argumentation using PhET simulations within a metacognitive learning environment. Pre- and post-intervention assessments, including teacher-made and adapted questionnaires, measured students' conceptual understanding, science process skills, and attitudes toward Physics. Quantitative data were analyzed using the Wilcoxon Signed Ranks Test, paired sample t-tests, and effect size calculations, while qualitative data were examined through thematic analysis. The results revealed significant improvements in students' conceptual understanding and science process skills. While no substantial changes were found in students' attitudes toward Physics based on the quantitative analysis, their interview responses highlighted a positive shift in their perceptions of the subject. These findings suggest that the PhET-integrated MADI approach is a promising pedagogical strategy for enhancing student outcomes in Physics and holds potential for broader application in teaching other scientific disciplines.

Keywords: physics education technology (PhET) simulations, metacognitive argument-driven inquiry, physics instruction, technology integration, education technology

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INTRODUCTION

The pandemic posed significant challenges for science educators striving to deliver high-quality instruction in online distance learning setups. Nevertheless, advancing students' scientific literacy remains a fundamental goal of science education. Scientific literacy encompasses the development of conceptual understanding, learning attitudes, and science process skills, which are integral components of effective science instruction (Baltikian, et al., 2024). Conceptual understanding involves students' comprehension of scientific concepts and their application in real-world contexts (Widiyatmoko, 2018). Learning attitudes, which encompass motivation, interest, and positive perspectives toward science, play a pivotal role in fostering engagement and academic success (Winkelmann et al., 2020). Science process skills, on the other hand, reflect students' abilities to engage in scientific inquiry, including observing, hypothesizing, experimenting, analyzing data, and effectively communicating findings (Taibu et al., 2021).

To achieve these objectives, science educators have increasingly turned to technology to enhance teaching and learning practices during the pandemic (Adedoyin & Soykan, 2020; Lemay et al., 2021). Technology integration fosters learner-centered approaches that engage students in mastering scientific concepts, developing positive attitudes, and participating in inquiry-based processes (Aljehani, 2024; Chang & Yang, 2018). For instance, interactive virtual simulations have proven effective in placing students at the center of instruction, enabling them to explore scientific phenomena independently (Pei-Lin, 2024). The growing use of Physics Education Technology (PhET) simulations in classroom instruction exemplifies this trend (Antonio & Castro, 2023; Dantic & Fluraon, 2022). These digital tools offer diverse, practical learning opportunities across various educational levels and topics, promoting interactive and engaging instruction (Salame & Makki, 2021). By creating safe, controlled environments, simulations facilitate experiments that are otherwise hazardous or logistically challenging in real laboratory settings. This is particularly beneficial for students in remote or underfunded schools lacking access to advanced laboratory equipment, a need that became especially apparent during pandemic restrictions (Lestari & Mansyur, 2021; Luliyarti & Astuti, 2020). Simulations can also be tailored to suit different educational levels or learning objectives, making them versatile tools for fostering conceptual understanding and engagement (Banda & Nzabahimana, 2023).

Despite their advantages, virtual simulations have limitations, such as the risk of students relying excessively on simulations without transferring knowledge to real-world contexts (Kapralos, 2024). Poorly designed or implemented simulations may also lead to disengagement or misconceptions (Alzahrani, 2020). Teachers must therefore provide appropriate guidance and adopt evidence-based practices to maximize the benefits of simulations while mitigating potential drawbacks (Lin & Sumardani, 2023; Yang et al., 2022).

The TPACK framework highlights the importance of integrating content, pedagogy, and technology for effective technology-enhanced instruction (Hurtado-Bermúdez, 2023; Mishra & Koehler, 2006). Argument-Driven Inquiry (ADI) has emerged as a potent pedagogical approach for authentic, inquiry-based learning experiences, emphasizing hands-on exploration and scientific argumentation (Sampson et al., 2009). Grounded in constructivist philosophy, ADI encourages students to develop evidence-based explanations, fostering reasoning, critical thinking, and communication skills (Giri & Paily, 2020; Hasnunidah & Undang Rosidin, 2024). When paired with digital tools, ADI can create technology-enhanced environments that promote inquiry-based learning aligned with scientific practices (Chang & Yang, 2018). Studies have demonstrated the effectiveness of ADI in improving critical thinking, metacognition, argumentation, and science process skills in Physics education (Arslan et al., 2023; Giri & Paily, 2020; Ping et al., 2020; Tucel Deprem et al., 2022). However, research on its application in local contexts, particularly among Filipino learners, remains limited.

Incorporating metacognitive strategies into inquiry-based learning has shown promise in enhancing students' engagement and understanding (Antonio, 2020; Farah & Ayoubi, 2020; Seraphin et al., 2012). Metacognition, which involves understanding and regulating one's thinking, can support students in completing inquiry tasks effectively (Kalemkus & Bulut-Ozek, 2022). Metacognitive scaffolding and prompting have been linked to improved conceptual understanding, performance, and engagement in Physics (Antonio & Prudente, 2022; Avargil et al., 2018; Moser et al., 2017). Integrating metacognitive elements with ADI can further enhance students' learning by fostering reflection and deeper engagement with scientific processes (Tucel Deprem et al., 2022).

Physics concepts are often perceived as challenging due to their reliance on mathematical reasoning, critical thinking, and problem-solving skills (Ibrahim et al., 2019; Wahyu et al., 2017). These challenges have become even more pronounced in the post-pandemic educational landscape, necessitating innovative pedagogies that support advanced understanding (Nerantzi, 2020). While numerous studies have explored the individual effectiveness of PhET simulations, Argument-Driven Inquiry (ADI), and metacognitive strategies, few have investigated their **combined use** in a single, coherent instructional framework, especially in the context of Philippine basic education.

This study introduces the PhET-integrated Metacognitive Argument-Driven Inquiry (MADI) approach, an innovative pedagogical design that merges technological integration, inquiry, and metacognitive learning to enhance students' learning experiences in Physics. The urgency of this research lies in supporting educational recovery in Physics following the disruptions caused by the pandemic, particularly in under-resourced schools lacking laboratory access. Additionally, as the Philippines transitions to its Revised K–12 science curriculum, this study provides timely, evidence-based insights into strategies that align with inquiry, metacognition, and digital integration. It posits that embedding metacognitive opportunities within inquiry-based learning via PhET simulations can promote meaningful and reflective learning.

To explore the impact of this pedagogical approach, the study aimed to address the following research questions:

1. Is there a significant improvement in students' conceptual understanding before and after exposure to the PhET-integrated MADI approach?
2. Is there a significant improvement in students' science process skills before and after exposure to the PhET-integrated MADI approach?

3. Is there a significant improvement in students' learning attitudes toward Physics before and after exposure to the PhET-integrated MADI approach?

Aims and Hypotheses

This study aimed to investigate the effects of integrating PhET simulations into the Metacognitive Argument-Driven Inquiry (MADI) approach on Grade 9 students' conceptual understanding, science process skills, and learning attitudes in Physics.

The following null and alternative hypotheses were tested:

H_0: There is no significant difference in students' conceptual understanding before and after exposure to the PhET-integrated MADI approach.

H_1: There is a significant difference in students' conceptual understanding before and after exposure to the PhET-integrated MADI approach.

H_0: There is no significant difference in students' science process skills before and after exposure to the PhET-integrated MADI approach.

H_1: There is a significant difference in students' science process skills before and after exposure to the PhET-integrated MADI approach.

H_0: There is no significant difference in students' learning attitudes toward Physics before and after exposure to the PhET-integrated MADI approach.

H_1: There is a significant difference in students' learning attitudes toward Physics before and after exposure to the PhET-integrated MADI approach.

METHOD

Research Design

This study employed a one-group pre-posttest design to evaluate the effectiveness of integrating Physics Education Technology (PhET) simulations into the Metacognitive Argument-Driven Inquiry (PhET-integrated MADI) approach in enhancing students' conceptual understanding, science process skills, and attitudes toward Physics learning. The one-group pretest-posttest design was chosen because it allows for a focused examination of the intervention's impact on a specific group of students over time. By comparing students' performance before and after the intervention, the design provided a straightforward method to measure changes in the targeted outcomes while controlling for variables such as prior knowledge and group characteristics (Creswell, 2014).

The study was conducted within the action research paradigm, which is particularly suitable for educational settings where practitioners seek to improve their own instructional practices through systematic inquiry. Action research emphasizes reflective practice and aims for practical solutions to educational problems, making it an ideal approach for evaluating new teaching strategies (Mills, 2018). The study followed the Plan-Do-Study-Act (PDSA) model to ensure a systematic and iterative process (Deming, 1986). In the Plan phase, pedagogical plans were developed, including the design of PhET-integrated MADI activities and preparation of research instruments. The Do phase involved implementing the approach and administering pre- and post-tests to measure learning outcomes. During the Study phase, quantitative and qualitative analyses were conducted to assess changes in students' conceptual understanding, science process skills, and attitudes. Finally, the Act phase focused on deriving educational implications and refining instructional practices based on the study findings. This design allowed for a comprehensive evaluation of the PhET-integrated MADI approach and its impact on Physics education.

Research Locale and Participants

The study was conducted with an intact class of Grade 9 junior high school students (n = 26) enrolled in a state university in Central Luzon, Philippines. The class consisted of 15 boys and 11 girls, all part of the Science, Technology, and Engineering (STE) Program, which offers an enriched curriculum that includes advanced science and research subjects alongside the standard K to 12 junior high school curriculum. The implementation of the study took place in their Grade 9 Science class, facilitated by one of the researchers through in-class instruction.

Research Instruments

Conceptual Understanding Test in Physics (CUT-P)

The Conceptual Understanding Test in Physics (CUT-P) was designed to assess students' conceptual understanding of four key topics in the Grade 9 Physics curriculum before and after exposure to the PhET-integrated MADI approach. These topics included: (a) Projectile Motion, (b) Conservation of Mechanical Energy, (c) Heat, Work, and Energy, and (d) Electricity Generation, Transmission, and Distribution. The CUT-P consisted of 30 multiple-choice items aligned with the curriculum's content. Each correct response was awarded one point, with a maximum possible score of 30. To ensure content validity, three Physics education teacher-experts with master's degrees evaluated the test using Morales' (2003) evaluation checklist. The instrument received an average rating of 3.77 out of 4.00, indicating high quality in terms of construction and content. Feedback and recommendations from the experts were incorporated to refine and enhance the test further.

Science Process Skills Inventory (SPSI)

The Science Process Skills Inventory (SPSI) developed by Arnold et al., (2013) was adopted to evaluate the extent to which students demonstrated scientific inquiry skills before and after exposure to the PhET-integrated MADI approach. The inventory comprises 11 statements, each representing a specific skill within the scientific inquiry process. Students responded to these statements using a 4-point Likert scale, indicating the frequency with which they engaged in each skill. The instrument demonstrated satisfactory internal consistency and reliability, with Cronbach's alpha values ranging from 0.84 to 0.93 for both pretest and posttest measurements, as reported by Arnold et al. (2013).

Integrated Process Skills Test (ITPST)

The Integrated Process Skills Test (IPST) developed by Burns et al., (1985) was employed to evaluate students' proficiency in integrated process skills before and after exposure to the PhET-integrated MADI approach. This 36-item multiple-choice test assesses specific skills critical to scientific inquiry, including identifying variables (12 items), defining operationally (6 items), formulating hypotheses (9 items), graphing and interpreting data (6 items), and designing investigations (3 items). Each question presents a problem and requires students to select the best answer from four options. The IPST demonstrated strong internal consistency and reliability, with a Cronbach's alpha value of 0.86.

Colorado Learning Attitudes about Science Survey - Physics (CLASS-Phy)

The Colorado Learning Attitudes about Science Survey for Physics (CLASS-Phy), developed by Adams et al., (2006), was administered both before and after the intervention to assess changes in students' attitudes toward learning Physics. This 42-item Likert-type instrument evaluates eight dimensions of student attitudes: (1) real-world connection, (2) personal interest, (3) sense-making or effort, (4) conceptual connections, (5) applied conceptual understanding, (6) problem solving in general, (7) problem-solving confidence, and (8) problem-solving sophistication. Each item presents statements that either align with (favorable responses) or contradict (unfavorable responses) expert opinions in Physics. Responses are rated on a five-point scale: "strongly disagree" (1), "disagree" (2), "neutral" (3), "agree" (4), and "strongly agree" (5).

Research Procedures

Before the implementation of the study, ethical clearance was obtained from the University Research Ethics Committee to ensure compliance with ethical standards in research involving human participants. An initial orientation session was conducted to inform students about the purpose, scope, and procedures of the study. Both students' assent and parental consent were sought to ensure informed participation. To assess students' baseline conceptual understanding, science process skills, and learning attitudes toward Physics, several pre-tests were administered, including the Conceptual Understanding Test in Physics (CUT-P), Science Process Skills Inventory (SPSI), Integrated Process Skills Test (IPST), and the Colorado Learning Attitudes toward Science Survey (CLASS-Phy).

Following these assessments, a separate orientation session was held to introduce students to the PhET-integrated Metacognitive Argument-Driven Inquiry (MADI) approach. This session aimed to familiarize students with the pedagogical approach and the specific simulation tools that would be used throughout the study. To begin the intervention, students were tasked with answering the question: “What is the relationship between mass and acceleration?” using the PhET interactive simulation titled "Forces and Motion: Basics." This initial activity required students to explore the simulation and develop a scientific argument to answer the posed question.

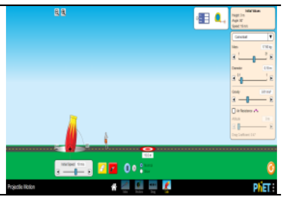
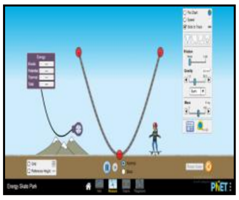
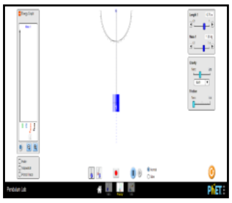
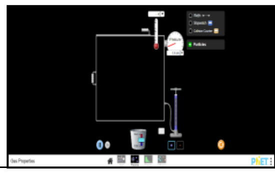
The study was implemented over a period of six weeks, during which students engaged in the seven inquiry phases of the PhET-integrated MADI approach (see Figure 1). This approach was inspired by the TI-MADI approach developed by Antonio and Prudente (2025). The students participated in two class sessions per week, with one session lasting 2 hours and the other lasting 3 hours, totaling 5 hours of instruction per week. Each session included active participation in inquiry-based activities designed to promote scientific argumentation and metacognitive reflection. A comprehensive breakdown of each phase of the PhET-integrated MADI approach is provided in Table 1, outlining the specific objectives and tasks for each stage of the inquiry process.

Table 1
PhET-integrated metacognitive argument-driven inquiry approach

Phases of Inquiry (Eisenkraft, 2003)	Description of Instructional Procedures
Elicit	Students were given metacognitive opportunities (i.e., pre-assessments) to assess their present thoughts or pre-existing understanding of the subject matter.
Engage	Students were presented with a guiding question at the start of the activity that they were tasked to explore and provide an answer to. Additionally, an overview of the activity and its procedures was provided. Before proceeding with the actual activity, students were directed to plan their strategies by answering planning metacognitive prompts in their respective groups.
Explore	Students explored the given PhET interactive simulation with the objective of constructing a scientific argument that included a claim, evidence, and reasoning in response to the given guiding question in the activity. Throughout the task, students were motivated to keep track of their progress by responding to monitoring metacognitive prompts.
Explain	The argumentation session was conducted in which every student-group had the chance to present their initial scientific arguments and evaluate those presented by other groups by using their argument boards. Here, the round-robin format was followed, where one student from each group remained at their lab station to present their group's initial argument while the rest of the group members rotated to other lab stations one by one to listen to and critique their classmates' arguments. While presenting their arguments, students were allowed to present and manipulate the PhET interactive simulation as well.
Elaborate	After the argumentation session, the teacher facilitated a reflective discussion on the topic or lesson. During this discussion, the teacher clarified any misunderstandings that were heard during the argumentation session by reviewing the lesson content and presenting the assigned PhET interactive simulation.
Evaluate	Following the argumentation session and reflective post-discussion, students were guided to write their argumentation report that reflects their final scientific arguments. After which, a peer-review session was held which required students to critique each other's final argumentation report based on the scoring rubric of McNeill and Krajcik (2011). Students were given the chance to revise their argumentation report following the peer review session.
Extend	As part of the metacognitive learning process, students were prompted to reflect on their understanding of a topic or concept by answering the evaluating metacognitive prompts and completing a post-assessment. They were encouraged to consider their initial thoughts about the topic or concept before the session and compare it to their thoughts after the lesson.

Over the course of six weeks, four successive topics from the Physics quarter were taught using the PhET-integrated Metacognitive Argument-Driven Inquiry (MADI) approach. The topics included 1) Projectile Motion, 2) Conservation of Mechanical Energy, 3) Heat, Work, and Energy, and 4) Electricity Generation, Transmission, and Distribution. Specifically, two activities were designed for the topics *Conservation of Mechanical Energy* and *Heat, Work, and Energy*, resulting in a total of six lessons. The activities incorporated five PhET simulations, sourced from the official PhET website (https://phet.colorado.edu/), which were carefully chosen to align with the specific learning objectives of each lesson. The development of these activities, including the integration of the simulations, underwent content validation by three Physics teachers with master's degrees in the field to ensure their educational relevance and accuracy. A detailed overview of each lesson and its corresponding activity is presented in Table 2.

Table 2
Physics lessons and PhET-integrated MADI activities

Lesson	Objectives	Title and Description of the Activity	PhET Simulation
Projectile Motion	*describe the different factors affecting the projectile motion; *predict the outcomes from the simulation when a factor is changed in the projectile motion, and; *explain how the components of a projectile motion affect the trajectory of an object	Follow the Flying Object's Path How does each factor (height, initial angle, and gravity) affect the trajectory of an object without air resistance?	
Conservation of Mechanical Energy (Skater Park)	*describe the different types of mechanical energy; *analyze how total energy is conserved in the simulation, and; *demonstrate the relationship between speed and mechanical energy.	Conservation of Mechanical Energy In a closed system, how does the increase in speed of the object affect the total mechanical energy?	
Conservation of Mechanical Energy (Pendulum)	*describe the different types of energy involved in the pendulum simulation; *explain the law of conservation of energy relating the pendulum simulation, and; *demonstrate the relationship between friction and the energy of a pendulum.	Conservation of Mechanical Energy (Pendulum) How does adding friction affect the energy of a pendulum?	
Heat, Work, and Energy (Engines)	*describe the behavior of molecules in the simulation; *predict outcome from the simulation when a variable (e.g. pressure, temperature) is changed; and, *explain the relationship between pressure and temperature using the simulation.	Heat, Work, and Energy (Heat Engines) What is the relationship between pressure and temperature?	
Heat, Work, and Energy (Efficiency)	*infer the factors affecting efficiency; *determine the more efficient bulb between incandescent bulb and CFL bulb, and; *describe how energy flows and changes one form of energy into another.	Heat, Work, and Efficiency Which is more energy efficient: incandescent bulb or compact fluorescent lamp (CFL) bulb?	
Electricity Generation, Transmission, and Distribution	*describe the sources of electricity included in the simulation; *explain the process of electricity generation from different forms of energy, and; *explore the different concepts behind the electricity generation, transmission, and distribution.	Electricity Generation How can electricity be generated from different forms of energy?	

After the implementation of the study, the CUT-P, SPSI, IPST, and CLASS-Phy assessments were post-administered to evaluate any changes in students' conceptual understanding, science process skills, and learning attitudes toward Physics. In addition, structured interview questions were distributed to the students via Google Forms to capture their perceptions of the PhET-integrated MADI approach. The qualitative data gathered from the interviews were then analyzed to complement and further substantiate the quantitative findings.

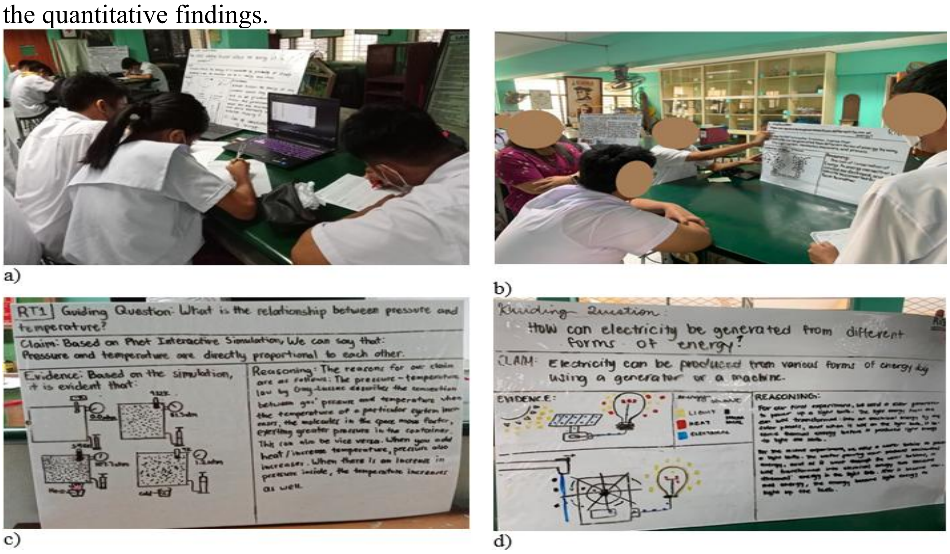


Figure 1
Students' Participation in PhET-integrated MADI Activities (a) Students exploring the PhET simulation; (b) Students participating in argumentation session; (c-d) Sample initial argument boards during the argumentation session

Data Analysis

To evaluate significant improvements in students' conceptual understanding, science process skills, and learning attitudes at the end of the study, both descriptive and inferential statistical analyses were employed. The Shapiro-Wilk test was used to examine the distribution of the data. Due to the non-normal distribution of CUT-P scores, the Wilcoxon Signed Ranks Test was applied to determine if the PhET-integrated MADI approach significantly enhanced students' conceptual understanding. For the SPSI, composite science process skills scores were computed by summing the ratings for each item, yielding a range of 11–44 (Arnold et al., 2013). Since the data were normally distributed, a paired sample t-test compared pre- and post-inventory scores.

For the CLASS-Phy instrument, students' responses were categorized as agreeing or disagreeing with expert-like perspectives to evaluate improvements in learning attitudes. The "shift" in percent favorable responses was calculated by subtracting the pretest class average percent favorable from the posttest class average. A positive shift indicated improved learning attitudes toward Physics (Adams et al., 2006). The strength of the PhET-integrated MADI approach's effectiveness was assessed by transforming the z statistic from the Wilcoxon Signed Ranks Test for CUT-P into an r effect size. This was done by dividing the z value by the square root of the total number of observations (N) (Allen & Bennett, 2008; Clark-Carter, 2004). Effect sizes were interpreted using Cohen's (1988) criteria, with classifications as large ($d \geq 0.80$), moderate ($d = 0.50–0.79$), small ($d = 0.20–0.49$), or no effect ($d < 0.19$). This interpretation was also applied to results from the SPSI and IPST. Quantitative data were analyzed using SPSS 23.0 software. Meanwhile, qualitative data from the structured interview responses were transcribed and analyzed thematically (Braun & Clarke, 2006) using Quikos® software.

FINDINGS

Students' Conceptual Understanding of Select Topics in Physics

The Wilcoxon Signed Ranks Test was used to determine whether there was a significant improvement in students' conceptual understanding at the end of the study.

Table 3
Wilcoxon signed ranks test for the difference between pretest and posttest scores in the CUT-P

	No. of items	Before		After		z	p	r
		M	SD	M	SD			
Overall	30	14.23	3.39	22.65	2.50	-4.467	.000*	0.82
Projectile Motion	6	1.96	.96	3.96	1.08	-4.521	.000*	0.70
Conservation of Mechanical Energy	9	3.96	1.43	5.62	1.50	-3.430	.001*	0.49
Heat, Work, and Energy	6	2.85	1.22	5.08	.80	-4.256	.000*	0.73
Electricity Generation, Transmission, and Distribution	9	5.46	1.92	8.00	1.02	-4.219	.000*	0.64

Note: *p < .05; large (d = 0.80 and above), moderate (d = 0.50 to 0.79), small (d = 0.20 to 0.49), no effect (d < 0.19)

The results, as shown in Table 3, indicate that there was a significant difference ($z = -4.467$, $p < 0.05$) in the overall mean scores between the pretest and posttest, with the posttest scores showing a statistically significant increase. Specifically, there were significant improvements in students' mean scores for each topic in Physics. The PhET-integrated MADI approach was found to have a substantial and positive impact on students' conceptual understanding in Physics, with an effect size of $r = 0.82$.

Table 4
Thematic analysis of the students' interview responses

Main Theme	Subthemes	Codes
development of conceptual understanding	improvement in cognitive aspect	deeper understanding
		critical thinking skills
	engaging lessons	results-oriented
		relevant topics
	features of MADI instruction	learning styles compatibility
		collaboration
		firsthand experiences
		better reviewing technique
		feedback
		independent learning

Table 4 displays the thematic analysis of the structured interview responses of the students, which supports the quantitative findings of the study. The subthemes identified demonstrate that the PhET-integrated MADI approach contributes to the advancement of students' conceptual understanding. The first subtheme highlights the students' improvement in cognitive processes as a result of the learning experiences provided to them. Selected students' responses regarding this subtheme are presented below:

> *It helped me a lot because the activities given to us made me understand more things by searching for more information about them and I got an eagerness to know more. The activities did a lot help for me because they did not only help me improve my knowledge but also tested me on how deeply I can think about a certain topic. (Student 24)*

> *It helps me think faster and know what topics relevant and what sites are to look at when researching. (Student 19)*

The above students' responses showed that the PhET-integrated MADI approach actively involved them in exploring and searching for answers to the questions posed to them. This process resulted to improved understanding of the concepts, and helped them assess the depth of their knowledge. Additionally, they became more discerning in their approach to finding information and selecting appropriate sources relevant in their activity. Another subtheme that emerged from the students' responses was the extent of student engagement fostered by the lessons. The students expressed agreement that the PhET-integrated MADI approach motivated them to participate actively in their Physics classes. Selected verbatim responses from the students can be read below:

> *The simulations along with researching for reasoning and argumentation helped me develop an in-depth understanding of each lesson by going into further detail and getting to explore the simulations. I think that exploring the simulations firsthand may help in understanding the topic better. (Student 15)*

> *I am the type of student to understand a specific lesson or subject by studying or experiencing an actual representation of the study. Through the PhET simulations, I was able to understand the lesson better, the simulation showed every detail and makes sense of it. The unclear parts of the lesson were explained by the simulation. At first, it was a bit tricky (the PhET Simulation) but as time goes by, I eventually got used to it too. (Student 24)*

> *I enjoyed exploring the PhET simulations. It provided us with illustrations of lessons that are difficult to understand. It's easy to grasp. I also enjoyed the interactivity of the said simulations. There are more discussions within the section, especially when there is a round-robin argumentation session, and that is what we want to achieve, especially for me as an officer, to have the section have a strong bond. (Student 14)*

To elaborate, the students' responses highlighted the affordances of using PhET simulations in aiding their understanding of the lessons through hands-on experience in controlling and manipulating the variables in the simulations. They expressed that the interactivity and visualizations in the simulations played an essential role in facilitating their learning and comprehension of the concepts. Additionally, the argumentation session helped them establish positive social relationships with their classmates. Additionally, the students' responses in the interview affirmed that the pedagogical approaches used in the study contributed to the development of their conceptual understanding. Here are some selected excerpts from the interviews:

> *The argumentative session. I like being critical and pointing out the other's works and had fun discussing our work. (Student 2)*

> *The argumentation session. It collaborates with every one of us and we can discuss certain lesson about Physics we get to combine our ideas and if there's something wrong with their board, we can correct them and explain to them how it works. (Student 21)*

> *The activities helped me improve my understanding of the Physics lessons because I was able to see the results of the processes. (Student 25)*

From these students' responses, they acknowledged that the argumentation sessions in the PhET-integrated MADI approach stimulated their critical thinking, as they were encouraged to provide constructive feedback on their peers' initial scientific arguments. This process enabled them to identify and correct their misconceptions, ultimately leading to the accurate understanding of the concept through collaborative exchange of ideas. Additionally, students highlighted the benefit of receiving immediate feedback through the simulations as they manipulated and controlled the parameters in the simulations.

Students' Science Process Skills

The paired sample t-test was utilized to evaluate whether there was a significant difference in students' application of science process skills before and after the implementation of the PhET-integrated MADI approach.

Table 5
Paired sample t-test for the difference between pretest and posttest scores in the SPSI

	N	Mean	SD	t	p	d
Before	26	33.54	4.35	-2.532	.018*	0.60
After	26	36.19	4.50			

*Note: *p < .05; large (d = 0.80 and above), moderate (d = 0.50 to 0.79), small (d = 0.20 to 0.49), no effect (d < 0.19)*

The results presented in Table 5 indicated a statistically significant difference (t = -2.532, $p < 0.05$) between the pre- and post-inventory scores, favoring the latter. The effect size of the PhET-integrated MADI approach on students' science process skills recorded a moderate effect, with a value of d = 0.60. Thus, this indicates that the approach had a significant and positive impact on students' perceptions of the extent to which they practiced science process skills.

To examine the students' integrated process skills, a paired sample t-test was employed to compare the pre- and posttest mean scores on the IPST instrument.

Table 6
Paired sample t-test for the difference between pretest and posttest scores in the IPST

	No. of items	Before		After		*t*	*p*	*d*
		M	SD	M	SD			
Overall	36	20.85	5.86	24.46	4.98	-2.723	.012*	0.66
identifying variables	12	6.85	2.78	7.38	2.19	-1.105	.280	0.22
identifying and stating hypotheses	9	5.08	1.55	6.23	1.82	-2.547	.017*	0.68
operationally defining	6	3.04	1.51	3.88	1.31	-2.142	.042*	0.60
designing investigations	3	1.92	.84	2.42	.58	-2.687	.013*	0.69
graphing and interpreting data	6	3.96	1.37	4.54	1.42	-1.893	.070	0.41

Note: $*p < .05$; large (d = 0.80 and above), moderate (d = 0.50 to 0.79), small (d = 0.20 to 0.49), no effect ($d < 0.19$)

The results detailed in Table 6 suggest that there was a statistically significant difference ($t = -2.72$, $p < 0.05$) between the pre- and posttest mean scores. The posttest mean scores recorded a substantial increase from the pretest scores. Specifically, the students' ability to identify and state hypotheses, operationally define, and design investigations showed significant improvements after the implementation of the PhET-integrated MADI approach. In contrast, no discernible differences were noted in their integrated process skills as regards identifying variables and graphing and interpreting data. The overall effect size of the approach on the students' integrated process skills was moderate (d = 0.66). These findings imply that the PhET-integrated MADI approach brought about a positive and significant improvement on students' integrated process skills.

Table 7
Thematic analysis of the students' interview responses

Main Theme	Subthemes	Codes
development of scientific process skills	process skills enhanced during PhET-integrated MADI Intervention	general scientific process skills
		analysis
		communication
		brainstorming
		experimenting
		evaluating
		hypothesizing
		observation
		gathering evidence
		inquiry
		classification
		measurement
		reasoning
	context-based skills improvements	familiarity with the process
		real-life application
		interest
		specific
		not aware of improvement
	stages of MADI that improved science process skills	ADI board creation
		simulation
		argumentation session

To strengthen the quantitative findings, a thematic analysis was conducted on the students' responses to the structured interview questions (Table 7). One of the subthemes was the improvement of the students' science process skills as a result of their learning activities. Some of their direct responses are presented below:

It helped me to improve my scientific process skills because to come up with a claim we have to experiment with the simulation and completely analyze the result. (Student 3)

Yes. It helped me to brainstorm ideas in a way that helps every one of us. we also hypothesize whenever we're learning new topics about Physics. (Student 21)

Yes, I believe that the activities have helped me improve my scientific process skills. In a way, we were exposed to scientific inquiries long before, so those skills have been honed even more now that the classes are face-to-face. Through time, it has become easier to make claims and reasoning and gather evidence. When there are peer evaluations, I can also observe that the claims and reasoning of other groups make sense, so I feel that not only my scientific process skills have improved but also those of my other classmates. (Student 14)

The students' responses above depict that the process of constructing a scientific argument, which involves making a claim, providing evidence, and reasoning, enhanced their science process skills. They stated that they needed to carefully examine the assigned virtual simulations and analyze the data in order to come up with a sound and correct argument. In this process, they also engaged in formulating hypotheses and communicated these with their groupmates. With repeated exposure to these activities, they claimed that their ability to develop such skills had progressed, making it easier for them to generate scientific arguments in the succeeding activities. Additionally, the opportunity to observe and analyze their peers' arguments stimulated their inquiry skills. Furthermore, students explicated on the stages of the PhET-integrated MADI approach that assisted them in developing science process skills. Some of the interview excerpts are provided below.:

The part I like the most is the argumentative session in which we get to convey our ideas to other groups as well. It also improves our critical thinking and how we communicate with other people. (Student 22)

The argumentation session and the data gathering in the PhET simulation helped my scientific process skills. (Student 5)

The part of the lesson that I like the most is when we'd explore the simulations because there are different variables that give off different results as well. (Student 25)

Students reported that the argumentation sessions aided them in communicating their findings through the inquiry-based activity they conducted using the simulations. Engaging in such activities allowed them to develop critical thinking skills as they were exposed to different ideas conveyed by their classmates.

Students' Learning Attitudes towards Physics

Students' favorable responses in the eight attitudinal domains of the CLASS-Phy instrument were examined to determine changes in students' learning attitudes towards Physics before and after exposure to the PhET-integrated MADI approach. According to Adams et al., (2006), students' responses are classified as either favorable or unfavorable, wherein favorable responses are identified as expert-like responses, while unfavorable responses are the opposite. The shifts in students' favorable and unfavorable responses are shown in Table 8.

Table 8
Students' learning attitudes towards physics

Categories	ALL	Number:	26	Diff. of Avgs	Avg. of diffs	*p*
	Status	PRE	POST	SHIFT	SHIFT	
Overall	fav	64.64	63.89	-0.7	-0.7	.680
(All 36 Q's with expert response)	unfav	35.36	36.11	0.7	0.7	
All categories	fav	70.56	68.34	-2.2	-2.2	.233
(26 Q's that appear in below categories)	unfav	29.44	31.66	2.2	2.2	
Personal Interest	fav	74.36	71.79	-2.6	-2.6	.367
	unfav	25.64	28.21	2.6	2.6	
Real World Connection	fav	84.62	76.92	-7.7	-7.7	.267
	unfav	15.38	23.08	7.7	7.7	
PS General	fav	80.77	78.37	-2.4	-2.4	.393
	unfav	19.23	21.63	2.4	2.4	
PS Confidence	fav	79.81	82.69	2.9	2.9	.564
	unfav	20.19	17.31	-2.9	-2.9	
PS Sophistication	fav	46.79	51.92	5.1	5.1	.246
	unfav	53.21	48.08	-5.1	-5.1	
Sensemaking/Effort	fav	86.81	84.62	-2.2	-2.2	.408
	unfav	13.19	15.38	2.2	2.2	
Conceptual understanding	fav	57.05	53.85	-3.2	-3.2	.582
	unfav	42.95	46.15	3.2	3.2	
Applied Conceptual understanding	fav	37.36	39.56	2.2	2.2	.566
	unfav	62.64	60.44	-2.2	-2.2	

Note: $^*p < .05$; a) Paired t-test; b) Wilcoxon-signed rank test

As can be gleaned in Table 8, the findings revealed that among the dimensions of students' learning attitudes toward Physics, only problem-solving sophistication and applied conceptual understanding recorded positive shifts following the study. Conversely, personal interest, real-world connection, general problem-solving ability, confidence, sensemaking/effort, and conceptual understanding all showed negative shifts. Overall, there was a slight negative shift of 0.7 across all dimensions of learning attitudes toward Physics. Despite these shifts, no significant differences ($p > .05$) observed across all dimensions, indicating that the PhET-integrated MADI instructional approach did not have a significant impact on students' learning attitudes toward Physics.

Table 9
Thematic analysis of the students' interview responses

Main Theme	Subthemes	Codes
development of learning attitudes	development of optimistic attitude to Physics	fun learning
		gain knowledge and skills
		positive attitude
		change in perspective
		collaboration
		interest
		study habits
	expounding learning opportunities	real-life application
		activity
		sensible concepts
	learners' perceived lack of interest	pessimistic attitude
		dislike Physics
		neutral

The interview responses of students were subjected to a thematic analysis (Table 9). As one of the emerging subthemes, students asserted that they have developed positive attitudes toward Physics learning as a result of their learning experiences. The following are some students' responses:

I also believe that the activities have helped me develop a positive attitude toward Physics lessons. It was effective because the scientific concepts that I couldn't grasp before made more sense, and I now understand better the situations in my life that I couldn't understand before. And I also believe that this is also what my other classmates think. And with that, the activities and the PhET simulations developed in us a positive attitude toward Physics. (Student 14)

Because unlike before, my interest in Physics grew and I became more interested towards learning Physics. (Student 22)

It [MADI intervention] did [improve the confidence]. I am positive that when there is a Physics question, I can trust myself to give an answer and defend it. (Student 19)

The students reported that the use of the PhET-integrated MADI approach helped them foster a positive attitude towards learning Physics by making it easier for them to understand the lessons and appreciate their real-life applications. They also indicated that the approach increased their interest in Physics learning and boosted their confidence in answering Physics-related questions and articulating explanations about the subject matter. Moreover, the students affirmed that the PhET-integrated MADI approach offered a diverse range of learning opportunities that emphasized practical application and hands-on experience. Here are some selected excerpts from the interviews:

Through answering the activities, I understand more how Physics is important to our daily lives and how big is the contribution of Physics for our everyday living. The feeling of understanding Physics is great, I was able to compare what am I doing everyday and what I am learning about Physics. (Student 24)

I like simulating the most. It's more of a real-time version of examples that a teacher gives during lectures. (Student 15)

If for a positive attitude, I think I'm realizing the more practical applications of Physics for everyday life. (Student 6)

The students' responses emphasized their ability to gain a deeper understanding and appreciation for Physics and its relevance in their daily lives through the activities provided to them. However, despite the student-centered approach, it was reported by some students that their learning attitudes toward Physics remained unchanged. Some students reasoned out the following:

The equations, because for me, math is a very hard concept to grasp. (Student 1)

Maybe other people would've said yes but I prefer other branches of science to Physics. Yes, I know that learning Physics is sometimes fun because it can change your point of view about something, but it's just not for me. (Student 18)

Students' responses indicate that learning Physics necessitates a grasp of mathematical or computational skills, which can be daunting for them. Specifically, one student expressed a reluctance towards Physics and favored other subjects due to its incompatibility with their skills.

DISCUSSION

This study aimed to explore how the PhET-integrated MADI approach impacted students' conceptual understanding, scientific process skills, and attitudes toward learning Physics. Over a six-week period, students engaged in inquiry-based learning and scientific argumentation through PhET virtual simulations, coupled with metacognitive strategies. Both quantitative and qualitative analyses revealed significant positive effects of this approach on students' understanding of key Physics concepts. The large effect size observed indicates the high efficacy of the PhET-integrated MADI approach in enhancing students' conceptual understanding. This finding aligns with previous studies that have highlighted the benefits of argument-driven inquiry (ADI) on conceptual understanding (Antonio & Prudente, 2021; Hasnunidah & Undang Rosidin, 2024; Işiker & İrfan, 2021; Tucel Deprem et al., 2022).

The students' active engagement in constructing evidence-based explanations and arguments was critical in fostering a deeper understanding of Physics. The combination of inquiry-based learning and scientific argumentation, facilitated by a technology-enhanced metacognitive environment, proved essential to this positive outcome. According to Kepalis et al., (2025), virtual simulations serve as effective tools for students to explore and manipulate key variables, enabling them to visualize complex concepts. In the lesson on projectile motion, students were given opportunities to manipulate variables such as height and initial angle, and observe the resulting changes in energy and speed. This hands-on interaction with simulations fostered a student-centered learning environment, where learners collaboratively constructed knowledge by generating scientific arguments supported by claims, evidence, and reasoning (Yang et al., 2022).

Additionally, Tong et al., (2025) argued that peer collaboration plays a vital role in enriching students' understanding. In the present study, this was evident through meaningful negotiations and peer-review sessions that transpired during the lessons where students communicated their knowledge, identified gaps in their understanding, and achieved a more accurate and shared understanding of the subject matter. Aside from this, the teacher-facilitated reflective post-discussions further addressed misunderstandings, deepening students' comprehension. The integration of metacognitive strategies helped students plan their investigations, activate prior knowledge, monitor their progress, and reflect on their learning. These strategies align with existing research showing that metacognitive support enhances the effectiveness of simulation-based learning (Torrevillas et al., 2025; Wang et al., 2021). Students also reported that these strategies were instrumental in improving their conceptual understanding, reinforcing the positive impact of the PhET-integrated MADI approach.

The present findings reinforce and extend existing literature on the effectiveness of integrating technology and inquiry-based learning in Physics education. For instance, the significant improvement in students' conceptual understanding supports previous meta-analytic findings by Antonio and Castro (2023) and the study of Almadrones and Tadifa (2024), who emphasized that PhET simulations foster active conceptual engagement and improve learning proficiencies. However, unlike earlier studies that solely focused on simulations, the current research uniquely integrates metacognitive scaffolding and structured argumentation, providing a more comprehensive learning experience.

In terms of science process skills, the pre- and post-inventory results indicated a significant increase in students' application of these skills. The moderate effect size suggests a positive impact on students' perceptions of their practice of science process skills. This was further corroborated by the integrated process skills test (IPST) results, which showed substantial improvements in students' overall scores. These findings are consistent with prior studies that demonstrate the effectiveness of ADI in enhancing process skills (Arslan et al., 2023; Belga, 2022). In addition, while Arslan et al. (2023) and Belga et al., (2022) reported gains in science process skills through Argument-Driven Inquiry (ADI), this study confirms that integrating ADI with PhET simulations and metacognitive prompts further enhances integrated process skills such as hypothesizing, operationally defining variables, and designing investigations. Thus, the current study extends these prior works by highlighting the added value of metacognitive elements in simulation-rich environments.

Throughout the study, students had numerous opportunities to apply and refine science process skills. They were encouraged to plan their investigations, form hypotheses, and analyze the data collected through simulations. For example, during the conservation of mechanical energy lesson, students used a simulation to track energy transformations in a pendulum. This hands-on experience enhanced their observation skills and provided concrete learning experiences that involved experimentation and data collection (Cruz et al., 2025). The opportunity to generate questions and evaluate the scientific arguments of peers further developed their communication skills, which are essential components of scientific inquiry.

Regarding attitudes toward Physics, the results indicated no significant changes in students' overall learning attitudes. Despite improvements in problem-solving sophistication and applied conceptual understanding, other dimensions, such as personal interest, general problem-solving, confidence, and real-world connection, showed negative shifts. Several factors may have influenced these results. Some students expressed a preference for subjects less reliant on mathematical concepts, which are integral to Physics (Ibrahim et al., 2019; Wahyu et al., 2017). Additionally, logistical issues such as limited access to laptops and the repetitiveness of certain activities may have contributed to a decrease in enthusiasm. Prolonged exposure to the intervention could have led to fatigue, which also might have dampened students' attitudes. It is possible that students enrolled in the STE program already had positive attitudes and expert-like thinking prior to the intervention.

In spite of these challenges, qualitative data revealed that students exhibited increased enthusiasm and interest in the subject matter. They expressed a greater appreciation for the real-world applications of Physics, suggesting that the PhET-integrated MADI approach fostered a positive shift in their attitudes toward learning the subject. The students' increased interest and understanding demonstrate the potential of this approach to create engaging, constructivist learning experiences that deepen conceptual understanding, enhance science process skills, and cultivate more favorable attitudes toward Physics. Hence, unlike some previous findings (e.g., Ibrahim et al., 2019) which observed persistent negative attitudes toward Physics despite pedagogical innovations, this study presents a mixed result—quantitative data showing no significant attitudinal change, but qualitative data suggesting increased appreciation of real-life applications. This divergence underscores the importance of combining quantitative and qualitative lenses to capture the nuanced effects of instruction.

Despite the promising findings, this study has several limitations. First, the use of a one-group pretest-posttest design without a control group limits the ability to make causal claims about the effectiveness of the intervention. Second, the relatively small sample size and focus on a single class from a specific context may affect the generalizability of the results. Third, while self-report instruments and structured interviews provided valuable insights, they may be subject to response bias. Finally, the intervention duration, although sufficient to capture short-term learning gains, may not reflect long-term retention or attitudinal changes. These limitations highlight areas for future research, such as including control groups, expanding to different grade levels and contexts, and employing longitudinal designs.

CONCLUSION

The findings of this study affirm the effectiveness of the PhET-integrated Metacognitive Argument-Driven Inquiry (MADI) approach in enhancing students' conceptual understanding and science process skills in Physics. Quantitative analyses revealed significant learning gains, particularly in students' ability to apply scientific processes, with moderate to large effect sizes observed across key competencies. While students' attitudes toward Physics did not exhibit statistically significant improvement based on quantitative measures, qualitative interview responses painted a more optimistic picture. Many students reported increased interest, confidence, and appreciation for the relevance of Physics in real-life contexts. These insights suggest that the intervention fostered more favorable dispositions toward the subject, even if not fully captured through traditional attitudinal scales. Overall, the PhET-integrated MADI approach presents a promising pedagogical strategy for supporting deeper learning and reflective scientific inquiry in Physics education.

RECOMMENDATIONS

Based on these findings, it is recommended that teachers consider integrating the PhET-based MADI approach into the teaching of various Physics topics, especially those requiring conceptual understanding and the application of science process skills. To optimize the approach's effectiveness, it would be beneficial to diversify the learning activities. Combining virtual simulations with non-internet-based methods, such as model building, problem-solving tasks, and wet-lab experiments, can help maintain students' engagement and address the challenges observed in their learning attitudes. By doing so, educators can provide a more balanced approach that caters to various learning preferences, fostering a deeper and more sustainable interest in Physics.

Additionally, reducing group sizes in collaborative activities may help minimize instances of social loafing, ensuring that all students actively participate and contribute to the learning process. To further validate the effectiveness of the PhET-integrated MADI approach, future research should involve larger sample sizes, ideally incorporating both experimental and control groups. This would enable a more robust comparison and help establish the intervention's broader applicability.

In terms of research instrumentation, the present study utilized validated and widely accepted tools that effectively captured the intended constructs of the study and demonstrated satisfactory reliability and validity. However, it is recommended that future studies consider integrating alternative or supplementary instruments such as performance-based assessments, structured classroom observations, and digital learning analytics to provide a more holistic evaluation of students' conceptual and process skill development. Moreover, the development or adaptation of localized and culturally relevant tools is encouraged, particularly when assessing affective domains like learning attitudes, to enhance contextual sensitivity and validity in diverse learning environments.

To ensure the successful implementation of this pedagogy, it is highly recommended to design and deliver teacher training programs focused on the PhET-integrated MADI approach. Such programs should provide professional development capitalizing on teachers' competencies on inquiry-based learning, metacognition, and technology integration. Training can include lesson modeling, resource development, and reflective practice to help teachers confidently adopt and adapt this innovative instructional strategy within their own classrooms.

Finally, future studies could explore the integration of the PhET-based MADI approach across other scientific disciplines and educational levels. Investigating its impact on higher-order thinking skills, creativity, and other critical 21st-century competencies would provide valuable insights into its potential for enhancing not only conceptual understanding but also students' readiness for future challenges in science and beyond.

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