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Enhancing critical thinking, metacognition, and conceptual understanding in introductory physics: The impact of direct and experiential instructional models

Endalamaw Dessie [1,2*], Desta Gebeyehu [1], Fikadu Eshetu [1]

[1] Addis Ababa University, Addis Ababa, ETHIOPIA
[2] Madda Walabu University, Bale Robe, ETHIOPIA

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Abstract

This study investigates the impact of three different instructional models, direct instructional model (DIM), experiential learning model (ELM), and their combinations (DIM-ELM) on enhancing critical thinking, metacognition, and conceptual understanding in an introductory physics course. The study included 84 first-year pre-engineering students aged 18-24 years who were enrolled in the introductory physics course at two public science and technology universities in Ethiopia. A quasi-experimental design was used with three intact classes randomly assigned to one of three treatment groups: ELM, DIM, and DIM-ELM. The instruments used to measure the outcomes were the critical thinking test in electricity and magnetism, electricity and magnetism conceptual assessment, and metacognitive awareness and regulation scale in electricity and magnetism. The study used one-way analysis of covariance to examine the impact of instructional models on students' conceptual understanding and critical thinking on the topic of electricity and magnetism, while a one-way analysis of variance was used to analyze the effects of instructional models on metacognition. Results showed that ELM was more effective than DIM and DIM-ELM in enhancing post-test conceptual understanding scores. ELM was also more effective than DIM-ELM method in improving post-test critical thinking scores, with the DIM-ELM showing better results than DIM. However, there were no significant differences in the effects of instructional approaches on metacognition. These findings suggest that ELM may be more effective than DIM and DIM-ELM in improving students' conceptual understanding and critical thinking in physics.

Keywords: instructional models, critical thinking, metacognition, conceptual understanding

INTRODUCTION

In the 21st-century, the rapidly changing world requires a new approach to the teaching and learning of science education. Physics education for the 21st-century aims to foster high-level cognitive skills such as critical thinking, metacognition, and deep conceptual understanding (Bao & Koenig, 2019). Several recent policy documents and research studies suggest that grasping scientific content is insufficient to understand a topic thoroughly. Instead, it is important to delve into a deeper conceptual understanding of content, acquire skills specific to the content (critical thinking), and become aware of one's knowledge of the content, referred to as metacognition (Bao & Koenig, 2019; Committee on STEM Education, 2018; NRC, 2011; Zhang, 2019).

In today's society, critical thinking, which refers to cognitive skills and strategies to support evidence-based decision-making, is considered indispensable (Ennis, 1993; Tiruneh et al., 2018). According to Bao and Koenig (2019) and Putra et al. (2021), physics education should prioritize the development of student's critical thinking skills so they can make informed decisions throughout the learning process. In addition, metacognition, the ability to actively direct and monitor one's thought process while learning (Zohar & Barzilai, 2013, 2015), is essential in today's world. Learners with developed metacognitive skills can identify and bridge knowledge gaps, enabling them to engage in lifelong learning

✉ endalamawmwu@gmail.com **(*Correspondence)** ✉ dgebeyeh68@gmail.com ✉ fik4jju@gmail.com

Contribution to the literature

- This study examines the co-development of critical thinking, metacognition, and conceptual understanding in introductory physics using different instructional models.
- This study explores the effectiveness of a combined approach that blends direct instruction and experiential learning.
- This study aims to provide insights and recommendations for improving physics education and enhancing these important skills among university students.

(Avargil et al., 2018). In addition, physics education should emphasize the importance of linking prior knowledge to new physics phenomena (Bao & Koenig, 2019; Mills, 2016; Shen et al., 2017). Harrison and Gibbons (2013) suggest that a deep conceptual understanding is crucial to equip students to apply their knowledge to real-world scenarios and foster innovation. Ministry of Education in Ethiopia aims to produce university graduates with balanced skills of cognitive and non-cognitive skills and higher-order thinking skills such as critical, creative, and problem-solving skills , and a high degree of digital literacy and recognizes the importance of these skills in the 21st-century (Teferra et al., 2018).

Despite the emphasis on developing critical thinking and metacognition skills in 21st-century science standards (Committee on STEM Education, 2018; NRC, 2011), there is limited research on the development of these skills in specific courses such as introduction to physics (Avargil et al., 2018; Tiruneh et al., 2018; Zohar & Barzilai, 2013). Previous studies have mainly focused on teaching general critical thinking and metacognitive skills rather than integrating them into domain-specific courses to improve domain-specific critical thinking and metacognitive skills (Avargil et al., 2018; Tiruneh et al., 2014, 2018). This research gap can be attributed to a lack of appropriate assessment tools to measure these skills in the context of science learning (Avargil et al., 2018; Tiruneh et al., 2017) and a lack of consensus among researchers as to whether these skills are domain-specific or domain-general (Georghiades, 2004; Thomas et al., 2008; Willingham, 2008).

However, recent studies (Avargil et al., 2018; Ngajie et al., 2020; Viennot, 2019; Zhao et al., 2019) suggest that critical thinking and metacognition are domain-dependent and should be integrated into domain-specific learning environments. We argue that critical thinking and metacognition skills are most effectively taught in the domain-specific context of physics education rather than as generic or non-discipline-specific skills as suggested by Davies (2013), Gunstone (2013), Willingham (2008), and Yuruk et al. (2009).

Teaching physics, particularly electricity and magnetism (E&M), can present challenges for students due to the abstract and intricate nature of the concepts being taught. E&M is a fundamental subject in physics underlying more advanced concepts and technologies (Chabay & Sherwood, 2006). Still, it can be challenging to teach and understand due to its abstract and intangible nature. Traditional classroom teaching methods often fail to deeply understand concepts of E&M (Dega et al., 2013). Despite instructional strategies and conceptual change efforts, persistent misconceptions about E&M exist (Dega, 2012, 2019; Dega et al., 2013; Mbonyiryivuze et al., 2019; McColgan et al., 2017; Shaikh et al., 2017). Science education researchers (Kervinen et al., 2020; Na & Song, 2014) attribute these difficulties partly to the lack of connection between scientific knowledge and students' everyday experiences during learning and teaching process. To address this problem, they advocate teaching strategies that integrate science into the context of students' daily lives (Kang et al., 2016). These approaches can increase the accessibility and engagement of science education and allow students to develop a deeper understanding of complex science concepts such as E&M (Kervinen et al., 2020).

Given the challenges in teaching E&M, innovative learning approaches are necessary to improve students' critical thinking, metacognition, and conceptual understanding. Therefore, this study aims to compare the effectiveness of three instructional models, namely direct instructional model (DIM), the experiential learning model (ELM), and DIM-ELM (a combination of DIM and ELM), in improving students' critical thinking, metacognitions, and conceptual understandings in the context of introductory physics, specifically E&M.

Previous research mainly investigated critical thinking, metacognition, and conceptual understanding in isolation or binary combinations. However, experts in the field recommend focusing on the joint development of these three outcomes to gain a more comprehensive understanding of the learning process (Viennot, 2019; Viennot & Décamp, 2015). By examining the co-development of critical thinking, metacognition, and conceptual understanding, we can improve physics education and enhance these important skills among university students. Additionally, while some studies have compared the effectiveness of different models separately (Chinaka, 2021; Liou, 2021), recent research suggests that combining DIM and ELM models offers a unique opportunity to blend the strengths of both methods (Schuster et al., 2018; You, 2022).

Our research aims to provide insights into the potential benefits of this combined approach and how it can enhance critical thinking, metacognition, and conceptual understanding in introductory physics. Moreover, the study seeks to propose theoretically sound and empirically valid instructional models that enhance these important learning outcomes.

Objectives of the Study

The main objective of this research is to examine and compare the effectiveness of three instructional strategies, namely ELM, DIM, and DIM-ELM, on enhancing the critical thinking skills, metacognition, and conceptual understanding of students in introductory physics. Thus, the specific objectives of the study are to

(1) compare the effectiveness of ELM, DIM, and DIM-ELM in improving students' conceptual understanding of E&M,

(2) determine the comparative effectiveness of the instructional strategies in enhancing critical thinking in E&M, and

(3) assess the relative effectiveness of the learning strategies in improving students' metacognitive awareness and regulation in E&M.

Research Hypotheses

1. There is no statistically significant difference in the conceptual understanding of students who receive instructions using ELM, DIM, and DIM-ELM in the context of E&M.
2. There is no statistically significant difference in students' critical thinking skills who receive instruction using ELM, DIM, and DIM-ELM in the context of E&M.
3. There is no statistically significant difference in the metacognitive awareness and regulation of students who receive instruction using ELM, DIM, and DIM-ELM in the context of E&M.

LITERATURE REVIEW

Direct Instructional Model

DIM, as defined by Eggen and Kauchak (2011), is an instructional approach in which the teacher is the central figure in the learning process. The teacher takes on the task of providing explanations, demonstrating concepts, encouraging critical thinking, and providing feedback to students (Bell et al., 2011). Students, on the other hand, actively participate in the learning process by listening carefully, analyzing information, participating in discussions, answering questions, and completing tasks independently (Kruit et al., 2018).

Research has shown that DIM effectively improves student learning outcomes across all disciplines, based on a meta-analysis of 50 years of research (Stockard et al., 2018). In addition, DIM is more effective than inquiry-based learning in fostering diverse skills, such as learning process skills and experimental designs, in science classrooms (Hushman & Marley, 2015). However, a study comparing inquiry-based instruction and DIM in middle school science education found no significant differences in students' understanding of science concepts (Schuster et al., 2018). In contrast, a study conducted in Taiwan showed that DIM positively impacted students' academic performance, while inquiry-based learning did not produce the same results (Liou, 2021). Additionally, a recent study by Kim et al. (2012) analyzed data from the program for international student assessment (PISA) 2015 and found that DIM was positively associated with science literacy, while inquiry-based instruction was negatively associated with science literacy. In sum, the effectiveness of inquiry-based instruction and DIM in promoting students' conceptual understanding, achievement, and motivation in science is still debated in the current literature.

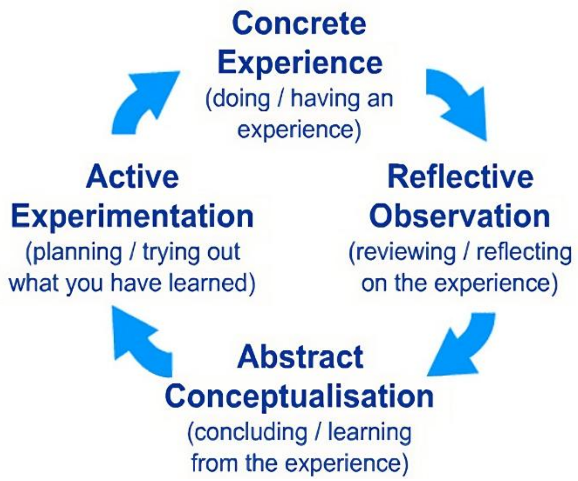

Figure 1. Experiential learning model (Kolb, 2014)

Experiential Learning Model

ELM (**Figure 1**) is an instructional approach based on constructivist theory. According to this model, learners construct knowledge by actively engaging with their experiences and ideas (Dewey, 1986; Kolb, 2017; Kolb & Kolb, 2009). ELM follows Kolb's (2017) four-phase model, which involves four learning modes that occur sequentially in a cycle. In this cycle, learners actively participate in a learning experience, reflect and analyze their experiences, draw conclusions, and apply their learning to new situations (Kolb, 1984). Through this cyclical process, learners can create knowledge by starting from concrete learning experiences (contextualizing knowledge) and turning them into abstract generalizations (de-contextualizing knowledge) and applying this new knowledge in other learning experiences (re-contextualizing knowledge) (Radović et al., 2021). ELM is highly beneficial in formal education as it helps students develop a deeper understanding and become more thoughtful, reflective, and critical (Roberts, 2018).

ELM is unique compared to other learning models because it emphasizes the interaction between experiences, thoughts, and behaviors that facilitate learning, resulting in a comprehensive understanding of the learning process, as noted by Healey and Jenkins (2000) and Kolb and Kolb (2009). ELM is advantageous in science education as it prompts students to identify and produce discoveries while exploring scientific processes using the elements and context of each learning (Alkan, 2016; Levy & Moore Mensah, 2020). This method fosters engagement and encourages questioning, critical thinking, experimentation, and reasoning.

Empirical research has provided evidence of the effectiveness of ELM in various fields, including art, machine learning, mathematics, science, technology, and clinical practices. A meta-analysis of 89 studies over 43 years has demonstrated that students taught using ELM outperform those taught with traditional methods (Burch et al., 2019). Falloon (2019) found that implementing ELM through simulation activities improves elementary students' understanding of physical concepts and reflective thinking, resulting in enhanced knowledge. Additional studies have indicated that ELM enhances student motivation and interest in science and mathematics (Weinberg et al., 2011), impacting student achievement and scientific process skills in chemistry (Alkan, 2016). A study by Samba et al. (2020) investigated the effects of graphic organizers (GO) and ELM with feedback on the academic performance and critical thinking skills of 75 junior secondary students in Plateau State, Nigeria. The study found that GO and ELM strategies positively impacted students' academic performance and critical thinking. Still, there was no significant difference in the post-test mean scores for achievement and critical thinking strategies. However, a comparative study by Chinaka (2021) on the effects of physics education technology simulation and ELM on students' understanding of projectile motion showed that physics education technology simulation was more effective in improving conceptual understanding. The study was conducted with a sample of 154 first-year physics students at a public university in South Africa, and the one-way analysis of variance (ANOVA) test results indicated that the physics education technology simulation groups scored significantly higher on the post-test than the phenomenon-based ELM groups.

Although the above literature asserts the effectiveness of ELM in learning and skill development, there is a lack of research that specifically evaluates whether ELM enhances students' critical thinking, metacognitions, and conceptual understandings in the context of introductory physics, specifically E&M.

Experiential Learning Model Versus Direct Instructional Model

The differentiation between the DIM and ELM pedagogical approaches pertains to how learners acquire fundamental concepts and principles. DIM involves the teacher presenting established scientific knowledge as the foundation of the subject matter (Schuster et al., 2018). On the other hand, ELM involves learners and instructors co-constructing the core concepts through inquiry, observation, and exploration, emphasizing the construction of understanding through experiences and interactions during the learning process (Kolb, 2017). This new information is integrated into the learner's long-term memory via their pre-existing knowledge structures or schemas. In the ELM approach, students engage in exploratory activities before constructing concepts and principles with the teacher. Both approaches seek to involve learners actively with the subject matter, but the difference lies in how the information is presented and knowledge is acquired. The differentiation is not between passivity and engagement or hands-on versus non-hands-on, as practical activities can occur in both models, but they are framed and sequenced differently (Schuster et al., 2018). This understanding of DIM and ELM, with the roles of teachers and students defined as such, has been applied in our research.

Debates

Educational researchers have long debated how to teach students most effectively. Some advocate teacher-led instruction (Stockard et al., 2018), while others support it (Freeman et al., 2014; Hake, 1998) student-led approaches. The empirical evidence for the superiority of one method over another is mixed, suggesting an interaction between the two general methods and specific features of the instructional context (e.g., type of learner, classroom culture, instructional content) and the desired outcomes (de Jong, 2019; Schuster et al., 2018). Theoretical aspects of this issue focus on different features of the learning process. Direct instruction advocates argue that unguided or minimally guided tax the limits of human cognitive architecture, mainly by increasing cognitive load (Kirschner et al., 2006). Unguided or minimally guided advocates argue that open-ended instructional methods enable learners to ultimately achieve deeper learning through exploration (Dean & Kuhn, 2007). By shifting the focus to more nuanced and context-specific questions about what works best for whom and in which area, a more productive conversation about the optimal combinations of teaching approaches can occur (de Jong, 2019; Schuster et al., 2018).

Combination of Direct Instructional Model With Experiential Learning Model

A compelling and effective solution to the long-standing debate over the optimal method for educating students is to introduce a combination of DIM and ELM. This combined approach leverages the unique strengths of both methods, resulting in a comprehensive education that provides a solid knowledge base and fosters practical skills (Schuster et al., 2018; You, 2022). DIM provides a clear and structured framework for building the foundational knowledge needed for success. In contrast, ELM encourages active engagement with the material and hands-on learning, leading to a deeper understanding of the subject and a more meaningful learning experience. Combining these two methods provides students with clear guidance while allowing them to actively engage with the material and apply their knowledge in real-world environments. The benefits of this synergistic approach have been well documented, with DIM reducing cognitive load by accommodating human cognitive limitations and ELM encouraging active knowledge building and multi-skill development (Kirschner et al., 2006).

THEORETICAL FRAMEWORK

The present study is built on two significant theories: Ausubel's (1963) meaningful learning theory and Sweller's (1994, 2000) cognitive load theory. Ausubel's (1963) meaningful learning theory posits that learners construct new knowledge by connecting it to their existing knowledge structures through active engagement with the learning material. This is consistent with constructivist learning (ELM) principles, which highlight the importance of learners' interactions with their environment in the learning process. The theory also provides a practical framework for designing effective instructional strategies and evaluating their impact (Ausubel, 1963). The present study can effectively analyze and assess the outcomes of different teaching approaches by utilizing this theory.

Furthermore, the study incorporates Sweller's (1994) cognitive load theory, which provides recommendations for instructional design that addresses the limitations of working memory. The theory distinguishes between intrinsic cognitive load, which refers to the complexity of the materials' elements and how they relate to each other in a learner's existing knowledge structure, and extraneous cognitive load, which pertains to the manner of presenting the learning material. Germane's cognitive load is the cognitive load required to learn effectively (Sweller, 2020). The theory offers strategies for reducing extraneous and intrinsic cognitive load while maximizing Germane cognitive load, which are critical in improving students' critical thinking, metacognition, and conceptual understanding of introductory physics (Sweller, 2020).

RESEARCH METHOD

Participants and Research Design

This study included 84 first-year pre-engineering students, 64 males, and 20 females, aged 18-24 years, enrolled in an introductory physics (Phys1011) course at two public science and technology universities in Ethiopia. The universities were chosen for their similar entry requirements (entrance exams and higher education admission scores) and academic calendars. The study used a type of research design called quasi-experimental, which means that it did not randomly assign individual students to different groups, but instead used existing groups that were already formed (Creswell & Creswell, 2017). These existing groups are called intact classes. The study chose three intact classes randomly from the two universities, with two classes from university 1 (ELM [n=28] and DIM [n=29]) and one class from university 2 (DIM-ELM [n=27]). Then, the study randomly assigned each intact class to one of three different treatments: ELM (n=28), DIM (n=29), or DIM-ELM (n=27).

Instructions

Our study focused on instructional interventions in a first-year algebra-based introductory physics course that covered various topics, including fluids, waves, thermodynamics, electricity, and magnetism. Specifically, our interventions targeted the topics of E&M, which included electrostatics, direct current (DC) electric circuits, and magnetism. Participants in the study were enrolled in the same course at two different universities and received identical credit hours and content from a nationally standardized module. We implemented instructional activities in three different groups: ELM, DIM, and DIM-ELM, with each group receiving unique instructional activities tailored to specific learning objectives. This study provides a detailed account of the sample lessons on electrostatics and the various instructional activities implemented for each group.

Example in experiential learning model

ELM involves four phases: concrete experience (CE), reflective observation (RO), abstract conceptualization (AC), and active experimentation (AE) (Kolb, 1984). In CE phase, learners need real-life examples and event involvement. RO phase involves developing different perspectives by reflecting on what is learned and observed. AC involves focusing on logic, thought, and concepts, while AE phase allows students to learn by implementing and applying what they learn. **Table 1** shows sample lesson on electrostatics based on ELM.

Table 1. Sample lesson on electrostatics based on ELM

ELM stages	Application to lesson on electrostatics
CE	Conducting experiments to observe electrostatic phenomena, such as rubbing a balloon on wool and sticking it to a wall or charging a Styrofoam ball with a charged rod and observing its motion.
RO	Reflect on observations and experiences, share observations and questions with groups, and discuss discrepancies or surprises.
AC	Applying abstract concepts such as Coulomb's law, electric field, and electric potential to explain observations and answer questions.
AE	Assign student's tasks to investigate real-life applications of electrostatics. This can involve researching and presenting how electrostatics is used in technology, industry, or everyday life. Have them design their experiments to explore the behavior of charged particles in these contexts.

Table 2. Sample lesson on electrostatics based on DIM

DIM phases	Application to lesson on electrostatics
Introduction and review	Review previous content on the basics of electric charge and Coulomb's law, introduce the concept of electrostatics and its applications in different fields and assess student motivation and learning goals.
Teacher presentation	Explain the properties of electric charge, electric field, and electrostatic force, demonstrate the process of charging objects and their behavior. Give specific examples of electrostatic phenomena such as lightning, electric fields in everyday objects such as balloons and hair.
Guided practice,	Assign students to work in pairs and provide them with objects to charge and observe. The teacher provides guidance and scaffolding for the students as they conduct their experiments.
Independent practice	Assign students to complete an independent worksheet on properties of electrostatic force & process of charging objects & complete an assessment activity such as a quiz or essay to assess student learning.

Example in direct instructional model

This study used an updated DIM by Eggen and Kauchak (2011) to design E&M classroom activities. The DIM has four phases:

1. introduction and review,
2. teacher presentation,
3. guided practice, and
4. independent practice.

In the first phase, teachers review previous content, assess student motivation, and review student learning goals. In the second phase, teachers impart new knowledge through concrete examples and modeling. During the third phase, students apply the newly learned information through guided activities, and the instructor works directly with the students through supervision and scaffolding. Finally, students' complete independent exercises such as homework and assessment activities. **Table 2** shows sample lesson on electrostatics based on DIM.

Example in direct instructional model-experiential learning model

Blended learning approaches that combine both DIM and ELM methods can be an effective way to reduce students' cognitive load during learning. By integrating DIM into the different stages of ELM, students are provided with frameworks and structures to help them navigate complex concepts and build on their knowledge (Sweller, 2020). Using DIM in ELM can break difficult concepts into manageable chunks, providing students with feedback and guidance as they move through the learning experience. This allows students to engage in direct experience and experimentation while receiving the support they need to process and apply new information effectively.

Begin with a pre-assessment: Use the first stage of DIM to assess the students' existing knowledge, skills, and motivation for learning the topic. This information can help you tailor your teaching approach to the needs of your students.

Provide concrete experiences: In the first stage of ELM, provide students with direct experiences and observations of the topic. This can be done through hands-on activities, demonstrations, or simulations.

Reflective observation: In the second stage of ELM, encourage students to reflect on their experiences and observations. Use the second stage of DIM to provide students with feedback on their performance and clarify misunderstandings.

Abstract conceptualization: In the third stage of ELM, help students apply abstract concepts to explain their observations and develop a deep understanding of the topic. Use the third stage of DIM to provide guided practice and feedback on how to apply the new knowledge.

Active experimentation: In the fourth stage of ELM, encourage students to investigate real-life applications of the topic and design their experiments. Use the fourth stage of DIM to assign independent practice exercises, such as homework or assessment activities, that allow students to apply what they have learned. **Table 3** shows sample lesson on electrostatics-based DIM-ELM.

Table 3. Sample lesson on electrostatics-based DIM-ELM

DIM stages	ELM stages	Descriptions
Introduction & review	CE	Begin the lesson by reviewing previous content and assessing student motivation and learning goals. Then provide hands-on activities and experiments for students to observe and experience electrostatic phenomena.
Teacher presentation	RO	Present new insights and concepts through concrete examples and modelling. After each presentation, allow students time to reflect on their experiences and share observations with their classmates. Encourage critical thinking and metacognition.
Guided practice	AC	Have students apply the newly learned information through guided activities that require them to apply abstract concepts such as Coulomb's law and electrical potential to explain their observations and develop a deeper understanding of the topic.
Independent practice	AE	Assign tasks for students to explore real-world applications of electrostatics. It can be about research & presentation of application of electrostatics in technology, industry, or everyday life. Let them design their own experiments to study behavior of charged particles in these contexts.

Intervention Procedures

This study is a quasi-experimental, three-group, pretest-posttest design. It involved administering various instruments and classroom instructions. The interventions were developed for all three conditions and executed during the academic year of 2021/2022, spanning five weeks, with three 50-minute lessons per week. To ensure consistency in the implementation of the interventions, teachers with the same level of education and equivalent years of teaching experience were enlisted. These teachers were provided with all relevant information concerning the purpose and design of the interventions. The study's first author was responsible for monitoring the execution of the interventions to control for potential teacher effects.

Instruments

Critical thinking test electricity and magnetism (CTEM) developed by Tiruneh et al. (2017) was used to assess students' critical thinking abilities in E&M. 12 of the original 20 CTEM questions were adopted, either with minor changes or without, and eight questions were rejected. Only 12 items were chosen to correspond with the course content. The modified test items were then presented to experts and experienced teachers for feedback before being adopted. Students had 50 minutes to complete the test. The questions are a mix of forced-choice and open-ended responses. For example, when a statement is presented, the student is asked to indicate whether it is correct or incorrect and then explain their choice. Pilot testing revealed that the modified version of the test had an acceptable level of internal consistency (Cronbach's alpha=0.74) (Nunnally, 1978) and a maximum score of 40. A scoring guide was also provided with CTEM.

Electricity and magnetism conceptual assessment (EMCA) test developed by McColgan et al. (2017) was used to assess students' conceptual understanding of E&M. EMCA is a multiple-choice test with correct answers and misconceptions as distractors. According to McColgan et al. (2017), the reason for developing this test was that other available assessments, such as the brief electricity and magnetism assessment and the conceptual survey on electricity and magnetism, were not comprehensive enough to cover the breadth of content covered in the topic. EMCA, on the other hand, is a more refined and precise tool for assessing students' level of understanding of E&M. The original test included 30 multiple-choice questions. However, this study's analysis was based on only 21 expert-validated questions covering electrostatics, DC circuits, and magnetism. After pilot testing, the EMCA processing time was between 30 and 40 minutes and demonstrated an acceptable level of reliability with an alpha value of 0.76 (Tabachnick et al., 2013).

The metacognition awareness and regulation in electricity and magnetism (MARS-EM) assessment tool was developed by researchers to evaluate university students' metacognition in the context of E&M. The development process involved a literature review of existing metacognition instruments in science, followed by the creation of a 15-item MARS-EM item pool informed by Schraw and Dennison (1994). The content validity of MARS-EM was established through expert review, resulting in the exclusion of three items.

Then MARS-EM was administered to 200 pre-engineering students at Addis Ababa science and technology university, and the results were analyzed using exploratory factor analysis (EFA). Before EFA, the assumptions for factor analysis was checked. Bartlett's test of sphericity was significant (χ^2=403, df=45, p<.001), indicating that the correlations between variables are sufficiently large for factor analysis. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.733, indicating that the sample size is adequate for factor analysis (Hu & Bentler, 1999). The final version of MARS-EM consisted of two factors with eight items. The inter-factor correlations table showed a moderate positive relationship between the two factors, with a value of 0.209. The model fit measures also suggest that MARS-EM fits the data well. The root mean square error of approximation (RMSEA) with a 90% confidence interval (CI) of 0.00 to 0.0538 is considered an acceptable fit, and Tucker-Lewis index (TLI) of 1.08 further supports this conclusion. The Bayesian information criterion (BIC) value of -59.2 is another indication of a good fit for the data, and the non-significant p-value of 0.706 from the Chi-square test (χ^2) with 9.85 and 13 degrees of freedom confirms this result (Hu & Bentler, 1999).

The reliability of MARS-EM was assessed by calculating Cronbach's alpha reliability coefficient, which was found to be 0.69 for the first factor (metacognitive awareness), 0.71 for the second factor (metacognitive regulation), and 0.74 for the entire scale. These results suggest that MARS-EM is reliable (Tabachnick et al., 2013). MARS-EM was administered to participants in pre-and post-test formats, with the main objective of contextualizing the development of metacognition within the specific content of E&M.

Data Analysis

The data were analyzed using both descriptive and inferential statistics. The study used the one-way analysis of covariance (ANCOVA) to examine the impact of different instructional approaches (DIM, ELM, and DIM-ELM) on students' conceptual understanding and critical thinking in E&M. ANCOVA, a statistical method known for controlling the effects of pre-test scores, was used to ensure that any observed differences in post-test scores were due to the instructional approach and not the pre-test scores (Köhler et al., 2021). However, the study used ANOVA to analyze the effects of instructional approaches on metacognition, as pre-test scores did not significantly impact post-test scores. Bonferroni adjustment was applied to the alpha level of the follow-up ANCOVA to control the type I error rate (Tabachnick et al., 2013)

RESULTS AND DISCUSSION

Effects of Instructional Strategies on Students' Conceptual Understanding in Electricity and Magnetism

Before investigating the effects of learning conditions on students' conceptual understanding of E&M, the assumptions underlying ANCOVA model, and the nature of the data were thoroughly examined. Results indicated that pre-EMCA covariate significantly affected post-EMCA scores ($F[1, 78]=8.685$, $p=.004$). Bivariate correlation analysis showed a significant positive correlation between post-EMCA and pre-EMCA scores ($r=.344$, $p=.025$). The normality assumptions for the three learning groups were met, as confirmed by Shapiro-Wilk test (ELM: $p=0.665$, DIM: $p=0.74$, and DIM-ELM: $p=0.650$). The assumption of equal variances for post-EMCA between the two groups was met, as indicated by Levene's test of equality of error variances ($F[2, 81]=2.692$, $p=.074$). The non-significant groups*pre-EMCA interaction effect ($F[2, 78]=.401$, $p=.671$) supported the use of ANCOVA in examining the effects of learning conditions on students' conceptual understanding in E&M. After adjusting for pre-EMCA scores, F test showed a significant effect of learning groups on post-EMCA scores ($F[2, 78]=8.896$, $p<.001$, partial eta squared=.186). **Table 4** shows descriptive and inferential statics for learning groups on post-EMCA scores.

Pairwise comparisons of the mean post-EMCA scores by learning group revealed significant differences between ELM and DIM groups (mean difference=2.090, S.E.=.535, $p=.001$) and between ELM and DIM-ELM groups (mean difference=1.824, standard error [SE]=.544, $p=.004$). However, DIM and DIM-ELM groups' mean difference was insignificant (mean difference=.266, SE=.537, $p=1.000$). These results were adjusted for multiple comparisons using the Bonferroni method (**Table 5**).

Based on the findings, it can be concluded that ELM method was more effective in improving post-EMCA

Table 4. Descriptive & inferential statics for learning groups on post-EMCA scores

Learning groups	n	Mean	Standard deviation	Adjusted mean	Standard error	F	η^2
ELM	28	11.71	2.242	11.832	0.384	8.896	0.186
DIM	29	9.79	2.274	9.742	0.373		
DIM-ELM	27	10.11	1.649	10.008	0.386		
Total	84	10.54	2.225				

Table 5. Pairwise comparisons for post-EMCA scores among learning groups

Learning groups	Mean difference (I-J)	Standard error	95% confidence interval	Sig.
ELM vs. DIM	2.090*	.535	(.781, 3.400)	.001
DIM vs. DIM-ELM	.266	.537	(-1.047, 1.579)	1.000
ELM vs. DIM-ELM	1.824*	.544	(.493, 3.156)	.004

Note. **Table 5** shows mean difference, standard error, confidence interval, & significance level for comparison of different learning groups on post-EMCA scores based on estimated marginal means; Significance level is indicated by *$p<.05$; & Bonferroni correction was applied to control for type I error rate scores than DIM method (mean difference=2.090, SE=.535, p=.001). ELM method was more effective than DIM-ELM method, although the difference was not as pronounced (mean difference=1.824, SE=.544, p=.004). However, DIM and DIM-ELM methods did not differ significantly in terms of their effect on post-EMCA scores (mean difference=.266, SE=.537, p=1.000).

These findings are consistent with prior research that suggests experiential learning. Experiential learning connects real-life experiences to learning objectives and motivates students to learn. Experiential learning is suitable for this complex professional field because it lets students construct knowledge in a continuously strengthened way, which can help students learn (Konak, 2018). Experiential learning involves allowing learners to have CEs, reflect on them, construct knowledge, and verify it through active experimentation (McMullan & Cahoon, 1979). This approach has been recognized as an effective teaching principle (Kolb, 1984; Murrell & Claxton, 1987) and can deepen learners' understanding of content by using different learning modes (abstract, concrete, reflective, and active) (Zhai et al., 2017). However, the study's findings contradict prior research suggesting combining both methods' advantages is the best approach for effective science teaching (Schuster et al., 2018; You, 2022). It is also inconsistent with other research that has found no statistically significant differences in student science conceptual understanding between inquiry instruction and direct instruction in middle school science lessons (Schuster et al., 2018). Possible reasons for these discrepancies include students' lack of prior experience with the instructional methods used in the interventions, which might require more time to produce noticeable benefits.

Effects of Instructional Strategies on Students' Critical Thinking in Electricity and Magnetism

Preliminary assumptions checks were performed to assess normality, linearity, homogeneity of variances, and homogeneity of regression slopes. The main effect of pre-CTEM on the dependent variable was significant (F[1, 78]=7.644, p=.007), indicating that participants' pre-test scores had a significant impact on the dependent variable. A bivariate correlation analysis showed a significant positive and moderate relationship between pre-CTEM and post-CTEM variables (r=.320, p=.008), satisfying the linearity assumption. Shapiro-Wilk test revealed that the normality assumption was met for all three learning groups (ELM, DIM, and DIM-ELM) with p-values of .665, .742, and .641, respectively. The interaction between groups and pre-CTEM was insignificant (F[2, 78]=.767, p=.468), suggesting that the effect of pre-CTEM on the dependent variable did not differ significantly across the groups, satisfying the homogeneity of regression slopes assumption. Finally, Levene's test of equality of error variances showed no significant difference across the groups (F[2, 81]=7.131, p=.130), satisfying the homogeneity of variances assumption.

The univariate F test conducted on the effect of learning groups on post-CTEM yielded a statistically significant result (F[2, 80]=12.69, p<.001), indicating that there was a significant difference in the mean post-CTEM scores across the three learning groups (**Table 6**).

In order to further examine these differences, pairwise comparisons were conducted between the three groups (**Table 7**).

The results of the pairwise comparisons indicated that the mean post-CTEM score for ELM group was significantly higher than that of DIM group (mean difference=3.10, SE=.66, p<.001). Furthermore, the mean post-CTEM score for ELM group was also found to be significantly higher than that of DIM-ELM group (mean difference=.68, SE=.69, p=.991), while the mean post-CTEM score for DIM-ELM group was significantly higher than that of DIM group (mean difference=2.42, SE=.66, p<.001). The multiple comparisons were adjusted using Bonferroni correction. These results suggest that ELM group had a significantly higher mean

Table 6. Descriptive & inferential statics for learning groups on groups' post-CTEM scores

Learning groups	n	Mean	Standard deviation	Adjusted mean	Standard error	F	Partial η^2
ELM	28	17.25	2.675	16.968	0.474	12.688	.000
DIM	29	13.86	1.382	13.865	0.454		
DIM-ELM	27	16.00	3.234	16.289	0.483		
Total	84	15.68	2.876				

Note. Covariates appearing in model are evaluated at following values: pre-CTEM=9.18; F test evaluates effect of learning groups; & This test is based on linearly independent pairwise comparisons among estimated marginal means

Table 7. Pairwise comparisons for post-CTEM scores among learning groups

Learning groups	Mean difference (I-J)	Standard error	p-value	95% confidence interval
ELM vs. DIM	3.104*	.656	.000	(1.499, 4.708)
DIM vs. DIM-ELM	0.679	.694	.991	(-1.017, 2.375)
ELM vs. DIM-ELM	-2.425*	.662	.001	(-4.044, -.805)

Note. Post-CTEM scores were compared among three learning groups (ELM, DIM, & DIM-ELM) using pairwise comparisons; Means, standard errors, p-values, & 95% confidence intervals are reported for each comparison; & Bonferroni adjustment was used to control for multiple comparisons

Table 8. Descriptive, test of homogeneity of variances, robust tests of equality of means, & ANOVA

Learning groups	Pre-MARS-EM			Post-MARS-EM	
	Means	SD		Means	SD
ELM	3.37	0.69		3.98	0.55
DIM	3.33	0.76		3.84	0.62
DIM-ELM	3.12	0.85		3.87	0.64
Total	3.28	0.78		3.90	0.59
Test of homogeneity of variances	Levene statistic	df1	df2	Sig.	
Pre-MARS-EM	9.59	2	81	.000	
Post-MARS-EM	1.40	2	81	.254	
Robust tests of equality of means (wleche)	Statistic	df1	df2	Sig.	
Pre-MARS-EM	1.442	2	50.8	.246	
ANOVA	Sum of squares	df	Mean square	F	Sig.
Pre-MARS-EM	0.974	2	0.487	2.101	.129
Post-MARS-EM	0.318	2	0.159	0.894	.413

Note. SD: Standard deviation

post-CTEM score than DIM and DIM-ELM groups. In addition, DIM-ELM group had a significantly higher mean post-CTEM score than DIM group.

According to our pairwise comparison analysis, ELM group attained significantly higher mean post-CTEM scores than DIM and DIM-ELM groups. This result is consistent with previous research conducted by Tiruneh et al. (2018), which observed that interventions utilizing Merrill's instructional model and including critical thinking through infusion improved skills and content knowledge. Additionally, our findings align with other studies demonstrating that incorporating evaluation tasks in ELM enhances learners' critical thinking abilities (Samba et al., 2020). Scholars have stressed the importance of providing students with genuine observation and experience to promote their critical thinking (Bustami et al., 2018).

Effects of Instructional Strategies on Students' Metacognitive Awareness and Regulation in Electricity and Magnetism

An ANOVA was conducted to compare the mean pre-MARS-EM scores of three learning groups: ELM, DIM, and DIM-ELM, before conducting ANOVA, the normality and variance homogeneity assumptions were assessed. All three groups met the normality assumptions, as demonstrated by the non-significant Shapiro-Wilk test p-values: ELM ($W=0.943$, $df=28$, $p=0.133$), DIM ($W=0.961$, $df=29$, $p=0.348$), and DIM-ELM ($W=0.954$, $df=27$, $p=0.263$). However, the assumption of equal variances across groups was violated ($p<0.001$) according to Levene's test for variance homogeneity, indicating that the variances of the groups were significantly different. A Welch test was performed to address this violation, and no significant difference in group means was found ($F[2, 50.805]=1.442$, $p=0.246$).

After checking the important assumptions of ANOVA, an ANOVA was conducted to compare the means of pre-MARS-EM variable across the three learning groups; the results indicated no significant differences in mean scores among the groups ($F[2, 81]=2.101$, $p=0.129$). This finding implies that the pre-MARS-EM scores of the three learning groups were comparable and did not differ significantly (**Table 8**).

To compare the mean scores of post-MARS-EM in the three learning groups, normality and homogeneity of variance assumptions were checked before conducting an ANOVA. The normality assumption was met for post-MARS-EM variable in all three learning groups, as demonstrated by non-significant p-values from the Shapiro-Wilk test (ELM: $W=.984$, $df=28$, $p=.936$; DIM: $W=.975$, $df=29$, $p=.711$; DIM-ELM: $W=.913$, $df=27$, $p=.670$). The homogeneity of variances assumption for post-MARS-EM variable was tested using various Levene tests. The mean-based Levene test produced a non-significant result ($F[2, 81]=1.396$, $p =.254$), indicating no violation of the assumption of variance homogeneity. An ANOVA was then conducted to examine the differences in post-MARS-EM scores between learning groups. The results showed no significant difference between groups regarding the post-MARS-EM score ($F[2, 81]=.894$, $p=.413$).

According to our study, there was no significant difference in post-MARS-EM scores between the three learning groups. This finding contrasts with previous research by Thomas(2013) and Thomas et al. (2008), who argued that teacher-led explanations of thinking and reasoning strategies are crucial for promoting metacognition in students. Avargil et al. (2018), also suggested that direct explanations should be subject-specific and tailored to the science content being taught. In this regard, DIM, a more teacher-led learning approach, was expected to produce changes in students' metacognition in the context of E&M. our study also contradicts the idea ELM is highly beneficial in formal education as it helps students develop a deeper understanding and become more thoughtful, reflective, and critical (Roberts, 2018). One possible explanation for our results may be that students lack a clear understanding of metacognition as Wang (2015) found that students do not differentiate between various components of metacognitive awareness. Avargil et al. (2018) suggest that researchers examining metacognition in science education should employ both qualitative and quantitative assessment tools to assess students' metacognitive processes. Nonetheless, our study solely employed a self-created quantitative instrument. Our study highlights need for further research to explore most effective instructional approaches for promoting metacognition in science education. We suggest that future research employ qualitative and quantitative assessment tools and pay particular attention to students' conceptual understanding of metacognition.

Study Limitations

The study encountered a limitation during the implementation of E&M lessons, where instructors faced challenges due to their unfamiliarity with the instructional approaches required. Although they received training and collaborated during the intervention's design phase, the implementation posed difficulties for both the teachers and students. This was likely due to the limited prior experience of both parties (students and instructors) with such learning environments, which may have impacted the optimal implementation of the instructional interventions as originally designed

CONCLUSIONS

In conclusion, the study examined the impact of three instructional models on critical thinking, metacognition, and conceptual understanding in an introductory physics course. The results indicated that ELM was more effective than DIM and the combination of both (DIM-ELM) in enhancing students' post-test scores regarding conceptual understanding and critical thinking in the topic of E&M. However, there were no significant differences in the effects of instructional approaches on metacognition. The findings suggest that incorporating ELM in teaching introductory physics could effectively improve students' conceptual understanding and critical thinking. The quasi-experimental design used in the study provided a useful framework for assessing the effectiveness of different instructional approaches in enhancing student learning outcomes.

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Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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