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Pedagogical Innovations to Reduce Cognitive Load of First-Year Engineering Students in Basic Electrical Engineering Course

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ABSTRACT

BACKGROUND & CONTEXT

Basic Electrical Engineering (BEE) is a course offered to all freshmen engineering students in undergraduate engineering institutions. The lack of foundational knowledge often hinders students from achieving the intended learning outcomes in the BEE course. This poses significant challenges in understanding core concepts and solving problems, especially for students transitioning from high school to engineering studies. Grounded in Cognitive Load Theory (CLT), this study investigates how the intrinsic and the extraneous cognitive load from complex pedagogical activities impact students' learning outcomes in BEE.

PURPOSE OR GOAL

This study aims to understand how pedagogical interventions could bridge the pre-requisite knowledge gaps among first-year engineering students in the BEE course. The addresses the following research question- To what extent does integrating principles of CLT affect students' performance in a BEE course for first-year engineering students?

APPROACH OR METHODOLOGY

The study employs a quasi-experiment with repeated measures to assess the impact of applying principles of CLT on students' performance in the BEE course for 60 students. Data is collected through a diagnostic test followed by pre-tests, assignments, and post-tests.

OUTCOMES

The results indicate that using CLT principles significantly enhances the student's ability to recall and apply concepts.

CONCLUSIONS

CLT-based interventions resulted in a significant and consistent increment in student learning performance. The repeated measures design provided strong evidence for a role of instruction that is aligned with cognitive abilities in closing gaps in foundational knowledge.

KEYWORDS

Cognitive Load Theory, Pre-requisite knowledge, Quasi-experimental design, Basic Electrical Engineering, Canvas LMS.

Introduction

Basic Electrical Engineering is a foundational course offered to first-year engineering students in India. This course covers the fundamental concepts of electrical circuits, electrical machines and various circuit analyses, which lay the base for future applications in emerging fields (Syed et al., 2024; Khamruddin & Kandakatla, 2020). Despite its significance many of the first-year students who enrolled in the course lack adequate prerequisite knowledge in the core subjects such as physics and mathematics that are essential to gain the understanding of basic electrical engineering concepts (Streveler, Litzinger, Miller, & Steif, 2008; Gunasekaran, Roy, & Rai, 2021). These gaps lead to difficulties in problem-solving, minimal classroom engagement and poor academic performance, which often stem from gaps in the curriculum at secondary school education (Baligar et al., 2023). This challenge is more complicated when the students face complex problem-solving concepts aligned with prior. A systematic design of educational intervention is required to address these multiple challenges, which supports the learning progress of first-year engineering students and increases their cognitive capacity. First-year engineering students in India transition from high school-level to engineering very quickly and face several issues which are not only related to prior knowledge but also in team-based learning (Kandakatla, 2015; Baligar et al., 2021). The variability in their prior learning could be observed, especially among students who are first generation learners, and who belong to backwards castes, and those who reside rural settings with limited exposure and opportunities (Martin et al., 2020). Therefore, when undergraduate students enroll in engineering programs, there are many challenges in courses that require students to use their prior knowledge. This challenges students without the necessary prior knowledge in their learning process and affects and confidence in gaining technical skills (Mayer & Mareno, 2003).

Literature studies have identified these challenges and emphasized the importance of foundational gaps in the early journey of the academic environment (Verdin, 2024). Studies have also mentioned that students with strong prerequisite knowledge in mathematics and physics will perform better in the foundational courses in the first year of engineering, especially those that involve problem-solving and reasoning (Panaoura et al., 2024; Pierson et al., 2001). Ineffective delivery can also lead to cognitive overload, especially when the students have gaps in core concepts (Klepsch & Seufert, 2020). Most pedagogical interventions mentioned in the literature have focused on the individual principles of cognitive load theory and controlled environments (Mayer, 2009; Likourezos, Kalyuga, & Sweller, 2019). Few studies have also applied holistic approaches including audio and video channels with the multiple principles of CLT in live classroom settings to identify and assess the prerequisite knowledge (Santiago & Guo, 2019).

This study implements the cognitive load theory framework to apply targeted pedagogical interventions in the introductory BEE course. By integrating the principles of cognitive load theory, such as pre-training, segmentation and variability, this study aims to improve students' academic performance in the course (Mayer, 2009; Likourezos, Kalyuga, & Sweller, 2019). The study also explores how these informed instructions bridge the foundational knowledge gaps of freshmen students through a quasi-experimental design, fostering enhanced understanding in the BEE course. This method enables tracking of students' learning progress through pre- and post-intervention over time and evaluating the effectiveness of the CLT principles. The research question for this study is as follows:

RQ: To what extent does integrating principles of cognitive load theory affect the student's performance in the introductory electrical engineering course for first-year engineering students?

Background Research

Cognitive Load Theory (CLT)

CLT is an instructional framework that categorizes cognitive load into intrinsic, extrinsic, and germane (Ayres, Sweller & Kalyuga, 2011). Intrinsic load is defined by the complexity of the content, which is often unavoidable in engineering subjects. It also refers to the material's complexity, determined by element interactivity, which means the number of elements that must be processed simultaneously. For instance, when solving an electrical circuit problem that involves high intrinsic load, such as Ohm's law, Kirchhoff's law, and other theorems, these should be understood together (Sweller, 2023), while learning isolated facts with low element interactivity carries less intrinsic load. In contrast, extrinsic load stems from poor instructional design that diverts students' attention from essential content (Mayer & Moreno, 2003) where the germane load refers to the construction of the schema.

Effective instruction can reduce extraneous load, thereby allowing for germane processing (Mayer, 2009). Cognitive load theory in STEM education has significantly improved students' academic performance. Impelluso (2009) has employed a hybrid course design with gaming elements, which helps manage cognitive load in mechanical engineering instruction, resulting in improved learning outcomes. Prince and Felder (2006) emphasized strategies like inductive teaching that support conceptual understanding, aligning with cognitive load theory principles. Segmentation and pre-training have proven effective strategies for managing cognitive load in multimedia learning (Mayer, 2009). The segmentation principle breaks complex content into manageable units, encouraging knowledge retention and transfer (Rey, Fischer, & Gurevych, 2019). Pre-training's foundational knowledge and introducing key terms help learners form mental schemas before learning (Mayer & Mareno, 2003). In problem-solving, the variability effect has also significantly enhanced schema and knowledge transfer (Likourezos, Kalyuga, & Sweller, 2019).

Challenges of Freshmen Engineering Students in Basic Electrical Engineering Course

As engineering curricula evolve to meet the demands of interdisciplinary and applied learning, many first-year students continue to struggle with foundational subjects like BEE, especially when their prior exposure to relevant mathematical and physical concepts is weak. Students who enroll in the course find it challenging due to unfamiliarity of core concepts which needs strong analytical and problem-solving skills. One of the most pressing challenges in freshman engineering education is a disparity in students' prior knowledge. Students often face challenges in understanding the conceptual knowledge in the fundamental courses (Streveler et al., 2008). The gaps in knowledge can be identified early using diagnostic tests (Brijlall & Ally, 2020). Hailikari, Nevgi, and Komulainen (2008) mentioned in existing research that students with strong prerequisite knowledge learn the material with less cognitive load. The students' performance in engineering courses like BEE can be increased by bridging all these gaps through pre-training material preparatory modules and a series of early assessments (Syed et al., 2024)

The existing research in engineering education supports the quasi-experimental designs to measure the impacts of the interventions (Zhang et al., 2004). Repeated measures like weekly assignments, quizzes and student surveys can help track the learning trajectories and the cognitive load over a period of time (Felder & Brent, 2005). Despite the vast research in cognitive load theory, limited strategies exist for integrating cognitive load theory principles into a single course. In addition, limited research has focused on the interventions related to the cognitive load theory principles for first-year engineering students in the Indian context. The lack of comprehensive research, especially regarding the design and delivery, has been observed in existing studies in bridging the engineering education programs, as stated by Marjoram, Dargaville, and Foley (2023).

Research Gap Identified

Several studies have mentioned the application of CLT strategies in STEM and have focused on isolated applications in various controlled settings (Impelluso, 2009; Sweller, Ayres, & Kalyuga, 2011). However, limited research has shown the integration of multiple cognitive load theory principles in classroom environments, especially in first-year engineering courses. This study applies cognitive load theory-informed strategies to bridge the gaps between the prior knowledge and foundational courses for first year students. It evaluates the impact of the same using a quasi-experimental repeated measures design in the introductory engineering course for freshman engineering.

Methodology

Context

The study specifically focuses on students enrolled in the CSE-AIML program taking the BEE. It is a 3-credit course offered to all freshmen engineering students in undergraduate engineering. The primary author was part of an Action Research program organized by the teaching and learning center in the institution (Tuti et al., 2016), where the goal of the program was to reflect and investigate the challenges encountered in the previous offering of course and to come up with pedagogical innovations to overcome them. The authors designed interventions using the cognitive load theory to address the need to equip students with the necessary prerequisite knowledge and enable them to be successful in the course.

Drawing on the principles of cognitive load theory - pre-training, segmentation and variability, the instructional content was restructured and administered through the Canvas Learning Management system. The interventions are designed using CLT principles such as Pre-training, Segmentation and Variability.

- *Pre-Training:* In this phase, the learners receive supporting materials, video lectures that cover prerequisite concepts from physics and mathematics related to the BEE course. This helps them to reduce the intrinsic cognitive load

- *Segmentation:* The topics in the BEE are divided into chunks of units, which include lecture segments, embedded quizzes, followed by lecture segments and reflections. The quizzes and assignments are designed and conducted in the Canvas LMS. The segmentation allows the students to learn the information in manageable chunks, which helps them to reduce the extrinsic cognitive load.

For instance, the Superposition theorem, which is a part of BEE course content is broken up into instructional units that minimize cognitive load and incorporate prerequisite concepts. It is carried out as mentioned in steps below:

(a) As a pre-task guide a video on linearity, Ohm's law and a review of KCL and KVL basics is recapped.

(b) In-class lecture segment to demonstrate with first source and apply KCL/KVL step-by-step to find the response in Step-I

(c) Mid reflection activity where pair of students have peer discussion and problem solving for Step-I of theorem.

(d) In-class lecture segment to demonstrate next source and apply KCL/KVL step-by-step to find the response obtained in Step-II

(e) Reflection at the end of the class to link the steps with previous knowledge and sum up learning and misconceptions. This organized method facilitates absorbing content effectively, consolidates prior knowledge and avoids overburden by learning content a certain sequence.

- *Variability:* After pre-training and segmentation, the students are introduced to diverse numerical problems which are varied in difficulty and context for practice. For example,

superposition theorems are made to practice, which have multiple sources, different source types and different connection methods. This enables the students to reduce the complexity and strengthen the schema to increase a deeper and comprehensive understanding of the BEE concepts. This process is presented in the Table 1 below.

Table 1: Integration of CLT principles

CLT Principles	Tasks	Cognitive load addressed
Pre-training	Students receive Pre-training material on fundamentals of mathematics and physics related to BEE concepts prior the lecture	Intrinsic load
Segmentation	Lecture is segmented into chunks and delivered integrating with peer discussions and reflection activities	Extraneous load
Variability	Students solve diverse numerical problems to strengthen the schema	Germane load

Research Design

This study aimed to investigate the effect of the interventions of CLT on the students' academic performance in the BEE course. The authors used a quantitative quasi-experimental design with repeated measures and has a single group of experimentation without any control group. As this study is conducted in natural settings for entire class without randomization a quasi-experimental design is selected. Repeated measures were used to track the learning performance of the students over time with CLT interventions.

A total of 5 tests were administered to the undergraduate students of first-year engineering students for a quasi-experimental repeated measures design - (1) Diagnostic test, (2) Pre-Test, (3) During intervention test, (4) Mid-Test (Summative) and (5) Post-Test. This entire study is carried over 8 weeks.

The conceptual diagram for this study is presented as Figure 1 below:

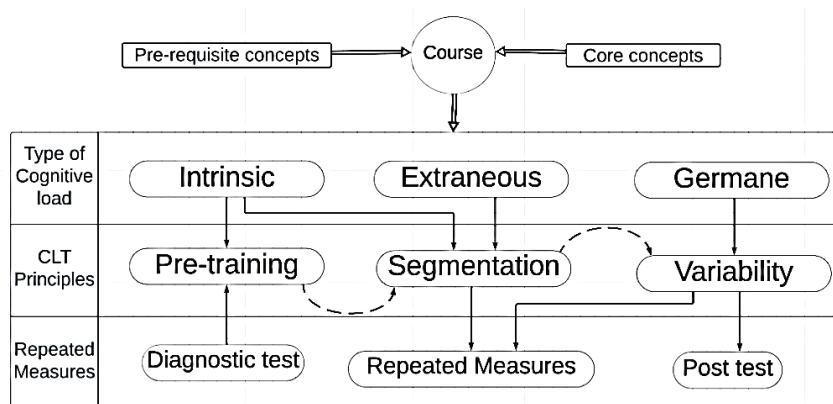


Figure 1: Conceptual diagram

Data Collection

Quantitative data was collected for eight weeks in different phases as mentioned below:

- Diagnostic test to identify the student's prior knowledge
- A series of pre-tests to observe the foundation knowledge required to grasp the BEE concepts
- Interventions based on the Cognitive Load Theory principles

- Post-test to measure the impact of the interventions in improving the students' academic performance

A diagnostic test was conducted at the beginning of the course to identify the students prior knowledge capability and helps to categorize the students with strong moderate and weak prior knowledge.

Table 2 shows the fundamental pre-requisite concepts required to gain knowledge in the Basic Electrical Engineering course:

Table 2: Pre-requisite concepts aligned with Basic Electrical Engineering course

Pre-requisite Concepts	Concepts of the BEE course
Lowest Common Multiples (LCM), Fractions, Basics of Derivations & Integrations (Mathematics)	· To find equivalent resistance in DC circuits · To solve theorems involving the fractional parts of circuit parameters · To find the time response of R-L with DC excitation · To obtain average and root mean square values of sinusoidal signals · To analyze R-L and R-C circuits with AC
Ohm's law, linearity principle, Kirchhoff's current and voltage law, Faraday's law of EMI, Lenz's law (Physics)	· Circuit theorems with DC excitation · DC and AC electrical machines

All the pre-training material are published in the Canvas Learning Management System (LMS). The lectures are delivered using segmentation principle where the lecture is divided into chunks with reflection spots in between which includes student-centric activities like peer-peer discussions. Weekly quizzes and assignments as a part of pre-test and post-test are administered to track the progress of the interventions and the understanding of the BEE concepts. Students are given with problem-solving exercises which include diverse elements in the numerical. The performance scores from the mentioned tests are used for quantitative analysis as indicators of learning improvement. Initial analysis is done to obtain the descriptive statistics of Mean, Median and Standard Deviation to summarize the students' progress over time

A total of 60 students from the first year of engineering enrolled in BEE course participated in the study. All the students belong to the CSE-AIML and the intervention is implemented for the entire class.

Results

The results are analyzed and presented to evaluate the effect of CLT interventions which shows significant growth in the performance of the students

Descriptive Statistics:

The average test scores of the students have been observed to increase through the phases of interventions. The increase of mean scores from the diagnostic test to post-test shows a desirable learning trajectory as shown in the Figure 2.

Assumption Check

The normality assumption was tested at each time by using the Shapiro-Wilk test. The outcomes exemplified lognormal distributions for the majority of test scores ($p < 0.05$ for

Diagnostic test, Pre-test, Mid-test and Post-test), deviating from the fundamental assumption of parametric repeated measures ANOVA. Hence, a non-parametric counterpart, the Friedman test, was used.

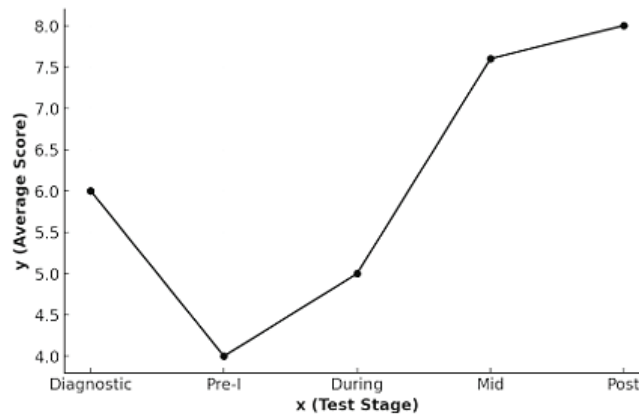


Figure 2: Average student scores across test stages

Friedman Test

Statistically significant difference is observed in the Friedman test across different time points in the five student scores as shown in equation (1).

$$\chi^2(4) = 155.42, p < 0.001 \quad (1)$$

This suggests that a minimum of one of the test stages had differed significantly from the others which indicates that there is a measurable impact of the interventions on the students' learning over time.

Post-hoc Analysis

To determine which positions differed, pairwise comparisons were performed with the Wilcoxon signed-rank test. There was a significant difference ($p < 0.05$) in the time spent in the test stages and the key points of transition between test stages were given below:

- *Diagnostic vs Pre-Test* ($p < 0.001$)
- *Pre-Test vs During* ($p < 0.001$)
- *During vs Mid-Test* ($p < 0.05$)
- *Mid-Test vs Post-Test* ($p < 0.001$)

These results confirm the efficacy of the pre-training approach, split-level Instruction and task differences concerning problem solving to enhance the understanding and solving of conceptual problems in the basic electrical engineering course.

Visualization

The figure 2 shows the line graph of the average scores for all the tests indicating the progressive growth of the students in terms of learning which further reinforces the quantitative findings. The average scores are calculated by taking sum of all the students scores in respective tests to the number of students attempted that test. There is a significant gain between the pretest and post-test stages observed from the visual representation coincides with the impact of CLT-based interventions.

Discussion

The results of the study demonstrate that applying CLT principles, specifically pre-training, segmentation, and variability, significantly enhanced student performance in a BEE course. The upward trend in scores across the five test points highlights the value of aligning instructional methods with students' cognitive capacities and prior knowledge. This pattern is consistent with the theories that well-designed instructional interventions according to CLT principles could decrease extraneous cognitive load and facilitate students' learning (Mayer, 2009; Likourezos, Kalyuga, & Sweller, 2019).

The observed improvement from the Diagnostic Test to the Post-Test indicates that the interventions not only helped bridge the gap in prerequisite knowledge but also facilitated deeper understanding through structured delivery. The Pre-training phase, which included fundamentals of mathematics and physics refresher tasks, likely reduced intrinsic load by activating relevant prior schemas (Streveler et al., 2008; Gunasekaran et al., 2021). Similarly, segmentation helped manage extraneous load by presenting information in smaller, digestible chunks rather than as lengthy traditional lectures (Mayer & Moreno, 2003; Klepsch & Seufert, 2020). Finally, introducing variability through different problem types and application scenarios may have promoted germane load, fostering meaningful learning and problem-solving flexibility (Ayres, Sweller & Kalyuga, 2011). The statistically significant differences confirmed by the Friedman and Wilcoxon tests provide empirical evidence that instructional design aligned with CLT can result in measurable academic gains. These findings resonate with prior studies that advocate the integration of instructional psychology into technical education (Mayer & Moreno, 2003). However, it is worth noting that the study was conducted on a single cohort within a specific course, and results may vary across disciplines, institutions, or learner profiles. Further research involving control groups, longitudinal tracking, or mixed-method designs could enrich the findings and uncover long-term impacts. Study conducted over time connecting the quantitative effects with qualitative narratives would help in deeper and more actionable insights. As the current is limited to a single course, future research should extend these interventions to the other courses and programs to yield higher improvements in students learning.

Conclusion

The implementation of pre-training, segmentation and variability in the CLT-based interventions resulted in a significant and consistent increment in student learning performance in BEE course. The repeated measures design provided strong evidence for a role of instruction that is aligned with cognitive abilities in closing gaps in foundational knowledge. These results highlight the necessity for careful instructional design in teaching technical content for first-year engineering students who often have difficulty with abstract knowledge and applying mathematical content. Teachers are also urged to use evidence-based frameworks like CLT not just to simplify mess but also to systematically foster deep and long-lasting learning. Future work could investigate whether the effectiveness of these interventions can be scaled up to larger groups or adapted to a blend of online and offline environments and measure to what extent they would impact the learning.

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