Evaluating Students' Learning in an Intensive Mode of Teaching in a Postgraduate Fire Engineering Course

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ABSTRACT

CONTEXT

In the postgraduate fire safety engineering program, students typically have diverse educational backgrounds, resulting in varying levels of familiarity with fundamental principles crucial for understanding fire engineering concepts. Hence a substantial amount of new knowledge must be conveyed, leading to an increase in the cognitive load among students.

PURPOSE OR GOAL

This paper uses some of the specific methodologies derived from Cognitive Load Theory to reduce cognitive load in an intensive teaching mode implemented within a module on fire safety engineering. This study aimed to optimise learning outcomes and promote the retention of information in long-term memory.

APPROACH OR METHODOLOGY/METHODS

The performance of eighteen students in terms of their learning was assessed through pre- and post-lecture tests. The results were then compared to evaluate their retention of some of the key elements taught in the class. The final exam results were also analysed and compared to the in-class test scores to ascertain the degree of knowledge retention in long-term memory. Moreover, students were interviewed to provide insights into the effectiveness of different instructional approaches used during the lectures.

ACTUAL OR ANTICIPATED OUTCOMES

The results indicate that after the lectures, almost all students showed improvement in the post-lecture tests and were able to retain the new knowledge in both their short-term and long-term memories. Student scores increased significantly, with a tenfold increase in multiple-choice questions and a threefold increase in discussion-type questions. The students who performed very well in discussion-type questions also demonstrated significant improvement in multiple-choice questions, but the opposite was not true.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

All lectures were structured into smaller sessions, each focusing on only two to three elements, aiming to alleviate both extraneous and intrinsic cognitive loads. In interviews, students affirmed that the interactive breaks, combined with rehearsal sessions after each segment, aided in absorbing content and prolonging knowledge retention. This paper recommends diversifying question types, encompassing multiple choice questions, discussion-based queries, and open-ended questions, during assessments to gauge the efficacy of instructional design approaches.

KEYWORDS

cognitive load theory, working memory, long-term memory, instructional design

Introduction

Fire safety engineering (FSE) is a multidisciplinary field, necessitating students to learn various aspects of other engineering and scientific disciplines, including mechanical, civil, chemistry, physics, architecture, structural engineering, and human psychology. As a result, the courses incorporate a diverse array of elements from these disciplines. Unfortunately, FSE is not commonly offered at the undergraduate level in many regions, with only a few universities worldwide providing undergraduate FSE programs, but they may have postgraduate programs. Despite the critical importance and demand for fire engineers in ever-evolving built environment, one of the primary reasons for the limited availability of fire safety engineering (FSE) programs is the historical reliance on prescriptive fire safety design methods. Before 1990, such designs were predominantly rule-based and implemented as "cook-book" approaches, obviating the need for professionals to have in-depth knowledge of fire science fundamentals. However, notable events over the past three decades, such as the collapse of World Trade Centre 7 in New York, have demonstrated the limitations of prescriptive design methodologies for modern structures. The field of FSE transitioned to performance-based design approaches in the early 1990s (Morgan et al., 2015). Unlike prescriptive methods, performance-based designs rely on engineering calculations and necessitate a thorough understanding of fire engineering principles by professionals. Thus, the rising demands for fire safety experts and growing interest in fire engineering have led to an influx of students and professionals enrolling in postgraduate programs in FSE.

The students who are enrolled in postgraduate programs mainly include FSE professionals who are accustomed to prescriptive design methods and students without prior experience in fire engineering. Both groups may need to grasp concepts across a range of disciplines, such as combustion chemistry, fluid dynamics, heat transfer, structural behaviour, and more. This may present a considerable challenge for students. Hence, it is crucial to meticulously design instructional methods to maximise student learning, particularly considering that much of the information may be new to the students.

The objective of lectures is to facilitate the transfer of information from an expert to the students, thereby enhancing their learning (Sullivan et al., 1996). An effective teaching method is one in which students can retain a significant portion of the information both in the short term and the long term. There is a direct correlation between short-term and long-term retention of information—lower retention in the short-term results in lower retention in the long term. Short-term learning can be referred to as the knowledge acquired by students during classroom instruction. Research indicates that the greater the quantity of “new” information presented in a lecture, the higher the cognitive load, which in turn reduces the students' learning during the class. Therefore, it is essential to design instructions in a manner that enhances student learning by reducing cognitive load. There is limited literature or specific instructional design methods available for teaching in FSE (Woodrow, 2013).

This paper assesses the learning outcomes of students in a postgraduate FSE module offered at the University of Somewhere. Usually, the university uses a ‘block course’ teaching method for post graduate programs, which involves teaching from morning to evening, for postgraduate modules. This approach, combined with the substantial volume of new information, significantly increases the cognitive load on students. The instructional design for this course employs the methodology - Cognitive Load Theory (CLT) outlined by Sweller et al. (1991) to mitigate the cognitive load. Student learning is assessed through pre- and post-lecture tests (pen and paper tests) to evaluate short-term retention of lecture content, with their performance compared to that of the final exam.

Cognitive load

At the postgraduate level at the university, some courses are conducted as block courses, typically spanning from morning to evening. Hence, these courses are quite intensive, potentially inundating students with a substantial amount of information that may be overwhelming for some.

Consequently, it is crucial for instructors to design lectures or instructional methods that optimise student learning. The instructional methods used for this specific course were based on CLT (Sweller et al., 1991). Further elaboration on these methods is provided in subsequent sub-sections, along with an explanation of how student learning was assessed.

How do we learn?

It is crucial to understand the mechanisms of learning within a classroom setting and how knowledge is transferred to learners. The new information must be effectively stored in memory for later application in practical scenarios or to establish a foundational understanding of concepts. However, how the information is stored in our memory requires further exploration. When examining human cognition, it becomes evident that two fundamental components shape it: working memory and long-term memory (Sweller, 2016). When dealing with instructional matters, it is crucial to carefully examine the interplay between working memory and long-term memory. This includes considering how working memory and long-term memory adapt when processing external information or retrieving information from long-term memory.

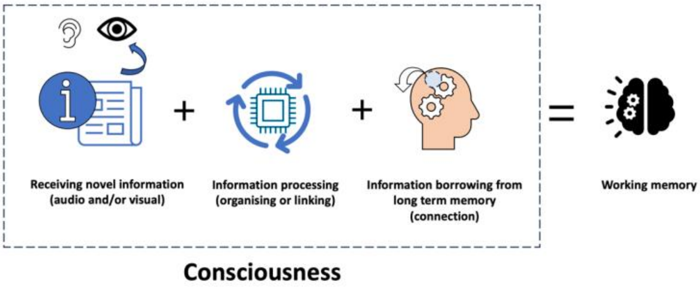

Figure 1: Human consciousness during learning

Information that one is familiar with and can use effortlessly when dealing with any task is stored in long-term memory. However, while dealing with “new” information it is required to process it before it goes to the listeners’ or students’ long-term memory (Sweller, 2016) . This “new” information is stored in what is called *working memory*. Learning is defined as the positive change in long-term memory; if no change occurs, learning has not taken place. So, an instructor’s goal is to facilitate the transfer of information from working memory to the student’s long-term memory; otherwise, instruction would be ineffective. Working memory serves as the bridge between the external environment and the information to be transferred to long-term memory storage. When information is delivered (listening or watching), our brain activates to receive and immediately begins processing and organising it. Simultaneously, the brain may draw upon a small portion of information from long-term memory to establish connections with the new information, if necessary. All these tasks occur simultaneously within our working memory. At any given moment, consciousness of new information can be conceptualised as working memory, in other words, we are only conscious of what is held in our working memory, as shown in Figure 1.

Working memory is subject to two fundamental limitations: capacity and duration. Its capacity to hold new information is highly restricted, allowing only a limited number of elements (an element can be considered as a concept) to be processed at once (Cowan, 2001). Similarly, new information can persist in our brain for only a brief period before it is lost. It is worth noting that long-term memory is not subject to such constraints; once information is learned, it can be retrieved automatically.

Cognitive load theory

Cognitive load refers to the amount of mental effort required to process “new” information before it is transferred to long-term memory. In essence, it is the load on the working memory. When learners are presented with new information, cognitive load is imposed on the working memory (or cognitive load). The theory suggests that the instructional design should aim at minimising the cognitive load to enhance the effectiveness of learning (or reduce the load on working memory) (Sweller et al., 2011).

According to cognitive load theory, students experience primarily two types of cognitive loads: (1) intrinsic cognitive load, stemming from the inherent complexity of the information they need to learn, and (2) extraneous cognitive load, influenced by the manner in which information is presented, including instructional techniques or class activities that may be extraneous to the learning goals. Both types of loads impact the working memory and are additive in nature. Reducing either type can alleviate the overall load on working memory.

While the working memory limit can vary among individuals—for instance, some students may adeptly manage five to six elements within the same timeframe while others may handle only three—prior knowledge can also influence working memory. This limitation stems from the "randomness as genesis" principle, which asserts that the brain must organise the new random

information before it can be learned or stored in long-term memory. During this process, the brain tests and explores various permutations to establish connections with existing information. As the number of elements increases, the permutations multiply—for instance, the number of permutations for three elements is six, whereas for six elements, it escalates to 720. Handling such a vast number of permutations can become challenging. Consequently, limiting the number of elements reduces cognitive load. Sweller suggests employing two to three items of "new" information when engaging working memory. Oakley et al. (2021) suggested that the number of elements in the instructions design should be based on the students who have low working memory capacity, as it may work for all. Using the CLT approach, Manson et al. (2016) redesigned the instructional methods for a Database course by applying principles like split attention and the redundancy effect. This resulted in a 34% improvement in the performance of students on the final exam. This paper also focuses on designing instructional methods but explores different principles of the CLT approach. It examines both students' learning during the class (short-term memory) and compares their performance in the final exam, assessing long-term knowledge retention.

Instruction methods

While Sweller et al. (2011) discusses various methods to reduce cognitive load, but not all of them were implemented in the lectures. The subsequent paragraphs discuss some of the methods recommended by him that are implemented during the lectures.

FSE, much like other engineering disciplines, encompasses numerous complex problems to solve, such as detecting time and calculating room temperature during a fire. To address these challenges, detailed calculations were conducted, incorporating all relevant elements and procedures. Subsequently, worked problems were presented for solving. To illustrate the problem-solving process, the *Worked Example* method was employed, which imposes a relatively low working memory load. The knowledge learned during the lecture is effectively acquired through borrowing from instructors (*'borrowing and reorganising'* information). Worked examples offer problem-solving elements that necessitate retention in long-term memory, aligning with the information storage principle. Furthermore, these examples provide procedural guidance for solving problems, enabling students to apply learned techniques to other scenarios. Studies demonstrate that students perform better when exposed to '*worked examples'* compared to those who solve problems independently (Cooper et al., 1987).

Each lecture was subdivided into several smaller segments, each containing two to three key elements (each segment was around 10-15 minutes long). Sweller (2016) recommended minimising the introduction of new elements within a domain-specific knowledge context to decrease extraneous cognitive load (*narrow limits of change principle*)(Sweller, 2016). Subsequently, a progress check, referred to as a *"knowledge check,"* was conducted. This involved posing questions to students, encompassing both discussion-based and direct response formats, which varied throughout the lectures. Such activities assist students in assessing whether the information has been transferred to their long-term memory and if they can establish connections with stored information (*environmental organising and linked principle* (Sweller, 2016)). Furthermore, repetition and interactive breaks can reduce the cognitive load.

Activities such as progress check questions serve to ensure that all students are acquainted with, or have learned the presented elements. Additionally, these activities function as a rehearsal mechanism, facilitating the transfer of information into long-term memory. Rehearsal techniques address the *temporal limitations* of working memory, as highlighted by Peterson et al. (1959), who suggested that "new" information can be retained in working memory for approximately 20 seconds before being lost. However, continuous rehearsal and repetition can refresh and prolong the retention of new material in working memory, aiding in its eventual transfer to long-term memory(Corbin, 1967; Dunbar, 2000). Moreover, during rehearsal, providing answers or listening to peers assists other students in revisiting and understanding the material. This process can also function as a worked example for students, either by presenting solutions on the next slide or by verbally reviewing answers. Repetition inherent in rehearsal aids in clarifying concepts and solidifying students' understanding. Furthermore, rehearsal and repetition diminish the likelihood of misconceptions being stored during instruction (Sweller et al., 2011).

For elements requiring a deeper understanding, such as those comprising sub-level information essential for grasping broader concepts, each sub-element is treated as an individual element in all lectures. This approach aims to alleviate both intrinsic and extraneous cognitive loads by addressing the interactivity of elements (*element interactivity* (Chen et al., 2015)). It is worth noting that an increase in the number of elements required to grasp a concept elevates intrinsic load. Consequently, minimising the number of elements or sub-elements is beneficial for reducing cognitive load, thereby lowering intrinsic load and mitigating the load imposed by interactivity, where all elements must be simultaneously processed in working memory (Chen et al., 2015). By reducing the number of elements (*isolated element effect*: learning pieces of information before integrating them into the instructional methods can reduce the unnecessary intrinsic and extraneous load.

Evaluation of learning

To assess student learning, a few tests were conducted, and their performance was compared. Additionally, students' in-class learning was compared with their performance in the final exam. This section discusses the evaluation methods employed to assess student learning, considering the diverse group of students present. The subsequent section will then present the results of these evaluations.

The cohort comprised a total of nineteen students, with eight enrolled as part-time and eleven as full-time students. Additionally, the majority of part-time students (six) were employed in the fire engineering industry. Twelve students had participated in an introductory course in fire engineering within the past year, a *prerequisite* for enrolment in the master's level program.

Students were given a test before commencing the lectures, and another upon completion of all lectures (on the third day). The students were explicitly informed that these tests would not be graded. To maintain consistency and monitor student learning progress, identical tests were administered both before and after the lectures. Notably, students were not informed in advance about the post-lecture tests. Moreover, the pre-test also serves to ascertain the expertise level of students and aids in mitigating extraneous cognitive load for those classified as "*expert students*" (*Expertise Reversal Effect* (Kalyuga et al., 2003)). The students who work in the fire industry and those who recently finished introductory courses may have a greater amount of information in their long-term memory.

The test comprised both multiple-choice questions (MCQs) and discussion-based questions. There were five MCQs, each offering four choices, with the final option labelled *"Don't Know"* for cases where students were unsure of the answer. Furthermore, for each MCQ, students were asked if they guessed the answer if it wasn't *"Don't Know,"* aiming to gauge the confidence level of the students in their responses. Additionally, certain options in the MCQs were deliberately included to address common *misconceptions*. Possessing an engineering background and an understanding of the fundamentals of physics and chemistry enables students to make educated guesses.

Additionally, four discussion-based questions were provided, necessitating detailed explanations in response. These questions were concept-based, requiring students to recall and understand the fundamental principles underlying the concepts presented. All of these questions (MCQs and discussion-type questions) encompass essential elements that students are expected to grasp through this module (part of the learning outcomes of the course).

Results and discussion

This section examines the outcomes of students' performance across all tests, including the final exam. It also looks for the factors contributing to varying levels of performance among students, investigating why some excel while others struggle to retain new information. Furthermore, interviews were conducted with both high-performing students and those who faced challenges in in-class post-lecture tests.

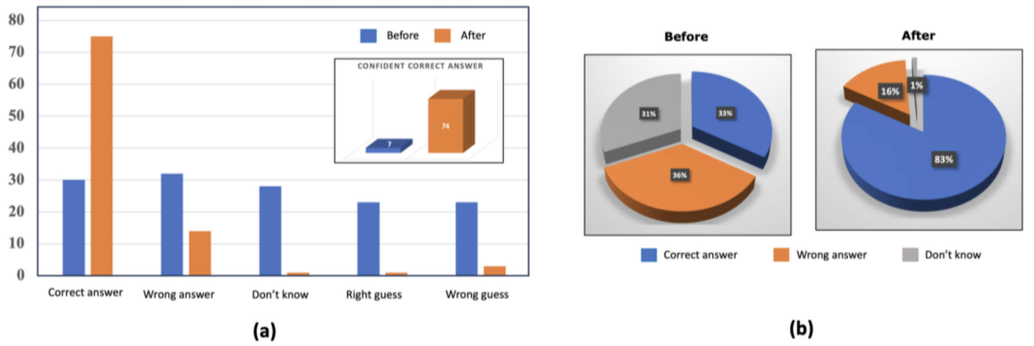

Figure 2 (a) Comparison of students' responses before and after lectures, and (b) Students' performance in MCQ in pre-lecture tests, and post-lecture tests

Multiple choice questions

Nineteen students were initially enrolled in this class; however, one student did not participate in the final exam. Therefore, the data presented here pertains to eighteen students only. As mentioned earlier, each test included five MCQs, resulting in a total of ninety MCQs administrated to evaluate the overall performance of the class.

Figure 2(b) illustrates the students' performance in terms of their responses before and after the lectures were delivered. The results of the pre-lecture assessment reveal that students achieved an accuracy rate of around 33% in their responses. Within the correct answers, approximately 26% were the result of educated guesses. Out of a total of 90 responses, in 31% of cases, students neither possessed the correct answer nor could provide an informed guess, selecting the *'Don't Know'* option. After three days of *block course* teaching and learning, there was a substantial improvement in students' knowledge retention. Their accuracy rate increased to 83% in MCQs, and also a 20% reduction in incorrect answers.

Answers provided by students without guessing and with confidence are referred to as *'Confident Answers*.' Fig. 2(a) illustrates the data in terms of the number of responses. In the pre-test, there were 46 guesses out of 90 questions, with 23 being correct and 23 incorrect. Conversely, in the post-test, students displayed more confidence, making only four guesses, of which only one was correct. Out of the 75 correct answers in the post-test, an impressive 74 were *'Confident Answers*.' This marked a significant improvement in their ability to grasp and retain concepts, after three days of intensive learning.

The study encompassed an examination of educated guesses, considering whether students' backgrounds influenced their likelihood of making such guesses. Out of the 18 students, 12 (66%) had completed introductory courses within the past year, while 4 (22.2%) were already working in the fire industry but had taken their introductory courses more than a year ago.

Discussion-type questions

Four questions type questions were given. These questions help to understand their understanding of the underlying concept. Contrary to the MCQs, here, students were asked to explain and provide the reasoning. In the pre-test, the average score was around 17%, which increased to 52% in the post-test. Students were given full marks only if they explained the concept and provided the proper reasoning. In terms of FSE, such questions are good indicators to understand a practical understanding of the topic. Considering the diversity among students, notable improvements were observed in their average scores. Specifically, students with experience in the fire industry saw their scores rise from an average of 1.8 to 6.5. The scores of other students also showed significant improvement, with their averages increasing from 1.6 to 4.5. The improvement can be attributed to the reduction in cognitive load achieved by dividing the lectures into segments (Oakley et al., 2021; Sweller et al., 2011). However, the differences between the '*experienced*' and 'new students' can be explained by Cognitive Load Theory, where Sweller suggests that prior experience plays a critical role in alleviating the load on working memory. Furthermore, the theory suggests that due to the "environmental organising and linking (Connecting new information with previously stored knowledge in long-term memory)" principle, an expert with extensive information stored in long-term memory in a domain-specific field is likely to outperform a novice in the same domain, regardless of any disparities in their working memories.

The students' performance in MCQs showed a tenfold improvement in terms of *'confident answers'*. In contrast, the average score in discussion-type questions improved by a little over threefold. Although there was a significant increase in MCQs, from an average of 7.8% of '*confident answers'* to 83%, through MCQs, it is difficult to deduce if students learned the concept in a practical sense. Therefore, the discussion-type questions can be a good indicator to assess performance.

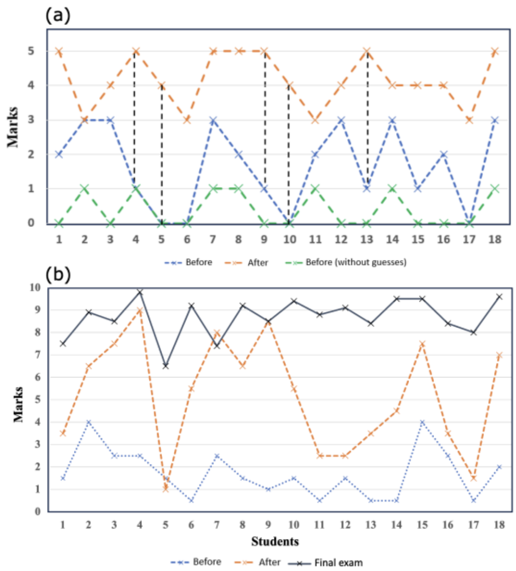

Fig. 3 Individual performance of students' in both in (a) MCQs and (b) discussion type questions before and after lectures, and final exam

Individual performance

Figure 3 illustrates the performance of each student before and after engaging in both MCQs and discussion-type questions. The data indicates that nearly all students exhibited improvement in their performance across both question types. However, there were only two exceptions (Student No. 3 in MCQs and Student No. 5 in discussion-type questions). For instance, Student No. 3 achieved the same score before and after the assessment. It's noteworthy that in the post-exam, this student made no guesses (compared to 2 correct guesses in the pre-test), resulting in an overall increase in confidence levels for all students.

In the context of discussion-type questions, Students numbered 4 and 9 demonstrated notably greater improvement compared to their peers. Generally, most students exhibited enhanced performance in discussion type, with the exception of student number 5, whose score decreased from 1.5 to 1. Interestingly, the improvement was more pronounced in MCQs, where the student's score increased from 0 to 4. These varying scores reflect the diversity in learning and comprehension during the lectures. Notably, students who showed significant improvement (50% or more) in post-discussion-type questions also demonstrated substantial progress in MCQs. This trend can be observed in the performance of students numbered 3, 4, 7, 8, 9, and 18. However, the reverse does not hold true, as evident in the performance of students numbered 4, 12, 13, and 16, as illustrated in Figure 3. These results suggest that MCQs alone may not accurately gauge their true understanding of underlying concepts, indicating the need for additional study time for these students and/or instruction methods may need to be improved.

Final Exam

After approximately one month of lecture sessions, the final exam was conducted. This exam featured mainly discussion-based and open-ended questions. All questions were different from the pre-test questions. Figure 3 also shows the individual performances of each student after the exam. Notably, the overall performance of each student exhibited a significant improvement compared to both the pre-test and, in many instances, the post-lecture tests. The class achieved an average score of 8.7 (out of 10), marking a significant 7-point increase from the pre-test and a 3.5-point rise from the post-lecture tests.

Interviews

Eight students were invited for interviews to ensure a comprehensive perspective. This group consisted of four students who exhibited notably high scores and four students who showed limited improvement. This approach allows to explore effective strategies for high-achieving students and potential areas of improvement for those who are underachieving.

All students noted that the '*knowledge check or progress check*' questions were beneficial during the class, aiding their comprehension of the material and rehearsing what was learned and discussed. These questions not only reinforced the current topic but also established connections to upcoming content (sub-elements: isolated element effect. Additionally, a few students pointed out that these questions played a role not only in retaining the underlying concepts in short-term memory but also in transitioning them to long-term memory. After all lectures, students were given a handout containing the questions posed during the class. Subsequently, during final exam revision, students found that the information had indeed become ingrained in their long-term memory, facilitating easy recall of the core aspects of the topic.

One student highlighted the valuable role of this rehearsal technique in helping them ensure that they were able to pick most of the lecture topics, especially within the demanding framework of an intensive three-day program. These reinforcement methods aid in retaining concepts by offering repeated exposure to the material. Students also mentioned that these regular checks activated the brain as it made them think about something rather than passively listening to a lecturer. Another student also noted that these questions stimulated their brain, transforming their mode of learning from passive to active and reinforcing the concepts effectively.

Student No. 5, who did not perform well in discussion-type questions, expressed that these questions played a crucial role in grasping the correct answers and following peers during discussions. The student emphasised that as a non-native English speaker, processing vast amounts of information and articulating it in writing was challenging. Hence, the language barrier likely impeded improvement in expressing understanding through discussion-type questions, although notable progress was observed in MCQs.

Limitations and Future Study

This study aims to assess both the qualitative and quantitative aspects of student learning during and after classroom instruction. However, there are some notable limitations, which are outlined below:

1. The pre- and post-lecture tests used the same questions, which may have caused students to focus more on pre-test topics during lectures. In future research, different questions will be used for the pre- and post-tests, along with follow-up tests one month later to assess the quantitative understanding and long-term retention of new knowledge.

2. The limited number of questions used in the tests did not cover all the learning outcomes of the course, restricting our ability to assess whether students grasped the broader course objectives. In future studies, a more comprehensive set of questions will be included to cover most of the learning outcomes.

Conclusions

The fundamental aim of learning is to instigate positive changes in long-term memory; without this outcome, true learning may not occur. The students' learning was assessed both before and after the lectures to gauge the retention of newly acquired knowledge from the classroom. To enhance student learning, instructional methods were designed based on cognitive load theory. The lectures were segmented into smaller sessions, each covering only two to three elements, with the intention of mitigating both extraneous and intrinsic cognitive loads. During interviews, students confirmed that the interactive breaks, coupled with rehearsal sessions following each segment, facilitated content absorption, extended knowledge retention, and assisted in linking the concepts learned in previous segments with those presented subsequently. Students' learning was assessed based on their performance in both pre-lecture and post-lecture tests. The majority of students demonstrated significant improvement in their scores, particularly in multiple-choice questions, along with an increase in their confidence levels. Similarly, improvement in scores for discussion-type questions was observed. It is also suggested to incorporate variation in question types, including MCQs, discussion-type, and open-ended questions, when assessing students' learning, as this can help identify the effectiveness of instructional design methods. Additionally, all students performed well in their final exam, with some attributing their success to the rehearsal technique employed during the lectures, which aided in retaining information in their long-term memory. Repeating key elements after each small segment of a lecture and providing lecture notes containing explicit key elements were found to be beneficial for all students.

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