Beginning to Understand and Promote Engineering Students' Metacognitive Development

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Introduction

Metacognition, defined as the knowledge and regulation of one's own cognitive processes [1, 2], is critically important to student learning and particularly instrumental in ill-structured problem-solving [3, 4]. Despite the importance of metacognition, much of the research on metacognition has occurred in controlled research settings, developing our understanding of what it is and why it is beneficial. Much less is known about how to help students develop metacognitive skills in classroom settings, that is, how to teach metacognition. Further, there are significant bodies of research on the role of metacognition in writing and solving math problems, but little work has been done on the role of metacognition within engineering disciplines.

Metacognition is particularly important in the training and development of engineers as problem solvers. Practicing engineers are problem solvers, engaging ill-structured and ill-defined real-world problems. Metacognitive skills function to help problem solvers navigate such messy problems – enabling them to reach solutions more efficiently and effectively and to continue learning from their experiences [5]. More specifically, metacognition improves ones awareness and regulation of how they think – identifying and defining problems and sub-problems, how well specific known strategies are matched to a particular problem, planning and monitoring a solution process, and evaluating the process and results. These same skills improve engineering student learning in present educational contexts and are connected to lifelong learning. In preparing to become practicing engineers, *i.e.*, messy problem solvers, engineering students will benefit greatly from explicit development of their metacognitive skills – now and throughout their lives.

The purpose of this project is to generate transferable tools which can be used to teach and evaluate undergraduate engineering students' metacognitive skills in the context of an engineering classroom. To accomplish this, we are working through a three-phase project in which we pilot a metacognitive intervention in one context, translate the intervention to a new context, and share the intervention and provide training on how to use it. This paper reports on the outcomes from Phase 1, which is focused on the development and pilot implementation of a metacognitive intervention for a sophomore engineering course at a small undergraduate-focused engineering school and assessing student's metacognitive development. The intervention is made up of six modules containing paired elements: training videos on metacognitive knowledge and awareness; contextualized in-class activities; and metacognitive assignments that provide opportunities to become more metacognitively self-aware and practice metacognitive regulation. In Phase 2, we will use the research outcomes from Phase 1 to revise the intervention and translate it to a second engineering education context, a freshman course at a large comprehensive state land-grant university. We measure students' metacognitive development through pre- and post- interviews and surveys, that is, early in the term and late in the term after most of the interventions, and through analysis of students' responses on post video questions, in-class activities, and metacognitive assignments. The assignments are designed to promote student metacognitive awareness and help them practice metacognitive regulation.

In the present analysis we focus on understanding if and how students are developing metacognitive skills through the intervention. We posed and answered these research questions:

RQ1. What strengths and gaps did students recognize in their primary learning approaches prior to the intervention?
RQ2. How did students engage in metacognitive regulation to improve their learning approaches during the intervention?
RQ3. How did students perceive the difficulty and usefulness of metacognition following the intervention?

To answer the questions we focus on the students' engagement with the intervention modules. Specifically we examine students' responses to questions about the videos, in class activities, and metacognitive assignments.

Framework

Metacognition is made up of the interacting and complementary elements of knowing about and regulating our thinking, *i.e.*, our cognitive processes, as shown in Figure 1.

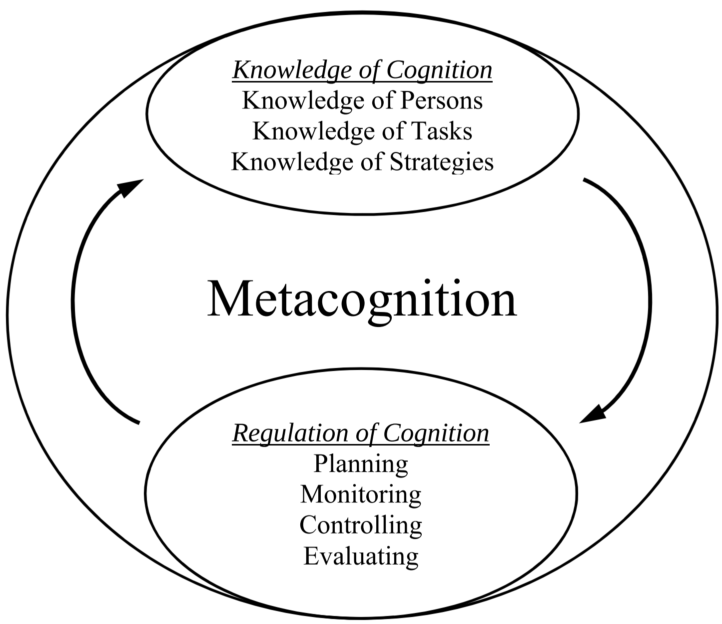

Figure 1: Conceptual Framework of Metacognition [6]

As the arrows in Figure 1 indicate, metacognition is cyclical. We draw on our current state of metacognitive knowledge as we engage in metacognitive regulation. As a result of our metacognitive regulation, there is feedback to expand and refine our metacognitive knowledge. Knowledge of persons refers to knowing how thinking and learning works for people in general and how we tend to, and prefer to process information in specific [1]. Knowledge of task includes things like task cognitive demands, goals, difficulty, complexity, and context [4, 7].

Knowledge of strategies encompasses general learning and problem-solving strategies, as well as task specific strategies [4, 8].

Within metacognitive regulation, our framework focuses on planning, monitoring, controlling, and evaluating. Metacognitive planning involves integrating the elements of metacognition focused on a specific task, setting task goals, sub-dividing more complex tasks, and predicting task outcomes [8, 9]. Monitoring and control are necessarily linked activities. Monitoring is being reflective during a task, keeping track of progress, how things are going, and if selected strategies are working [8, 10]. Control is the response to findings from reflective monitoring, including changing strategies and adjusting goals. Of course, awareness of a problem does not guarantee a change, rather, it provides the opportunity for a control action. Metacognitive evaluation is reflection after a task (or sub-task) is completed, including examining artifacts of learning and how the task was navigated [9].

Metacognition is not hierarchical or one-dimensional. These elements are intertwined, and as the arrows in Figure 1 suggest, we cycle through these elements and draw on elements in concert as we practice metacognition while engaging in cognitively demanding tasks.

Methods

Our Methods section consists of three parts. The first part describes the research site. The second part describes the intervention. The third part describes the data collection and analysis.

Site Description

The pilot of the metacognition intervention was implemented at a small private engineering, math, and science school in an engineering problem solving course entitled Conservation and Accounting Principles (ConAPs). Two sections of this course, including 25-30 students each, received the intervention, out of eight total sections. The intervention was a graded element of the course, counting for a modest part of the homework grade. The point allocation was tied to the expected time required to complete the intervention elements relative to time to complete regular homework assignments. Even though the intervention was graded and required as part of the course, some students opted to not complete it. Because the assignments were graded, using direct quotes could make participants identifiable to instructors or peers. Therefore, we do not use any direct quotes as evidence though direct student statements contributed to the development of our findings.

Intervention Design

The entire metacognition intervention consists of six modules, though we only piloted five modules in this first implementation. Each module includes a video operationalizing elements of metacognition within an engineering education context, reflection questions following the video, an in-class assignment, and a homework assignment. Students were asked to watch the video prior to attending class and submit responses to reflection questions. The in-class activities asked them to further engage with the content to build understanding. The follow-up homework assignments generally asked students to apply the content. To facilitate ease of use of the modules, we designed the modules to be short and customizable so they can fit with current content rather than forcing instructors to eliminate course content to accommodate the modules. The videos are five to ten minutes long as are the in-class activities. The follow-up homework assignments take another 15 to 20 minutes.

Module 1, "What is metacognition and why should I care?" introduces students to the metacognition framework and argues for importance of metacognitive knowledge and regulation. The in-class and homework extensions ask students to consider how they approach learning and identify the value of being able to use multiple approaches.

Module 2, "Knowing about Thinking" focuses on metacognitive knowledge of self, tasks and strategies. The in-class module asks students to think about the problem-solving format used in the class and why they are asked to write particular steps in a particular order. The assignment extension first prompts each student to inventory the specific study strategies he or she uses (based on Svinicki's GAMES survey [11]). The assignment extension prompts the students to choose an area in which he or she wants to improve and reflect on why they choose this area and specifically what he or she will do differently to improve in this area.

Module 3, "Evaluation" introduced students to the idea of assessing a learning experience to determine what worked and what did not. This module also helps students make short-term plans to correct knowledge gaps and long term plans for more effective learning in the future. The in-class activity included a list of questions students could ask themselves to determine the learning experience effectiveness. The assignment extension was an "exam wrapper" which asked students to evaluate exam performance, correct knowledge gaps and develop plans to better prepare for the next exam.

Module 4, "Planning for Our Thinking" focused on the metacognitive regulatory strategy of planning. The video introduces the idea of elephants (tasks tied to big projects and most important goals) and rabbits (tasks that can become distractions, which may or may not need to get done but generally do not attach to big goals). In class students are asked to identify elephants and rabbits associated with the course and asked students to use a calendar to plan for addressing the elephants and rabbits. The assignment extension asked students to extend the planning to include elephants and rabbits from other courses and activities that might impact the elephants and rabbits for the subject course. They were also asked to consider how they might plan to use other learning strategies they tackled in prior weeks.

Module 5, when completed, will focus on monitoring and control. Metacognitive monitoring is keeping track of how a task is going while you are working on the task, and metacognitive control is taking action in response to your awareness of how your learning is going.

Module 6, "Thinking Back and Thinking Ahead", asks students to reflect on topics from the prior weeks and think about how they can apply what they have learned going forward. The in-class activity asks students to identify one learning behavior or strategy they use that is most challenged, one learning behavior or strategy they use that is most confirmed and one or more enduring lessons from the module they can use going forward. The final module wrapped up the whole sequence in class and had no follow-up homework assignment.

Data Collection and Analysis

Our data consisted of short, written responses collected electronically from students in reply to assignment questions as part of metacognition modules. While we intentionally collected data that could tell many stories regarding the intervention, we selected the following assignment questions to answer our research questions:

Table 1: Intervention Assignment Questions Relevant to Research Questions

Research Question (RQ)	**Assignment Question (Q)**	**Module**	**Week**
RQ1. What strengths and gaps did students recognize in their primary learning approaches prior to the intervention?	Q1. What is your primary learning strategy for problem solving courses like ConAPs? Why do you think you rely on this strategy so much?	1	2
	Q2. Using the framework of the learning strategy categories from the video: rehearsal, elaboration, and organization, evaluate how well your primary learning strategy helps you engage with course material. Summarize your thoughts here.	2	4
RQ2. How did students engage in metacognitive regulation to improve their learning approaches during the intervention?	Q3. (After taking GAMES Survey [11]) Refer to your scrap paper where you kept track of your scores in each area. In what area did you score the highest? In what area did you score the lowest?	2	4
	Q4. [Directly after Q3] Pick an area in which you want to improve by the end of ConAPs. State why you picked that area and brainstorm three strategies you could and are likely to implement to improve in this area. What are you going to do tomorrow (or the next time you study ConAPs) to start doing this?	2	4
	Q5. Name one new thing you have been doing since completing the GAMES survey. How is it helping you be a more skilled and efficient learner? Review your plan and strategies to implement your plan from your submission to the previous assignment if necessary.	3	7
RQ3. How did students perceive the difficulty and usefulness of metacognition following the intervention?	Q6. Is it easier, about the same, or harder to work on developing your metacognitive skills than to develop your athletic/music skills (whichever is meaningful to you)? Please explain your answer.	6	10
	Q7. Are you convinced that intentionally developing your metacognitive skills can help you be successful? Please explain your answer.	6	10

For each cluster of assignment questions corresponding to a research question (see Table 1), students' responses were paired such that we could track responses from each student across questions. In cases where a student completed some questions in a cluster but not others, that student's responses were excluded from that cluster's analysis. For example, for RQ2, a student who responded to the assignment for Module 2 but not the assignment for Module 3 was excluded for analysis, as we could not compare that student's planned strategies with her actual strategies she implemented in the intermediate weeks. We observed a decline in the number of responses to each assignment as the modules progressed. We were able to analyze 37 responses for RQ1, 25 responses for RQ2, and only 14 responses for RQ3. We suspect that this decline in participation was due to student prioritization of other course activities, particularly as later course exams began to draw their attention.

Data were analyzed qualitatively by open coding for emergent characteristics relevant to our research questions, categorizing these codes based on their apparent similarities, and authoring memos, all of which helped us make sense of the data [12]. Code categories were then analyzed based on their content, relative frequencies of occurrence, and patterns of co-occurrence to answer each research question. MAXQDA, a computer-aided qualitative data analysis software, was used to facilitate this analysis.

Results and Discussion

Our analysis provided evidence of student metacognition in connection with the intervention we implemented. Moreover, while our analysis focused on answering our research questions, our results also illuminated several points of improvement for future implementations of the interventions designed to address metacognition, and identified methodological limitations to address when collecting further data on such interventions. To tell the story of our results in a way that flows logically, we have intentionally merged our Results and Discussion sections. This merging enables us to present and interpret the results by research question. We intersperse three types of insight throughout this section, highlighting them as **evidence**, **intervention design**, and **methodological limitation**.

RQ1. What strengths and gaps did students recognize in their primary learning approaches prior to the intervention?

Responses to Q2, in which students evaluated their primary learning strategies, provided some **evidence** that students demonstrated meaningful knowledge of themselves and their strategies when provided with a framework for doing so. While some students deviated from the rehearsal, elaboration, and organization framework we requested, those that used the framework most often cited rehearsal as a strength of their primary learning strategies, while most commonly citing elaboration as a weakness. All but one of these students cited working problems provided by the course as part of their primary learning strategies, which we consider to be a form of rehearsal because it helps students recall strategies to solve similar types of problems on exams.

Responses to Q1 and Q2 also helped us identify two **methodological limitations** in the ways we framed the questions. First, in Q2, although we asked students to frame their discussion in terms of rehearsal, elaboration, and organization, many students did not do so, and instead summarized strengths and weaknesses from their own perspectives. These responses covered a large breadth of strengths and weaknesses and rarely overlapped, reducing our ability to categorize codes and thereby extract meaning from the data. Second, while we asked students to focus on their singular primary strategies in Q1 and Q2, students often listed multiple primary strategies in Q2—which frequently conflicted with their responses from Q1—further complicating our ability to systematically make meaning of the data. Both limitations can be addressed in further data collection by scaffolding student responses, e.g., by asking them to repeat the one strategy they use most on Q2 or by providing a table students can fill in to evaluate their strategies on each of rehearsal, elaboration, and organization.

RQ2: How did students engage in metacognitive regulation to improve their learning approaches during the intervention?

Combined, responses Q3, Q4, and Q5 offered **evidence** that students engaged in metacognitive regulation to improve their learning strategies throughout the academic term. Responding to Q3 and Q4, students identified their strongest and weakest areas of learning through the GAMES survey, and then suggested changes to their learning strategies accordingly. Students suggested strategies for improvement that more often aligned with their lowest scores in the GAMES survey than not, and that would be productive in improving their weakest areas of learning. This demonstrated that they were able to brainstorm productive strategies to improve their learning by identifying areas of weakness and developing plans to address these weaknesses.

Student responses to Q3 and Q4, in combination with responses to Q2, also alerted us that future metacognition **intervention design** should press students to give the same amount of attention to their weaknesses as they give to their strengths. When evaluating their primary learning strategies, as Q2 asked, students were nearly twice as likely to discuss their strengths as they were to discuss their weaknesses. Contrarily, when students were asked to give equal attention to both in Q3 and Q4 through the GAMES survey, identifying areas of weakness proved to be an effective way to brainstorm productive strategies for improvement.

Other **evidence** of metacognitive regulation was not as straightforward. When a student discussed in Q5 the strategies he actually implemented 3 weeks later, these strategies rarely matched those the student initially suggested. The most commonly cited actual strategies focused on planning time to study, how to interact with problems, and ways of reviewing or referencing course material during study. We found these to be less ambitious than the most common suggested strategies, which focused on setting goals, getting help, and finding ways to improve productivity during study. One area where suggested and actual strategies overlapped with similar frequency was working with peers, such as participating in study groups and discussing course material with classmates.

However, we found that the actual strategies were progressive compared to the types of strategies students first described in the Q1. To illustrate this, student responses to Q1 and Q5 both commonly discussed using problems during study, but the ways they described using problems differed. In Q1, students who discussed problems contended that working a problem was intrinsically valuable. In Q5, by contrast, students who discussed problems pointed out that reworking previously worked problems was not necessarily productive. These students discussed using strategies such as seeking out new problems, utilizing university-archived test problems from previous semesters, and even creating their own problems based on course concepts, none of which were present in responses to Q1.

We believe that the differences in students' suggested and actual strategies was due in large part to a **methodological limitation** involving the timing of data collection. In the 3 weeks between module 2 (where students suggested strategies) and module 3 (where students reported actual strategies), students spent much of their time preparing for an upcoming exam. As such, actual strategies employed tended to focus primarily on test preparation, while suggested strategies tended to focus on more general coursework. In future data collection, these assignments could be positioned in such a way that the circumstances of learning are similar between the two assignments.

RQ3: How did students perceive the difficulty and usefulness of metacognition following the intervention?

Q6 and Q7 both provided **evidence** that students find metacognition both useful and difficult to develop compared to skills in music and sports, as almost every student response explicitly stated both points. Moreover, we found some evidence that both metacognitive knowledge and regulation were important to students. When responding to Q7 regarding why metacognition contributed to their success, most students offered the straightforward logic that metacognition improves learning, and better learning leads to more success. However, those responses that offered more substantive explanations most commonly cited knowledge of self and strategies—understanding one's own habits and weaknesses and knowing strategies to remedy them—as contributive to their success. Moreover, while almost every student felt metacognition was more difficult to develop than skills in sports or music, two students felt metacognition was equal in difficulty to develop. Both of these students said they recognized that metacognition required the same level of perseverance and attention that sports/music require, and realizing this made the skills seem equal in difficulty. This suggests the importance of encouraging students to follow through on their metacognitive regulation plans.

These questions also highlight an important point for metacognition **intervention design**. When answering Q6 regarding the difficulty of metacognition, students either explained the difficulty of metacognition comes from lack of enjoyment or noted difficulty developing and measuring competence compared to music/sports skills—most commonly because metacognition yielded less visible results. This ties in to research on self-determination theory, which asserts that developing and monitoring one's competence is essential to intrinsic motivation (often described as enjoyment) [13]. As such, interventions targeting metacognition should build in ways to help students visibly track their progress. Such an approach is reinforced by the two students who, in response to Q7, were not sure metacognition would contribute to their success; both cited a failure to see progress during the semester among their reasons for being skeptical.

One potentially effective intervention strategy to address a number of issues highlighted in this paper would be to ask students to track a particular (self-selected) learning strategy through the planning phase to complete implementation. This would (1) provide stronger evidence for or against students' continuation of metacognitive planning to metacognitive regulation, (2) allow students to visualize their progress, and (3) give students practice in metacognitive regulation, perhaps lowering the high perceived difficulty of metacognition.

Conclusions, Implications and Future Work

At a high level, our study reveals three important findings. First, students demonstrated meaningful knowledge of themselves and their strategies when provided with a framework for doing so. Second, students engaged in metacognitive regulation to improve their learning strategies throughout the academic term. Finally, students find metacognition both useful and difficult to develop. While these findings have implications for the design of our project as we go forward, they also have important implications for educators.

Our findings suggest that it is possible to teach students about metacognition and to help them develop metacognitive stills. Doing so requires providing students with a framework to know how to think about their learning processes. Our findings also suggest not just sharing the framework and hoping students grab onto it, but instead helping them learn how to focus on specific aspects and to consider both strengths and weaknesses. Our findings also suggest that students are willing to engage in developing metacognitive skills, but recognize that doing so is hard work. There are many ways students might be motivated to engage in developing metacognitive skills; students might want to improve grades or develop more efficient approaches to learning to ease the tight schedules that can come with engineering majors. Asking students what would motivate them to change their approach to learning could be a good way to start.

Future work for our project team includes revising the intervention materials and testing them in a different engineering education context. We can directly draw on the findings from this analysis to help us. Beyond the scope of this project, investigating the intersection of motivation and metacognition could be a fruitful avenue for finding ways to encourage students to engage fully in the intervention activities.

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