Board 343: Outcomes from Metacognition Support in a Fluid Mechanics Flipped Classroom

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1. Introduction

Planning, monitoring, and evaluation are valuable skills that comprise the regulation of cognition, also known as metacognition. These skills can be promoted through reflection, or thought about one's own actions. With reflection, students become more aware of their own processes. Although reflection is essential for learning, there has tended to be limited systematic reflection and metacognitive instructional activity in engineering (Ambrose, 2013; Cunningham et al., 2015; Marra et al., 2017).

Our NSF-funded research aimed to address this gap. Our research was conducted in a flipped fluid mechanics classroom, in which step-by-step instruction in planning, monitoring, and evaluating (PME) of problem-solving was provided as part of in-class exercises (i.e., direct instruction "in context") to support metacognitive skills development and problem-solving. Students also reflected weekly in writing about their planning, monitoring, and evaluating, as well as about their pre-class and exam preparation. This intervention consisting of intentional PME instruction and reflection occurred during three semesters between fall 2021 and fall 2023.

To assess the outcomes of this intervention, two semesters of the flipped course without the intervention were also conducted. We assessed cohort differences in discipline-specific, cognitive skills using a final exam. The perspectives of students in the intervention group about the weekly reflections were also gathered via the reflections, whereby we also assessed evidence of self-regulatory, metacognitive skills within their written reflections.

2. Relevant Literature

Metacognition is indispensable to learning because it enables people to manage and correct (if needed) their domain-specific cognitive knowledge and skills (Schraw, 1998). The self-regulatory practices of planning, monitoring, and evaluating oneself with respect to learning and performance are embodied within and support metacognition (Schraw, 1998). Metacognition is also defined as thought, knowledge, or awareness about one's own cognition and cognitive processes and is a *general* skill that supports specific cognitive skills (Schraw, 1998).

Planning entails items such as setting goals and assessing needs *before* the task (Schraw, 1998; Wengrowicz et al., 2018). Monitoring occurs "in real time" *during* the task and involves ongoing self-awareness and tracking of progress and self-testing (Schraw, 1998; Wengrowicz et al., 2018; Cunningham et al., 2015). Evaluating occurs *after* the task and involves assessing one's performance (Schraw, 1998; Cunningham et al., 2015).

Our research utilized Tanner's reflection framework, which was developed to promote the metacognition of biology students as part of usual course practices (Tanner, 2012). Tanner developed a matrix of planning, monitoring, and evaluation reflection questions related to typical classroom sessions, active learning exercises, and other course elements (Tanner, 2012). In addition to promoting metacognition through reflection, our research provided metacognition instruction during flipped-classroom problem-solving, as described more fully in a previous publication (Authors, 2023).

3. Methods

Outcomes from the semesters in which the intervention was employed were compared to those from semesters in which the intervention was *not* employed. The intervention consisted of intentional instruction in planning, monitoring, and evaluation of one's in-class problem-solving processes, as well as weekly reflection. The weekly reflection prompted students to think about their in-class problem-solving; classroom and exam preparation; and performance, learning, and academic behavior.

3.1 Reflection Questions: Description and Content Analysis

A total of 12 reflection questions were assigned throughout the semester during each of the fall 2021, fall 2022, and fall 2023 semesters (i.e., intervention semesters). Each weekly question corresponded to a planning (P), monitoring (M), evaluation (E), or post-exam question, or possibly a combination of these. We referenced a matrix of reflective questions developed by Tanner in developing our questions (Tanner, 2012). The question type (i.e., P, M, or E) was alternated weekly.

The responses from these weekly questions underwent an emergent, inductive content analysis with two coders and coding schemes (Neuendorf, 2002). During the first semester of the study, approximately 17% of the reflections were coded by two analysts weekly given the limited resources (Neundorf, 2002; Geisler & Swarts, 2019). Aside from two of the weeks this semester, the inter-rater reliability was in the range of Cohen's $\kappa = 0.60$ to $\kappa = 0.90$, with values between 0.61 and 0.80 indicating substantial agreement, and values of 0.81 or above being "almost perfect." (Landis & Koch, 1977). For the other two semesters, all reflections were independently coded by two analysts (i.e., double-coded), with subsequent discussion to reach a consensus on the final codes. The inter-rater reliability was in the range $\kappa = 0.74$ to $\kappa = 0.93$ across all weeks, suggesting substantial (or greater) agreement (Landis & Koch, 1977). A sample of the weekly questions (i.e., from a subset of the weeks throughout the semester) is presented next.

Weeks 1-3: The week 1 question prompted students to plan (P) an approach for supporting their in-class problem-solving, while taking into account their pre-requisite knowledge, as shown in Table 1. The week 3 reflection question asked students to evaluate (E) their performance during the in-class problem-solving exercises. The week 2 question changed somewhat between fall 2021 and fall 2023. The fall 2021 question prompted students to monitor (M) their in-class problem-solving. However, students did not truly conduct monitoring (M), but rather tended to write planning (P) reflections in the future tense. This may have been due to not having a laptop during class to submit the reflection, or just being occupied with the problem-solving itself. Thus, the fall 2022 question was changed to ask students to monitor (M) their pre-class preparation outside of class. However, during the fall 2023 semester, this question was again changed to include future planning, in case the student was not doing the pre-class preparation as they should have been.

Table 1: Week 1-3 Reflection Questions

Week	Metacognition Element	Reflection Question (Fall 2023 wording)
1	P	Based on your preparation for Fluid Mechanics (including pre-requisite material), how can you best support and approach your in-class problem-solving in this course?
2	P&M	In your honest assessment, are you preparing before class for the in-class problem solving in Fluid Mechanics (yes/no)? How are you (or how should you be) preparing, including clarifying confusions about the material or grasping challenging concepts using resources or opportunities available to you?
3	E	Based on your work and experience with this week's in-class problem solving in Fluid Mechanics (week 3), evaluate your performance as either good or in need of improvement. State what you should do to either maintain your good performance or improve it if necessary.

Weeks 5 & 7: The reflection questions posed in weeks 5 and 7 (shown in Table 2) related to the first exam. The week 5 question asked students about their current or planned preparation for this exam. The week 7 question was the post-exam question asking students if they would do things differently in preparing for the next exam given their performance on the first exam. A reflection question was *not* posed in week 6, the exam week.

Table 2: Weeks 5 & 7 Reflection Question

Week	Metacognition Element	Reflection Question (Fall 2023)
5	P & M	To what extent are you currently preparing for exam #1 in Fluid Mechanics? Indicate by choosing one of the following: 1) Preparing well, 2) Preparing only to a limited degree, or 3) not preparing at all. What are you currently doing or planning to do to prepare for the first Fluids exam? (P+M)
7	P (Post Exam)	Will you do things differently in preparing for the next exam in Fluid Mechanics based on your performance on this exam, and if so, what will you do differently?

Week 15: The final reflection question of the semester (Table 3) prompted students to reflect on the weekly reflection questions themselves. This served not only as a reflection opportunity in itself but also as an evaluation of the weekly reflection questions from the students' perspectives.

Table 3: Week 15 Reflection Question

Week	Metacognition Element	Reflection Question
15	E	What are your thoughts about these weekly Canvas questions you've been answering related to the in-class exercises, exams, or other items in Fluid Mechanics?

3.2 Final Exam and Demographics Survey

An identical final exam was given to students in the intervention and non-intervention groups as a direct assessment to compare their content knowledge. There were 12 multiple choice (MC) questions related to the lower-order skills in Bloom's taxonomy. The three free-response (FR) questions on the exam required a written demonstration of the problem-solving process. An analysis of covariance (ANCOVA) was used to statistically compare the final exam scores for the two cohorts, using prerequisite GPA as a control variable (Norusis, 2005). This GPA was based on the grades obtained in the prerequisite coursework (i.e., calculus 2, calculus 3, ordinary differential equations, statics, dynamics, and thermodynamics), which were gathered via a demographics survey. The demographics survey was also used to gather gender, ethnicity, Pell Grant status, and transfer information (i.e., transfer into the engineering program) to enable stratified analyses.

Given the small sample sizes associated with some of the demographic strata, the nonparametric version of ANCOVA - Quade's test - was also run (Quade, 1967; Lawson, 1983). The *p*-values based on the parametric and nonparametric versions of ANCOVA were generally in agreement, however. Because of the multiple statistical tests run, Bonferroni's correction was considered (Bland & Altman, 1995; Perneger, 1998). Practical significance was assessed using Cohen's *d* effect size.

4. Results

The participants in this study were junior and senior-level mechanical engineering students at a large research university in the southeastern U.S. The average weekly reflection participation rates ranged from 79% to 85% depending on the semester, with a total overall rate of 83% of enrolled students.

4.1 Weekly Reflections: Content Analysis Results

Week 1: The top response categories for the week 1 planning question about how to support one's in-class problem solving are shown in Table 4 and were as follows: 1) study or pre-class preparation with the current course material (49%), followed by review or use of pre-requisite coursework (44%). The planned use of a structured approach during the problem-solving was encouraging and noteworthy at 31%.

Table 4: Week 1 Content Analysis of Reflections

Week 1 (P): *Based on your preparation for Fluid Mechanics (including pre-requisite material), how can you best support and approach your in-class problem-solving in this course?*	
Top Categories (*n*=262)	**Additional Description**
49% Study or pre-class prep w/ present course	Diligent or timely study or pre-class preparation with fluid mechanics (e.g., watch videos, formula sheet, take notes)
44% Previous coursework	Review or use previous or pre-requisite coursework or problem-solving skills
31% Structured problem-solving approach or independent/critical thought	Describe or understand problem, break problem into parts, plan solution approach, apply knowledge, use structured problem-solving process, use independent or critical thought
28% Practice problems	Do practice problems
26% Ask for help	Request or receive help from instructor, TA, peer

Week 3: Not unexpectedly, the top response category for how to improve or maintain performance with in-class problem solving was practicing or solving problems (80%), followed by studying content or preparing for class (61%). However, the discipline-based category of *carefulness, organization, and diligence* was discussed in 33% of the responses. This pointed to an awareness of the importance of actionable, self-management behavior, including monitoring oneself in real-time (i.e., check one's work) or evaluating one's progress and responding (i.e., catching up if behind).

Table 5: Week 3 Content Analysis of Reflections

Week 3 (E): *Based on your work and experience with this week's in-class in Fluid Mechanics (week 3), evaluate your performance as either good or in need of improvement. State what you should do to either maintain your good performance or improve it if necessary.*

Top Categories (*n*=267)	**Additional Description**
80% Practice problems	Do or solve practice problems
61% Study or pre-class prep	Watch videos, read textbook, review notes, study/learn content
33% Carefulness, organization, diligence	Check work or be careful, spend sufficient time or be diligent, catch up if behind, attend class, be organized, pay attention to details, take notes, have study schedule or routine to stay on pace, create formula sheet

Weeks 5-7: At week 5 of the semester, students were asked to assess the degree to which they were preparing for the first upcoming exam. Half (50%) indicated they were preparing well, and the remainder acknowledged either preparing to a limited degree (36%) or not preparing at all (9%). Thus, 45% of the students (*n*=123) recognized an opportunity and/or need to enhance their exam preparation. The most prevalent or planned preparation method was solving or practicing problems, (i.e., 90% of the respondents). However, 22% said they were following or planning to follow a study schedule, again indicating self-regulatory behavior.

In week 7, after the first exam was returned, students were asked what they would do differently in preparing for the second exam based on their performance on the first exam. Nearly all students (95%) indicated they would do at least something (e.g., one item) differently in preparing for exam 2 (*n*=250). A much smaller proportion (22%) said they planned to maintain one or more desirable items or possibly make no changes at all. Seventeen percent (17%) indicated both sentiments. Not unexpectedly, the top response category for doing things differently was "practicing or solving problems," including doing more problems (67%), as shown in Table 6. However, this category was "balanced" by the category of *carefulness, organization, and diligence*, which was mentioned by nearly two-thirds of respondents (64%). This discipline-based category indicated the development or valuation of fundamental, self-regulatory planning skills and behaviors.

Table 6: Week 7 Content Analysis of Reflections

Week 7 (P; post exam): *Will you do things differently in preparing for the next exam in Fluid Mechanics based on your performance on this exam, and if so, what will you do differently?*

Top Categories (*n*=250)	**Additional Description**
67% Practice problems	Do or solve practice problems, including more difficult ones

Week 7 (P; post exam): *Will you do things differently in preparing for the next exam in Fluid Mechanics based on your performance on this exam, and if so, what will you do differently?*	
64% Carefulness, organization, diligence	Double check work or ensure result makes sense, be careful, allow sufficient exam prep time, don't cram, time management and spacing of work, attend class, diligence, keep up with study, take better notes, use better formula sheet, create difficult topics list
34% Study or pre-class prep	Watch videos, read textbook, review notes, study/learn content

Week 15: The final reflection question of the semester prompted students to reflect on the weekly reflection questions themselves. The weekly questions were viewed foremost by students as a means of academic support throughout our three-year study, as described in Table 7. This included support for their course performance, content understanding, exam preparation, study habits, accountability, and realization of improvement opportunities. This viewpoint was held by two-thirds (67%) of the respondents throughout the study (n=253) and is a key outcome of this research. To our satisfaction, there was a shift in perspective during the final semester, compared to the previous two semesters of the project. Specifically, in the final semester, 52% of the respondents indicated they "enjoyed or liked" the weekly questions, compared to just 13% during the previous two semesters. The difference in these proportions was significant based on a z-test of proportions ($p \sim 0.000$) (Agresti & Finlay, 1997).

Table 7: Week 15 Content Analysis of Reflections

Week 15 (E): *What are your thoughts about these weekly Canvas questions you've been answering related to the in-class exercises, exams, or other items in Fluid Mechanics?*	
Top Categories (n=253)	**Additional Description**
67% Academic support	Supports or improves performance, study habits or methods, understanding of content, motivation, exam prep, accountability Helpful in realizing or acknowledging one's problems, flaws, strengths, progress, improvement opportunities, or action items Helpful to evaluating one's approach
54% Reflect or think	Opportunity to think, think back, or reflect; thought-provoking
21% Enjoyed or liked	Student enjoyed, liked, or felt positive about the questions
16% Low gain	Student gained little to nothing from the questions; questions unhelpful, useless, or unnecessary

4.2 Direct Assessment Results

The final exam in the course consisted of multiple-choice and free-response portions. For the multiple-choice questions, the effect with the metacognitive support was positive overall (i.e., for all students) at $d = 0.19$, as shown in Table 8. The effect was largest for the majority group in engineering (i.e., white male students) at $d = 0.52$, with a significant difference in the adjusted mean scores ($p = 0.008$), which remained significant even after Bonferroni's correction for multiple comparisons. The metacognitive support may have also benefitted the community college transfer students, with $d = 0.46$.

Table 8: Multiple-Choice Comparison: Flip vs. Flip with Metacognition Support

Dem Group	Adjusted Mean Percentage % (s_{adj}) n		ANCOVA *p* QUADE'S *p*	Effect Size *d*
	Flip	**Flip + Metacog**		
All	54.8 (16.1) 100	57.8 (16.0) 259	0.114 0.187	0.19
White male (majority in engr)	51.9 (16.1) 36	60.3 (16.0) 106	0.008 0.008	0.52
Non-white or non-male	55.9 (15.7) 56	55.7 (15.6) 138	0.915 0.772	-0.02
CC transfer w/ assoc deg	48.0 (15.4) 28	55.1 (15.4) 57	0.051 0.045	0.46
Pell grant	53.3 (15.7) 34	57.8 (15.6) 70	0.178 0.263	0.29

The free-response questions were associated with a medium effect with the metacognitive support (*d* = 0.46) for all students combined (Table 9). The difference in adjusted means was statistically significant, with $p < 0.001$ for the parametric ANCOVA and $p = 0.008$ for non-parametric Quade's test, both of which remained significant after Bonferroni's correction for multiple comparisons. Among the demographic segments considered, the effect for the free-response questions was largest for the majority group in engineering (i.e., white male students), in alignment with the multiple-choice results. For this majority group, *d* = 0.80, with a statistically significant difference.

Table 9: Free-Response Comparison: Flip vs. Flip with Metacognition Support

Dem Group	Adjusted Mean Percentage % (s_{adj}) n		ANCOVA *p* QUADE'S *p*	Effect Size *d*
	Flip	**Flip + Metacog**		
All	76.5 (14.6) 100	83.1 (14.5) 259	<0.001 0.008	0.46
White male (majority in engr)	72.6 (14.1) 36	83.8 (14.0) 106	<0.001 0.002	0.80
Non-white or non-male	78.4 (14.8) 56	83.0 (14.8) 138	0.053 0.290	0.31
CC transfer w/ assoc deg	78.5 (13.3) 28	81.7 (13.3) 57	0.296 0.827	0.24

Dem Group	Adjusted Mean Percentage % (s_{adj}) n		ANCOVA *p* QUADE'S *p*	Effect Size *d*
Pell grant	77.3 (14.4) 34	82.0 (14.3) 70	0.124 0.657	0.33

5. Summary and Conclusions

This article presented the methods and outcomes from a three-year study on the use of weekly, systematic reflection and intentional metacognition instruction during problem-solving in a flipped mechanical engineering course. This study suggests the desirability of providing metacognition support, including through systematic reflection, as part of STEM problem-solving. The weekly reflection questions and associated content analysis presented in sections 3.1 and 4.1 can be readily implemented in other courses (for example using the course management system) to drive student metacognition. Future implementation and research should be undertaken within other courses to further explore the degree to which academic self-regulation can impact student success within STEM.

The metacognition support was associated with positive effects for both portions of the final exam for the students as a whole. Relative to particular strata, medium and large effects were observed for the majority group in engineering (i.e., white male students), with $d = 0.52$ and $d = 0.80$ for the multiple- choice and free-response questions, respectively. Further, with the multiple-choice questions, there was a medium effect associated with metacognition support for community college transfer students ($d = 0.46$). For the free-response questions, the Pell Grant recipients were the stratum with the second-highest effect in favor of the metacognition support at $d = 0.33$. Thus, these results provide some evidence for the potential betterment of course performance with intentional metacognition support.

Throughout the three years of the study, the weekly reflections were viewed foremost by students as a means of academic support. This highly positive perspective was held by two-thirds of respondents (n=253) and is a key outcome of this research. In general, 76% of respondents viewed the reflections positively (based on their reflection categories), versus only 19% who viewed them negatively. There was actually a positive shift in student perspectives during the final (fall 2023) semester, compared to the initial semesters. This may have resulted from the research team's efforts to refine and optimize the weekly reflection questions throughout the study by considering student input on them.

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