Using Scaffolded Exams and Post-Exam Reflection to Foster Students' Metacognitive Regulation of Learning in a Mechanics of Materials Class

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Introduction

Metacognition is the awareness and control of thinking for learning [1]. Strong metacognitive skills wield significant influence over student learning outcomes and performance [2], [3], [4]. Through practicing metacognitive regulation of learning, students engage in a cycle of planning, monitoring, evaluating, and adjusting their learning strategies to become more successful in completing tasks [5]. Effective metacognitive regulation hinges on students' abilities to accurately understand the required learning outcomes, and thus gauges students' proficiency in achieving these outcomes [6].

When learning an engineering topic, there are different levels of learning outcomes to achieve. One of the most widely used models in higher education for describing the levels of learning is Bloom's [7] pyramid of cognitive outcomes. Bloom's taxonomy classifies learning outcomes into six levels: remember, understand, apply, analyze, evaluate, and create, ranked from lower to higher. The lower-level learning outcomes are often a prerequisite to achieving higher-order learning outcomes. However, when failing to solve a complex problem, students often fail to precisely evaluate what component knowledge they lack or what skills they need. This can hinder the student's metacognitive regulation of their learning progress, lower their self-efficacy, and stifle their motivation. Learning activities and assessments that explicitly communicate and scaffold students' learning progress across the different levels of learning outcomes will provide students with a better opportunity to plan and adjust their learning plan accordingly.

Scaffolding is the process that aims to deconstruct a complex assignment into smaller, more manageable tasks that target specific skills or types of knowledge necessary to complete the larger goal. Afterward, scaffolding typically involves sequencing these tasks into a progressive order that builds towards accomplishing the ultimate goal of the larger assignment. Not only does scaffolding and sequencing focus learners on their skills and knowledge development, but it also encourages their engagement by creating manageable cognitive tasks, which reduces cognitive load. Participation in scaffolded learning activities prompts clearer and more structured students' acquisition of skills and knowledge. We propose that scaffolded exams would be particularly effective because students tend to pay more attention to exams as an indicator of their learning progress.

In this study, we investigated how scaffolded and sequenced exams impact students' metacognitive regulation of learning in a Mechanics of Materials class. The scaffolded exam is designed to be an in-class exam (ICE) followed by a take-home exam (THE). In engineering education, both exam formats are widely used. Implementations of ICE and THE have received positive and negative feedback from students and instructors alike. For this study, an ICE is a

30-minute closed-note exam confined to the classroom space. Conversely, during a THE, students choose their testing environment and the exam is open note with a longer time available. With day-long time limits for ICEs not feasible, implementation of THEs is being analyzed as a method to encourage cognitive and metacognitive growth in students. From interviews with instructors and students in STEM fields, instructors welcome the flexibility THEs provide but recognize the challenges posed by exam formulation [8]. Similarly, students positively view the flexibility of the exam environment with THEs [8]. Benefits of THE implementations also include increased class time for learning material [9]. From a student mentality standpoint, THEs are shown to reduce anxiety, encourage higher cognitive level questions, and increase the capacity for meta-reflection within students [9], [10]. However, a general concern for THEs implementation is cheating among students [9], [10]. Especially for online formats, fairness of the exam is a point of discussion, where factors such as slow adjustment to the format, setting up a proper exam environment, and increased anxiety over mistakes also impact equality amongst students during a THE [11]. To reduce the effects of cheating on THEs, methods such as proctoring via camera angles and statistical methods in performance analysis are currently being explored [12].

The assessment of knowledge at a "deep level" (i.e. connects and applies knowledge in new ways) [13] versus a "surface level" affects how students approach their learning strategies [14]. According to the learning strategies accessed, different assessment formats can be classified using Bloom's taxonomy. The types of skills accessed can be broadly divided into LOTS (lower-order thinking skills) and HOTS (higher-order thinking skills) [15]. Balancing the categories of questions within examination formats ensures students retain a comprehensive knowledge base of the subject [15], [16]. Research has also shown that maintaining such a balance plays a key role in developing a student's ability to reach a higher level of thinking and self-reflection in their learning [4]. Within THE testing formats, the questions accessing LOTS of Bloom's taxonomy, which include multiple choice and short answer formats, tend to have higher performance outcomes. In contrast, HOTS question results remain approximately the same across ICE and THE [17]. Traditional ICEs potentially limit the areas of Bloom's taxonomy accessible, as questions primarily test middle-level thinking skills, leaving HOTS underutilized due to time constraints [18]. Attempts to integrate questions accessing HOTS can be detrimental to students, where the pressure within an ICE format limits their resulting performance [19]. Failure to properly assess this knowledge at deeper levels of thinking can also disincentivize students from developing proper mental models of problems, especially in physics courses, where cheat sheets are used as a crutch for true understanding [20]. Limitations of both ICEs and THEs could thus potentially lead to underdeveloped skills in students for areas of Bloom's taxonomy if only one format is used [15], [18].

To optimize metacognitive development within students, one might then seek to incorporate both ICEs and THEs within a student's routine. Implementations of these assessments exist in forms

such as pre-assessments for metacognitive planning and journals for reflection on metacognition within students [21]. Combining in-class and take-home exam formats addresses metacognitive skills within students directly, rather than their specific study skills, which has a greater impact on their overall critical thinking skills [22]. Specifically, the combination ICE and THE format aims to achieve deeper learning within students [19], where they become adept at identifying different cognitive processes for studying questions [6]. While inconsistencies remain present in studies of metacognition and academic performance, negative impacts are found on scores where exam formats incompatible with a student's thinking process continue to be used [23].

Thus, the combination of an ICE followed by a THE can test students at multiple learning outcome levels. In this study, the questions in the ICEs focus on the individual component of knowledge, aiming to test fluent retrieval of core conceptual and procedural knowledge. The learning outcomes in the ICEs usually focus on the remembering and understanding level. In the THE, students must analyze the information given and apply their component knowledge to solve a real-world problem. The in-class then take-home exam sequence can help students to understand their proficiency in the various learning outcomes. Students could use their performance on the ICE to understand which individual component knowledge they need to polish before tackling the complex application-oriented THE question. Each exam is followed by a post-exam reflection, which prompts students to reflect on their performance on each part of the exam and identify learning strategies and patterns that worked or did not work well to achieve various levels of learning outcomes. For example, a student who relies heavily on rote memorization may achieve satisfactory performance on ICEs due to the immediate recall of information, whereas their expected performance would not be met during the THE in which more critical thinking is required. This can prompt the student to reflect and adjust their learning strategies for the rest of the course.

The research questions in this study are:
R1. How does the scaffolded exam impact students' learning performance?
R2. How do the exam components promote students' metacognitive regulation of learning, respectively?
R3. What are students' perceptions towards the scaffolded exams?

Method

In this study, we designed and implemented three scaffolding and sequencing midterm exams in a Mechanics of Materials class with 119 students in Spring 2023. The three exams were held in weeks 3, 6, and 9 over a 10-week class term. Each exam had two parts: a timed 30-minute in-class exam (ICE) that focuses on the individual component of conceptual and procedural knowledge that students need to master to solve complex problems, and an untimed take-home exam (THE) that requires students to integrate and apply individual knowledge together to solve a more complex problem. The timed ICEs were closed-book and closed-note exams administered

during class time, with necessary equations provided to students. The THEs were released one or two days before the in-class quiz and were open for 4 to 7 days. Students could join the instructional team's office hours and ask for clarification questions. The academic integrity of the THE was enforced through a signature-based honor pledge system, with the reserved right to conduct one-on-one interviews about the thought processes behind each student's solutions to verify that they did not receive outside assistance. There is room for alternative methods to be explored to further ensure academic integrity is not violated in similar THEs.

To understand the impact of scaffolded exams on students' learning, we compared the final exam performance from two cohorts of students: students (N=119) from Spring 2023 in a mechanics of materials class, to students (N=99) from Spring 2022 for the same class taught by the same professor. Both classes were taught in person. Lecture sequences and the overall class structure, including homework, assignments, and other logistics such as class time, had high similarities. The only difference between the two classes was the midterm exams: the Spring 2023 class used the scaffolded and sequencing two-part exam structure described in this paper, whereas the Spring 2022 had two midterms, 80 minutes each, with 3 text-book style full problem-solving questions. A sample of the Spring 2022 exam question is shown in Box 1.

A round bar is made from a ductile material that has a modulus of elasticity of E = 60 GPa and yielding strength of σ_y= 270 MPa. It is known that F1 = [F1] kN, and F2 = [F2] kN. The diameters, as shown in Figure 1, are D1 = [D1] mm and D2 = [D2] mm.

Determine:

a) Which segment has the largest average normal stress? (neglect stress concentration)

b) The yielding factor of safety in segment CD

c) Comment on the magnitude of the factor of safety. Is it a reasonable factor of safety according to common practice? (Is it too high or too low?)

d) If we want to increase/ decrease the factor of safety, what methods could be used? List all the possible ones.

e) The total displacement of Point B.

Reminder: Please show all necessary FBDs and critical steps

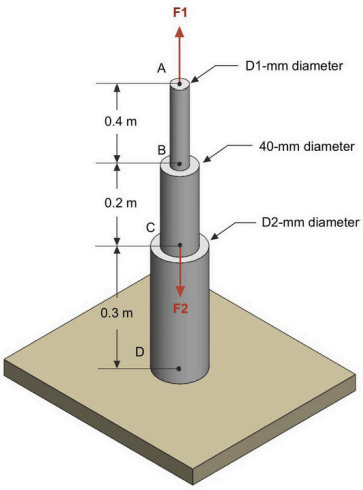


Figure 1: A round bar made from a ductile material.

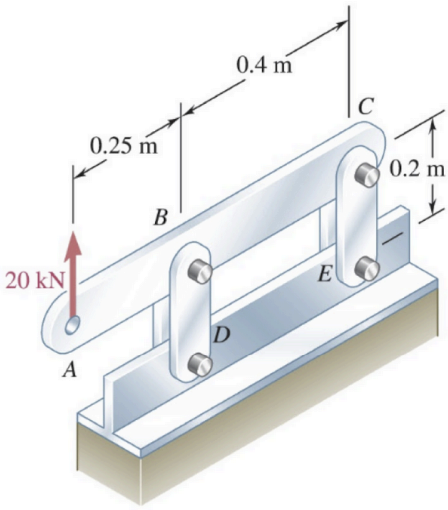
Box 1. Spring 2022 Midterm Exam sample question

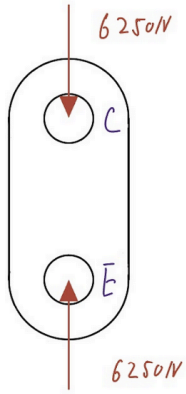
Communication with students to understand learning outcome taxonomy

During the first lecture of the semester, the course instructor introduced Bloom's Taxonomy of learning outcomes and helped students understand how it related to their learning and course assessment. This information was also written into the exam preparation guidance, which was available well before each exam.

In-class exam in Spring 2023

The in-class exam focuses on the individual component of knowledge, aiming to test fluent retrieval of core conceptual and procedural knowledge. The level of learning outcomes in the in-class exams usually focuses on the "remember" and "understand" levels. A sample in-class exam question for the first exam (at the end of week 3) is shown in box 2.





FBD of link CE

Bar ABC is connected to a fixed bracket through four vertical links. A pin is at points B, C, D, and E. **Each** of the four vertical links has a rectangular cross-section of 8mm x 36mm, and the four pins have a 16mm diameter.
We know that a compressive force of, 6250N acts axially on link CE, as shown in the FBD of link CE.

Box 2. Sample in-class fundamental knowledge exam question

Take-home exam in Spring 2023

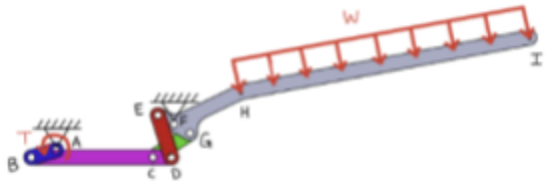
In the take-home exam, students must analyze the information given and apply their component knowledge to solve a real-world problem. A sample take-home exam question for the first exam (submitted by the end of week 3) is shown in box 3.

Problem Description

An illustration of a car's wiper blade system is shown below. Each separate component is color-coded, and all joints are pins in single shear. The wiper blade and wiper arm are treated as a single body here (gray component)

The standard operation and motion is shown in this animation. Suppose that the wiper blade cannot move as a result of snow and ice build-up on the windshield. An inexperienced driver decides to turn on the wipers.

The home position of the wiper is shown below, where member BCD is horizontal.



At the current position, the coordinates of all relevant points are as follows (in inches):

- A (-8.00, -1.75)
- B (-9.68, -2.24)
- C (-1.43, -2.24)
- D (-0.18, -2.24)
- E (-1.09, 0.61)
- F (0, 0)
- G (1.09, -0.61)
- H (4.51, 2.16)
- I (24.17, 5.84)

The wiper arm pivots about pin F. Segment HI of the wiper arm is stuck as a result of snow and ice, which can be approximated by a uniformly distributed force, w, normal to segment HI. Point A is pinned and connected to the wiper motor, which can apply a maximum torque, T, of 20 lb-ft in the counterclockwise direction.

All links (AB, BCD, DE, CG) have a rectangular cross section of 1 inch x ¼ inch. All pins have circular cross sections with ⅛-inch diameter.

Determine the following

a) Average normal stress (neglecting effects of stress concentrations) in:
   i) Link DE
   ii) Link CG

b) Internal loadings at the following locations:
   i) Point J in member BCD (exactly halfway between points B and D)
   ii) Point K in member AB (exactly halfway between points A and B)

c) Average shear stress in all pins: A, B, C, D, E, F, G

d) Suppose we change the material of pin A to one with higher shear modulus, but all other material properties are unchanged. Address the following using relevant equations and appropriate justifications/reasoning.
   i) How would this impact the factor of safety of pin A against yielding in shear?
   ii) How would this impact the amount of deformation experienced by pin A in shear?

Box 3. Sample take-home higher-order problem-solving exam question

Post-exam reflection

The post-exam reflection, often called exam wrapper, is one of the tools used outside the classroom to intervene and assist metacognitive development within students [24]. The application of an exam wrapper then potentially increases the students' metacognition through awareness of testing oneself as a viable means of studying [25]. The post-exam reflection was used in Spring 2023 to help students reflect on their performance on each component of the exam, and think critically about how they can change their learning strategies to perform better for the following exams.

The questions on the post-exam reflection were:

1. Overall, what did you learn from the In-class quiz?
2. How could you do differently in your exam preparation/ learning process to do better in a future In-class quiz?
3. What did you learn from the Take-home quiz?
4. How could you do differently in your exam preparation/ learning process to do better in a future Take-home quiz?
5. How do the in-class quiz and take-home quiz challenge you and help your learning differently, if any? How does it help you to steer learning strategies differently if applicable?
6. What learning strategies worked for you well so far? Please be specific and comment on both the learning method and learning time. For example, a student may say, "For

learning time, I found spacing study instead of cramming works well; in terms of learning method, doing retrieval practice and testing myself works well", etc.

7. Do you plan to adjust your learning strategies for the next step if applicable? Comment how for yes, and why if not.

Final exam

For both cohorts we studied, the final exam was a 3-hour long closed-book and closed-note exam. An equation sheet was given to the students. Both exams include 4 problems, each with 2 to 3 sub-questions. The topics were similar between the two final exams. The level of difficulty of the two exams was calibrated.

Results and Discussion

Data used for this study were the in-class and take-home midterm exam scores, final exam scores, students' responses to the post-exam reflection questions for the Spring 2023 quarter, and final exam scores from the compared group in Spring 2022. Students' open-ended responses to survey questions were analyzed to understand the different metacognitive strategies they employ for these two types of assessments. This was done by creating codes in ATLAS.ti, identifying similarities between themes across student responses.

R1. How does the scaffolded exam impact students' learning performance?

We compared the students' final learning outcomes performance in final exams between Spring 2022 (non-scaffolded exams) and Spring 2023 (scaffolded exams). The two final exams were evaluated to be at the same difficulty level, and both in closed-book format. Descriptive statistics results are: For Spring 2023, m=73.03%, SD=15.02%, N=119; For Spring 2022, m=66.14%, SD=19.61%, N=99. Hypothesis testing was performed to investigate if there exists a significant difference between the performance of the two cohorts. A non-parametric, permutation test was performed, with the assumption that final grades for the two groups of students are independent, under the null hypothesis that there isn't a significant difference between the two groups. With a 95% significance level ($\alpha = 0.05$), we reject the null hypothesis with a p-value of 0.013. The student cohort who had scaffolded two-part midterm exams did significantly better than the students who had the traditional text-book style midterm exams.

R2. How do the ICE and THE exam components promote students' metacognitive regulation of learning, respectively?

For the ICE, where students perceive the need to grasp fundamental concepts, metacognition seems to push them toward a more intensive and thorough study regimen. They recognize the importance of comprehending and mastering basic concepts, which suggests that they are engaging in metacognitive monitoring – actively assessing their current knowledge and identifying gaps. This metacognitive awareness prompts them to invest more time and effort in practice problems and prepare earlier, as they understand that deepening their understanding of

core concepts is crucial for success on the ICE (44 codes for practice problems, 39 codes for preparing earlier).

On the other hand, for the THE, where students describe the need for higher-order thinking and the integration of multiple concepts, metacognition leads them to a different set of strategies. The emphasis here is on metacognitive control – regulating one's cognitive processes to meet the demands of the task. Students perceive that they don't need to study more but rather start the exam earlier. This suggests that they recognize the cognitive load associated with integrating multiple concepts and the need for time management. Metacognition prompts them to allocate their resources differently, focusing on temporal aspects such as exam timing (16 codes for practice problems, 10 codes for preparing earlier, 90 codes for starting the THE earlier).

The preference for utilizing office hours more for THE further illustrates metacognitive control in adapting their study approaches. Students recognize that they may need additional support or clarification for complex, integrative tasks. Their metacognitive awareness guides them to seek help when faced with more challenging cognitive tasks.

R3. What are students' perceptions towards the scaffolded exams?

Students were surveyed at the end of the quarter regarding their perception of the exam format. They could choose from the following: a two-part scaffolded exam with the ICE and THE combination, a traditional exam, no preference, or other. As shown in Figure 1, from the 95 students who responded to the survey, 70 said they preferred the two-part exam model, while 13 preferred the traditional format. 9 had no preference, and 3 preferred other kinds of assessment, which were not specified. Students' preference for an exam format can be divided into three main categories: Student well-being, metacognition, and logistics.

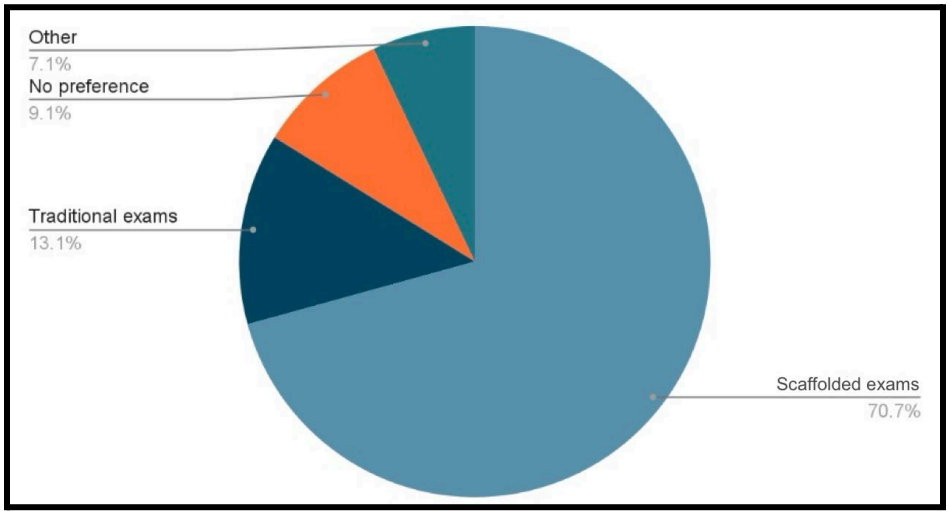


Figure 1. Students' preference for the exam models

The first category, student well-being, encompasses students' physical, mental, and emotional health. Students who preferred the two-part exam commented on how this assessment model endorsed their well-being by lowering their stress levels: "*The in-class and take-home combo was good in making sure that I knew the basics while also providing time to show that I can apply the basics to a more advanced situation. It alleviates a lot of stress on the student while still being effective in doing its job.*" Students associated stress with not being able to fully demonstrate their knowledge; since the two-part scaffolded exam was composed of a combination of a timed lower-order thinking test and a higher-order thinking take-home test, it was perceived as less stressful, and students, consequently, mentioned they were able to more accurately represent their knowledge.

On the other hand, three of the students said that the two-part exam format includes a large amount of assignments — 3 ICEs and 3 THEs in one quarter — whereas traditional assessments usually consist of one or two timed exams. These students mentioned that the large quantity of assignments added to their stress levels especially when those overlapped with assignments from other classes: "*... having three quizzes was a lot, considering they all had two parts (in class and take home). I especially get stressed the last couple weeks of school so the quiz on week 9 plus the take home due week 10 makes it difficult to start actually studying for the final.*" Students also mentioned that a lot of their weekends were consumed to complete the assignments, and having less or no free time interfered with their overall well-being.

The second category, metacognition, refers to how the exam format impacts students' learning outcome reflection. The two-part exam model consisted of two parts: an in-class exam (ICE) which tested basic concepts and knowledge, and a take-home exam (THE) which presented students with a real-life application of those basic concepts and tested students' higher-order thinking skills. Students who preferred this assessment model appreciated the explicit separation of lower and higher-order thinking questions. They mentioned that the exposure to different question formats and the explicit separation provided for an improved understanding of the class material, as can be seen in the following comment: "*Traditional exams don't promote very much learning beyond the effort to study for them. The two-part exam model allowed me to prepare myself with conceptual knowledge and basic problem solving with the in-class quizzes while the take-home quizzes forced me to think long and hard about the problems and how to solve them. I think this is a much bigger benefit than traditional exams which just force students to problem solve under pressure and either you get it or you don't.*"

When comparing the two-part scaffolded exam with the traditional exam format, students relate the latter to be misrepresentative of their knowledge as the exam does not include the class material entirely and has the pressure of a timed, in-person exam: "*I think the traditional exam can sometimes be misrepresentative because when there is only 3 questions sometimes it does not allow for the student to demonstrate full knowledge of the course content. Where the take-home*

in class combo can allow for a wider expression of knowledge of material and how to use it," and "*(...) The difference in questions helps me not only maximize my scores, but also think about the problems differently. A traditional exam (like the final) is exhausting and causes me to forget how to do some very simple processes that I could do normally and make many mistakes.*"

Students also mentioned how the THE builds upon the ICE. After taking the ICE, students are assured about the background knowledge of which content still needs to be enhanced to perform better in the take-home portion of the assessment. Such a process consequently improves their understanding of the class material: "*I believe that the in class quiz makes me rethink and see if I am truly understanding the basics of the course while the take home quiz humbles me. Even if I did good on the in class quiz the take home quiz makes me think more and sometimes I make stupid mistakes which could have been avoided if I gave it a deeper thought. This helps me reflect on what and how I study.*" As the ICE assisted students with a reflection on their comprehension of solid mechanics and informed them about their study needs, the two-part exam successfully promoted metacognition. Students also commented on how this different assessment format worked as a motivator to adjust their studying habits not only for the Mechanics of Materials class but for all other classes they were taking.

Students also mentioned that having 4 days to complete the THE offered them the opportunity to further validate their answers by revising the solved problems with a fresh perspective. This opportunity for revision encouraged self-reflection on their learning process, which consequently deepened their understanding of the class concepts. One student said they "*really enjoy having longer periods of time to work on harder problems like the take-home quizzes. I like the ability to pace myself and come back to my work with a fresh mind, I tend to get stressed in strictly timed testing environments and overthink small mistakes or gaps in my understanding, leading me to do much worse overall that what I think my learning comprehension is at. Having the take home quizzes was much more enjoyable and accurate representation of my knowledge from class.*"

In regards to logistics, a couple of students noted that because the two-part exam is not a common assessment format, they encountered difficulty in successfully preparing for and executing the exam, especially the THE portion: "*I'm definitely more use to the 'traditional' exams so that is what I'm more comfortable but because of this other exam style it made my studying method different which hurt me academically for a little but I think it helped in the long run.*" From some students' perspectives, more guidance on how to prepare for THE and greater exposure to problems like the THE is needed for them to become more comfortable with the scaffolded exam format. However, testing students with a non-standardized exam was the objective of the teaching team for applying the ICEs and THEs. Therefore, students' concerns were the purpose of adopting the two-part scaffolded exam as an assessment tool. Nonetheless, for future classes, it could be beneficial to have more transparent communication with students regarding the exam format and its objective concerning their learning.

Students who had a preference for a traditional exam format mentioned that they had a preference for exams being held during class periods. Those students encountered difficulty scheduling a time outside of the class to complete the THE and had to work on it during the weekends, as can be seen in the following comment: *"I liked the in-class quizzes a lot since they should've been easy for the most part, except I just didn't study as much as I should've been. However, in my opinion I disliked the take-home quizzes because they would open maybe 2 days before the in-class but I would be studying for the in class quiz, meaning i'd have the weekend to do it but during the weekend I usually distressed/had other things going on, so it was really difficult for me to actually do good on them. It felt like there was too much to keep track of for the actual problem, but that might've just been me.*"

Within the group of students that either had no preference or preferred a different kind of assessment (which was not specified), one student noted that they enjoyed having a change in the exam format as the majority of the classes test students with a more traditional timed format. On the other hand, a couple of students mentioned that because they were more used to traditional exams, they would have felt more confident being tested and having their performance reflected in that way. Once again, the students' concerns matched with the teaching team's goal of promoting metacognition. Some students also mentioned how difficult it was to manage studying for the ICE and solving the THE in the same week, especially with the additional loads from the course homework.

After analyzing students' preferences and comments, it can be concluded that most students preferred the two-part scaffolded exam and metacognition was the aspect that was most taken into consideration by them. The majority of students who did not prefer the two-part exam model reasoned their choice on logistics concerns. The main objective of implementing a scaffold exam model was to promote metacognition, which was successfully attained. Employing more transparent communication with students about the format and objective of this exam format is a way to address some of the students' concerns regarding the exam's logistics.

Conclusion

In this study, we investigated the impact of a scaffold exam model with the combination of in-class exams and take-home exams on students' learning metacognitive regulation and learning performance. Students under the scaffold exam model performed significantly better than those who had traditional midterm exams. This may be because the two-part scaffolded exam model better directs students' metacognitive regulation of their learning, and adjusts learning strategies as needed. Students also prefer the scaffolded model as the exam is more helpful in assisting students understand their learning progress for different levels of learning outcomes, and is less stressful.

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