Writing-to-learn exercises to improve student understanding and metacognition in an engineering statics course

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Abstract

Our work focuses on how students can use writing to identify sources of confusion, to articulate productive questions, and to improve their metacognitive understanding. To explore this, we implemented writing-to-learn prompts in a statics course that included self-questioning and revision components. After students solved homework problems, they were asked in class to write about any confusion they had regarding the concepts or computations required in the problems. Cohort effects obscured our ability to discern a correlation between the intervention and improved performance; however, surveys suggest that students could identify how the intervention contributed to their learning. To better understand this, we used qualitative coding to analyze students' level of metacognitive awareness. While we found that 85% of students could recognize that they had made an error, only 58% could accurately articulate sources of confusion. Our analyses serve as a basis for creating approaches to help students further develop question-asking skills.

Keywords

Statics, writing-to-learn, metacognition, question-asking, reflective practice

Introduction

Metacognition is critical for student learning and is particularly salient in engineering education because of its close links to problem-solving.[e.g.,1, 3-5] While significant work on metacognition has been conducted in other learning domains, few researchers have focused on engineering. Also, very few studies[1,2] have provided strategies that engineering educators can use to help students develop metacognitive skills focused on problem-solving practices central to engineering work. To help address these gaps, we draw on work in both writing-to-learn and reflective practice to investigate the effect of metacognitive writing-to-learn prompts on student performance, to explore students' current levels of metacognitive awareness, and to identify fruitful interventions that may enhance such performance and awareness.

Metacognition

Broadly, metacognition is the ability to understand and be aware of one's own thinking processes. Metacognitive approaches to learning encourage students to examine their own thinking processes as a means of deepening their understanding.[3, 6, 7] Cunningham et al.[1]

highlight two broad categories of metacognition explored in the literature: *knowledge* of cognition (including understanding people, tasks, and strategies) and *regulation* of cognition (including planning, monitoring, controlling, and evaluating one's own practices in learning and doing). In our work, we focus on students' knowledge of engineering tasks and their corresponding ability to effectively monitor their task performance. To do so, we implement writing-to-learn and reflective practice strategies as tools to both support and evaluate students' monitoring capabilities with the goal of improving student learning and performance.

Writing-to-Learn

The Writing-to-Learn movement began in the 1980s in the wake of Emig's seminal 1977 article, "Writing as a Mode of Learning." In this article, Emig describes the ways in which the act of writing both corresponds to and supports the cognitive processes of learning.[8] In the decades since, writing-to-learn has become ubiquitous in many fields across all levels of education. Hundreds of articles have been written both theorizing and empirically testing writing as a tool for learning, and studies have demonstrated that writing can support learning in mathematics, the sciences, the social sciences, and the humanities.[e.g., 9-16] Meta-reviews, though limited, generally find support for writing-to-learn practices. For example, Bangert-Drowns, Hurley, and Wilkinson's 2004 meta-analysis of studies on the impact of writing-to-learn on learning[17] indicates that writing-to-learn prompts that are frequent and calibrated to the students' learning context "produced small, positive effects on school achievement" (p. 49). Most relevant to our work, they found that short, frequent prompts that required students to "reflect on their current knowledge, confusions, and learning processes" were the most effective writing-to-learn exercises, yielding better outcomes than writing assignments that did not focus on these metacognitive practices (p.50).

Reflective writing-to-learn assignments in the sciences usually attempt to make the student aware of his or her learning issues; they frequently require the student to reflect on which concepts he or she may not understand. The modalities for such reflection are various: students have been required to write step-by-step explanations of their problem-solving;[18-20] they have been asked to explain how to do a problem to a relative neophyte in the class;[20] and they have been encouraged to embed literary modes in their problem-solving narratives (e.g. explaining how to solve stoichiometric equations through baking analogies).[22] While these approaches have resulted in some anecdotal evidence of increased understanding on the part of students, there is limited evidence that these modes actually lead to better student performance in traditional exams and course grades.

In more recent work, one mode that has shown promise is the integration of revision into writing-to-learn assignments. This incorporation of revision has been predominantly practiced in math and chemistry classroom contexts. Revision can take different forms: sometimes, revision is simply having the student reexamine what he or she has written after instructor input and correct his or her initial written response to a question or questions.[5, 21-24] Other modes of incorporating revision include sharing written work with peers and rewriting based on their feedback.[21,24] Still others have students revisit old problems later on in the semester (e.g. after a midterm or final) and rewrite their answers in light of new knowledge gained during the semester.[21-23]

Though evidence of improved performance along traditional measures is limited, there is significant anecdotal evidence that revision helps students achieve higher metacognitive understanding of the problems about which they write.[23-25] In one study that examines the integration of multi-modal writing exercises into a chemistry class, students were asked to write a description of a chemistry concept to a "non-expert reader."[22] The premise behind this assignment was that students' understanding of science would be deepened if they were actively engaged in explaining concepts in writing to a neophyte audience. As the authors note, "the tasks are designed to allow students to experience a 'write, react, revise' scenario…"[22] The study found that there were "positive correlations" between engaging in multi-modal writing tasks and end-of-unit performance.

Other studies have also focused on revision as a potentially important component of students' metacognitive competence.[22-25] In another Chemistry study, researchers had students embed a multi-modal writing task at the end of each unit, as well as a unit assessment.[22] While these writing tasks differed depending upon the context of the course and the particular instructor's goals, all of them had in common a "write, react, revise" component, prompting the student to revisit their writing task after input from a peer, instructor, or both. The researchers concluded that this revision step was instrumental in helping students understand and recognize limitations in their own understanding.[19, 21-23] Based on the compelling evidence of the utility of revision, we included this as a key component in our writing-to-learn prompt.

Self-monitoring and Question-asking

To encourage self-monitoring in our students, our writing-to-learn-prompt focused on students' ability to both identify current knowledge gaps and ask questions addressing those gaps to support learning. Asking students to generate their own questions is a form of metacognition that provides a clear window into sources of student confusion. [e.g., 26, 27]

Many researchers have investigated the steps needed to generate effective question-asking in students.[e.g.,28-30] Historically, studies involving self-generated questions in STEM fields have focused on improving reading comprehension, formulating research questions, and learning new content through group discussions,[28] with limited exploration of improving students' ability to articulate questions to support problem-solving activities. King[26] uses question prompts such as "What is our plan?," "What do we know about the problem so far?," and "Do we need a different strategy?" to guide elementary school students through the various stages of problem-solving. These prompts led guided questioners to outperform their unguided peers and controls on a written test of problem-solving as well as on a new task. These students also asked more strategic questions during the problem-solving process. King postulated that the question prompt taught students how to be more effective problem-solvers.

One of the first steps in framing a useful question, however, is recognizing knowledge deficits.[30] To that end, it is not surprising that high-performing students realize that they do not understand a concept more often than low-performing students.[28] At the same time, research by Kruger and Dunning suggests that the less domain knowledge or competence individuals possess in an area, the less able they are to assess their own performance and the more likely they are to overrate their ability.[32] Thus, students who most need help may be least able to identify their need and ask effective questions that support self-regulation.

Therefore, we are interested in strategies that encourage both accurate self-monitoring and effective question-asking. Our long-term goal is to develop a heuristic that trains students to ask questions that more effectively support their learning and problem-solving. To develop such a heuristic, we must first identify the source of college-level engineering students' difficulty in formulating questions: Are students able to recognize when they are confused? Are they able to accurately identify what confuses them? Such questions are directly linked to students' metacognitive awareness and specifically to their ability to monitor their learning.

One way to explore students' metacognitive awareness is to have them rate their confidence regarding homework problems they complete. As noted above, there is evidence that those who are poor at assessing their own skill levels are more likely to be over-confident.[e.g.,31,32] To explore this possibility in engineering students, we can both compare students' level of confidence to their performance and assess whether their self-described areas of confusion match the kinds of errors they make. By tracking such comparisons across a semester, we can see whether there are metacognitive gains over time as students build domain knowledge in a course.

Our work examines how student performance is affected by a metacognitive writing-to-learn intervention, which also serves as a tool for assessing students' capacity for accurate monitoring in statics. Data are drawn from a study in which students were asked to reflect and write about their problem-solving ability in an engineering statics course.[4] Specifically, they were asked to write about the source(s) of their confusion with reference to a select homework problem, pose a question related to their confusion, and then revisit in writing their confusion after the homework problem was reviewed in class. Although the study originally focused on achieving measurable improvements in conceptual understanding, initial findings showed limited effects on students' performance based on an analysis of course grades. At the same time, interview and survey data indicated that many students found the writing intervention helpful,[4] which prompted new research questions regarding the links between the in-class writing prompts and students' metacognitive awareness of their statics knowledge. To better understand these links, we examined students' homework and in-class written responses to determine the extent to which students were able accurately to assess their performance and their understanding.

Methods

As reported in Goldberg et al.,[4] data were collected from three sections of an introductory statics course; one section was taught in the spring and two were taught the following fall, all by the same instructor. The three sections included a total of 69 students. To assess the impact of the intervention on student performance, data from this cohort were compared with those from 40 students who took the same course in two sections across two semesters four years earlier. The course content and the grading were substantively the same, except that the students in the pre-intervention semester neither completed the intervention questionnaires nor received feedback from the instructor on these questionnaires.

Writing Prompt Data Collection

As with many statics courses, students completed weekly out-of-class problem sets focused on concepts such as expressing forces and moments as vectors, drawing free-body diagrams, and writing and solving equilibrium equations. The course included ten problem sets across a fifteenweek semester. On the day each problem set was due, students were asked in class to complete a questionnaire which included multiple components. First they were asked to rate their confidence in their solution for one selected problem from the set. Then students were prompted to write about any confusion they had about the concepts or computations required to solve the problem and write a question to help clarify their confusion. The professor then demonstrated the solution to the class as students corrected their own work. Finally, students revisited their initial response and wrote out their revised understanding of the problem. The instructor read the responses after class and gave feedback to students on any questions or confusion expressed.

The skills required to solve the problem selected on each assignment directly correlated to those needed to solve a problem on the upcoming exam. Completion of the in-class questionnaire was worth 20% of the homework grade to motivate their completion, and all work was graded by the instructor using an algorithm that was shared with the students. The grade was based on whether the student completed the in-class questionnaire in a thorough manner, with what was perceived to be a full effort. All activities associated with the writing prompts took place in class, such that students only missed responding if they did not attend class or did not turn in the homework.

At the end of the semester, student surveys were administered in class to learn more about students' perceptions of the value of completing the in-class questionnaire. As part of the end-of-semester survey, students answered 11 multiple-choice questions, such as:

> Writing out questions that I had about a problem in the first part of the in-class questionnaire made it
> a) **a lot easier** to identify concepts/computational steps with which I had trouble.
> b) **somewhat easier** to identify concepts/computational steps with which I had trouble.
> c) **neither easier nor harder** to identify concepts/computational steps with which I had trouble.
> d) **somewhat harder** to identify concepts/computational steps with which I had trouble.
> e) **a lot harder** to identify concepts/computational steps with which I had trouble.

Students were also given space for open-ended feedback about their experiences with the in-class questionnaires. In addition, 10 student volunteers were interviewed (by an author who was not their professor) about their experiences with the in-class questionnaires.

Through student surveys and interviews, we assessed the effect of responding to these questionnaires on students' perceptions of their understanding of statics concepts and on students' ability to identify when they did not understand a concept. We also assessed whether the inclusion of the in-class questionnaires improved student performance on exams.

For the intervention and control semesters we compiled anonymous pre-requisite course grades (in math and physics) and high school GPA data to compare cohorts across semesters. In addition, for the students who took the course in Fall 2014, we asked for permission to access identified student pre-requisite grades and high school GPA.

Qualitative Coding of Student Written Responses

To explore the utility of the writing intervention as a tool for self-monitoring, we focused our analysis on the first two questions from the in-class questionnaire, shown in Figure 1.

Figure 1: In-class Questionnaire Questions 1 and 2

1. Circle the letter that best describes your understanding of the starred homework problem on this assignment:
   a) I did not understand the problem and didn't really know how to approach it.
   b) I understood some aspects of the problem, but wasn't very confident in how to solve it.
   c) I was not 100% certain, but for the most part I knew what I was doing.
   d) I felt that I had a complete understanding of the problem.

2. If you answered a, b, or c above: In at least 3 sentences, describe what confused you about this problem, or what you were unsure about. When writing, imagine that you are talking to another student in the class.

If you answered d above: In at least 3 sentences, explain to another student how you solved the problem.

To capture student work for subsequent analysis, both homework assignments and in-class questionnaires were collected and scanned to PDF before being returned to students. Not all 69 students completed all 10 homework assignments and not all students completing an assignment attended class to provide an in-class questionnaire. As a result, the data set consisted of a total of 556 analyzable homework/questionnaire data pairs (out of a possible 690). Each student was assigned a unique identifier to allow the research team to track individual changes over time; student names were replaced with these identifiers prior to analysis.

Data analysis followed the procedures outlined by Miles et al.[33] using a combination of *a priori* and inductive coding in two phases. In Phase 1, the homework submissions and responses to Question 2 (see Figure 1) were coded to identify specific sources of error and confusion based on relevant course concepts. In Phase 2, we compared students self-reported level of understanding from Question 1 (see Figure 1), their reported sources of confusion from Question 2 (see Figure 1), and their homework performance to categorize their self-regulation. The following sections describe these phases in more detail.

<u>Phase 1</u>

Phase 1 used descriptive coding[33] to categorize sources of error (on the completed homework) and points of confusion (when applicable) on the in-class questionnaire. These codes served two purposes. First, they provided a way meaningfully to describe and to group the kinds of errors seen on student assignments across the data set. Second, they provided a means to compare actual errors on the homework with students' perceived errors or areas of confusion as reported in writing. This latter step was essential for identifying the nature of students' metacognitive awareness in Phase 2.

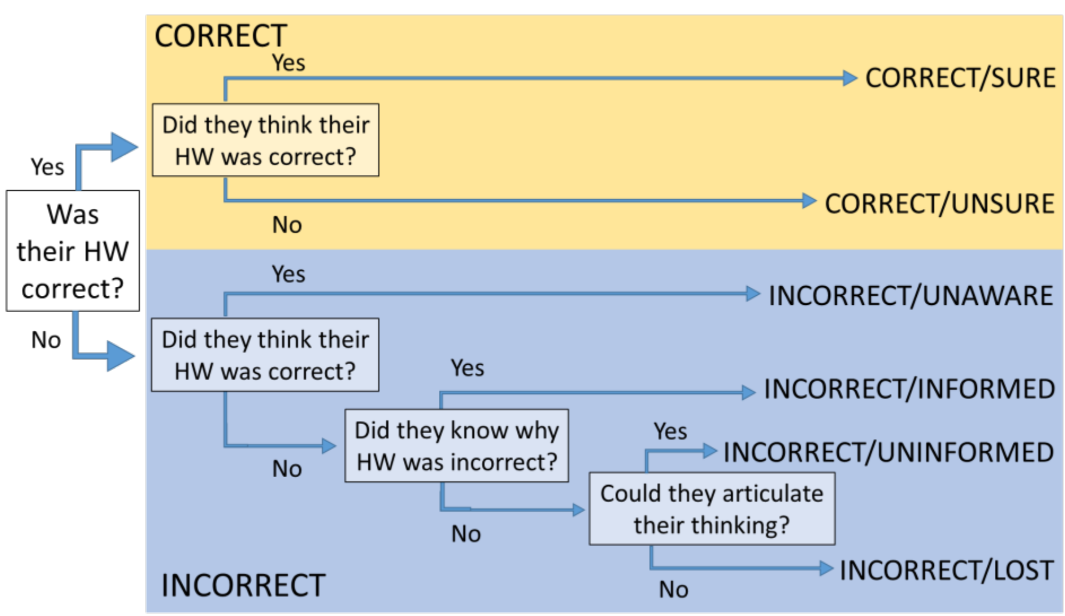
While the frameworks for misconceptions in statics developed by Steif et al.[34,35] provided sensitizing concepts, the codes themselves were developed and inductively refined via an iterative process. Initial error codes were developed using an early and a late set of homework problems and then applied to the corresponding questionnaire responses for those assignments (see Goldberg et al., 2016 [36]). The same codes were then applied to the remaining problems; new codes emerged during this round of coding as the homework sets addressed statics concepts not covered in the initial subset.

The final codebook included three major error categories: vectors, mathematical operations, and statics-specific concepts (such as free-body diagrams and two-force members). Within each category, we developed a robust set of subcodes for each category to delineate specific errors. As we moved between students' mathematical solutions and their written explanations, these subcodes were refined, expanded, or combined to ensure that the final codebook both adequately captured all possible sources of error and could be applied equally well to both the mathematical solutions and the written questionnaire responses. To ensure trustworthiness of this analysis, we used both systematic intercoder reliability checks at key points and sustained discussion among the coders as the codebook developed.

Phase 2

Where Phase 1 focused on descriptive coding to represent students' sources of error, Phase 2 focused on analytic coding to explore the types of metacognitive awareness students' demonstrated. To explore the ways metacognition emerged in students' responses to the writing prompt, we compared their self-reported level of understanding as indicated by their responses to Question 1 (see Figure 1), their performance on the mathematical solution (i.e. correctness of solution and, if present, nature of errors), and their written explanation of either the source of their confusion or their approach to the solution (from Question 2, see Figure 1). These three data points for each homework assignment allowed us to compare students' self-perceptions of both their performance and their understanding. In reviewing students' responses to the questionnaire, two different metacognitive categories emerged for students whose answers were correct, and four different categories emerged for students whose answers were incorrect. The coding scheme was modeled as a decision tree, shown in Figure 2.

Figure 2: Coding scheme for metacognitive awareness.



Students who were correct were either *sure* about their understanding, and thus chose item d, "I felt that I had a complete understanding of the problem" or *unsure*, and thus chose item c, "I was not 100% certain, but for the most part I knew what I was doing." Students who were incorrect had a more complex metacognitive profile. Some were incorrect and *unaware* in that their homework problem was incorrect, but they believed it to be correct; that is, they selected item d. Others recognized that their homework was incorrect and thus typically selected item b ("I understood some aspects of the problem, but wasn't very confident in how to solve it") or c, but differed in the degree to which they could describe their errors or confusion. Students designated as *informed* described points of confusion that matched errors they made on the homework. Those who were *uninformed*, in contrast, described points of confusion that were not linked to errors made on the homework; that is, they could not verbally articulate areas of confusion that mapped to the problems evident in the mathematical solutions. Finally, some responses were so vague or disconnected that the students lacked sufficient understanding to enable to them to describe specific points of confusion. These students often selected item a, "I did not understand the problem and didn't really know how to approach it." These responses were categorized as *lost*.

Results

Effect of Writing Intervention on Student Performance

Our main dependent outcome was course performance as assessed by students' final course grades. The data indicate that final course grades were higher in the intervention semesters as compared to the control semesters, as seen in Table 1. Students' grades on the questionnaires were strongly correlated with their final grades in the course, $r = .70$, $p < .001$.

We used anonymized high school GPA and prerequisite math and physics course grades, unmatchable to specific students, to examine whether there were overall cohort differences in preparation for the statics course. We found significant differences in high school GPAs between those in the control semesters and those in the intervention semesters, with those in the intervention semesters having a higher average high school GPA. Similarly, those in the intervention semesters had, on average, higher grades in both the math and physics prerequisites for the statics course. Details are shown in Table 1. Note that the precise number of students in each analysis differs because a few students earned prerequisite credit with AP scores, and we did not have high school GPA information for some students.

In the Fall 2014 semester, we asked students for permission to access their prerequisite and admissions data by student ID number so that it could be matched. Of the students who completed the course that semester, 44 students gave permission for us to access their prerequisite and admissions information after the statics course was completed. We used a regression model that included the following predictors: grades on the intervention questionnaires, answer on the survey about how easy it is to formulate questions (the survey question most strongly correlated with final grades), high school GPA, math prerequisite grade, and physics prerequisite grade. The full model was significant, but only two predictors affected the outcome: grades on the intervention, and grades in the math prerequisite. Thus, the final model included only these two predictors. This led to a model with $R^2 = .698$, adjusted $R^2 = .683$, $F(2, 42) = 46.19$, $p < .001$ (note this model excluded one student who earned AP credit for the math prerequisite and did not have a grade). The average final course grade of those who gave permission for us to see their prerequisite grades and who had a grade for the math prerequisite was 86.51, *SD* = 7.72, a little higher than the course average for all students that semester. The final regression model is:

Final grade = 42.23 + 31.08 * intervention grades + 5.482 * prerequisite math grades

Note that the intervention grades are from 0-1 and the math prerequisite grades are on a 4.0 GPA scale. The standardized beta coefficients are 6.31 and 6.83, respectively, and both *p*-values are <.001. In sum, this model indicates that fully completing the intervention questionnaires and math background independently contribute to explaining the variance in final course grades.

Table 1. Final grades in statics, high school GPA, physics prerequisite, and math prerequisite grades by intervention condition.

	Control semesters		**Intervention semesters**		**t statistic**
	N	Mean (SD)	N	Mean (SD)	
Final grade in statics	40	**77.8** (15.3)	66	**84.6** (10.1)	$t(104) = -2.79, p = .007$
High school GPA	34	**3.26** (.49)	59	**3.59** (.37)	$t(91) = -2.51, p = .014$
Physics prerequisite grade	38	**2.61** (1.03)	60	**3.10** (.71)	$t(96) = -2.80, p = .006$
Math prerequisite grade	35	**2.50** (1.11)	65	**3.03** (.93)	$t(98) = -2.52, p = .013$

At the end of the semester, students filled out surveys that evaluated their experience completing the in-class questionnaires. Some also participated in interviews in which they discussed their views of the efficacy of the questionnaires in improving their comprehension of material.

Student self-reports of the value of the questionnaires showed that the majority of students believed them to be valuable. In answering the surveys, 72.7% of students said that completing the in-class questionnaires made them a lot more likely or somewhat more likely to take time to think about what confused them about the problem. Similarly, 75.8% of students said that completing the in-class questionnaires made it either a lot easier or somewhat easier to identify what confused them about the problem. Further, 71.2% of students said that they believed that completing the questionnaires has and would continue to improve their performance on exams in the course.

In the open-ended portion of the surveys, some students noted that the writing intervention allowed them to ask questions that they might not ordinarily have asked in class and with allowed them to "think about what you know and what you need to work on." They also noted that this venue provided students with an alternative to asking their question(s) in class. If they felt unsure about the value of their question(s), they were able to ask it (them) in a way that did not interrupt class time and was more private.

A similar sentiment was expressed in the interviews. Students reported that the questionnaires allowed them to think more carefully about the way in which they were solving problems and to review or revise their approach when needed. This second look gave them the opportunity to catch more details, and to be more confident in their overall understanding of the problem. Yet another student remarked that the questionnaires stretched his thinking. It allowed him to think more thoroughly about the question, thus pushing him to think a bit outside of the box.

A few students felt that the questionnaires were not helpful to them because they were already doing well in the course and did not struggle with the concepts. One student, for example, noted that he understood how the method could be useful for others who struggled more with statics, and how it might be useful for him in other more challenging courses, but that he didn't feel it helped him directly in the statics course. In sum, the students saw the value of the methodology, and those who had to work hard to master the statics concepts tended to note that they found this intervention helpful to their learning.

Qualitative Coding Analysis of Student Metacognition

Categorizing all students using the coding scheme for metacognitive awareness (Figure 2) enabled us to determine the extent to which students were able to accurately assess their performance and their understanding. The distribution of the 556 student responses across the six metacognitive awareness categories is presented in Table 2.

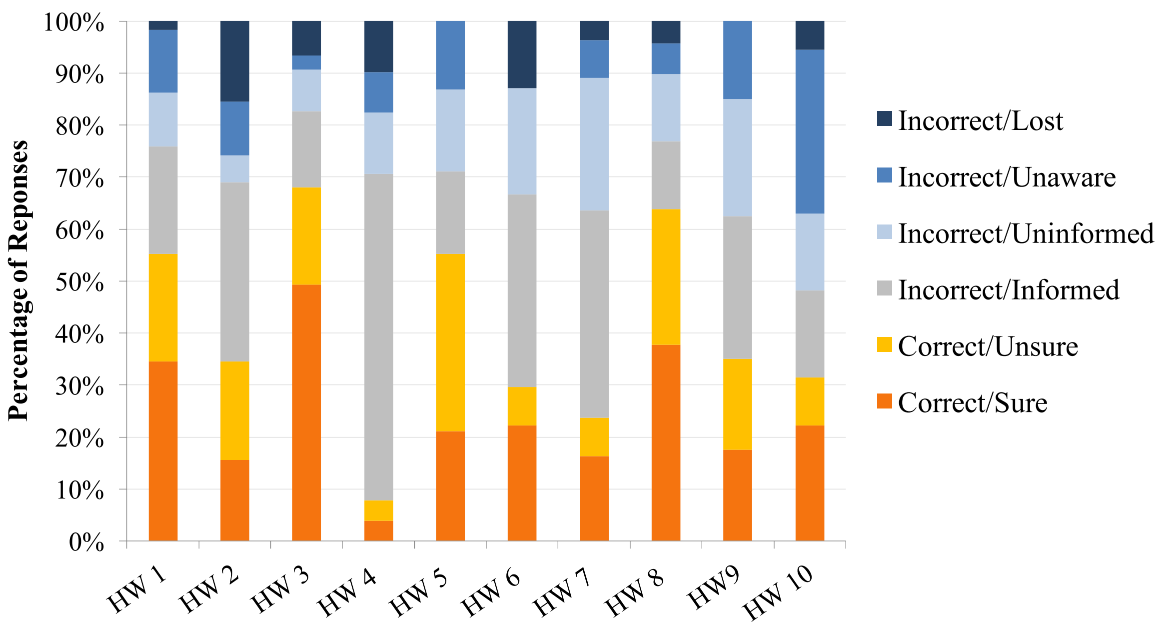
Table 2. Distribution of 556 total student responses across metacognitive categories.

Metacognitive Category	Total Number of Student Responses
Correct/Sure	143
Correct/Unsure	97
Incorrect/Informed	152
Incorrect/Uninformed	79
Incorrect/Unaware	52
Incorrect/Lost	33

As shown in Table 2, the Correct/Sure and Incorrect/Informed categories contain the most responses, while the Incorrect/Unaware and Incorrect/Lost contain the least responses, which is encouraging from a pedagogical point of view. The Correct/Unsure and Incorrect/Uninformed categories both have a large number of responses, indicating that students could potentially benefit from an intervention aimed at improving metacognitive awareness. More specifically, we found that approximately 85% of students who made errors recognized that they did so. However, only 58% of these students could accurately articulate one or more sources of their confusion, suggesting that future efforts should focus on improving students' ability to identify and articulate what they are confused about.

We also looked for patterns in students' metacognitive awareness. We first considered overall awareness across the semester to determine whether the process of regularly responding to the writing-to-learn prompts was helping students increase their capacity for monitoring and evaluation. Figure 3 illustrates the proportion of responses in each category for each of the ten homework assignments.

Figure 3. Distribution of student responses for each homework assignment.



As Figure 3 suggests, the responses show no overall pattern of either gains or declines in awareness over time. Instead, these patterns appear more indicative of the material itself, with spikes in the unskilled categories corresponding generally to the introduction of new concepts in the course (e.g. HW 4 on free body diagrams, HW 6 on equilibrium).

Given that the general trends in awareness appeared to be linked to the introduction of new concepts rather than to growth in students' evaluative capabilities in general, we also looked at patterns by individual students. Here, too, however, trends were elusive. A few students remained relatively competent and aware across the homework sets, moving for example, back and forth among Correct/Sure, Correct/Unsure, and Incorrect/Informed across the semester. Most others showed significant variation, moving back and forth across four (or sometimes more) of the six categories throughout the semester. No students appeared to remain generally unaware (i.e. Incorrect and Uninformed, Lost, or Unaware) consistently throughout the semester, and few students had responses in the Incorrect/Lost or Incorrect/Unaware category more than once. However, responses in these categories appeared throughout the semester; it was not necessarily true, that is, that students began in those less aware categories and moved into more aware categories consistently.

Discussion

The results show that course grades were higher for students who participated in the intervention than for those who were in the control semesters, but it is important to note that prerequisite grades were also higher for the students in the intervention group, indicating a potential cohort effect. Math preparation does explain a sizeable percentage of the final grade, so the improvement in math preparation likely explains a large portion of the improvement in course performance

However, grades on the intervention questionnaire (and simple completion of the questionnaire) were an independent predictor of final grades in the course, above and beyond prerequisite grades. This finding suggests that students who put effort into the questionnaires (that is, those who took the intervention seriously and gave it full attention) benefited from it by performing better in the course. It is also possible that conscientious students were more likely to put a good effort into the questionnaires and thus perform well in the course. It may also be that some combination of these two factors led to this outcome.

Survey and interview responses suggest that students found aspects of the questionnaire interventions useful. There were largely positive ratings on the utility of questionnaire, and some students noted in their open-ended responses that they felt as though it added to their metacognitive understanding. One enthusiastic student even said the intervention inspired her to use this evaluation technique in her other courses.

These positive student comments indicate that students seem receptive to this kind of pedagogical approach. We specifically designed this intervention such that student efforts were directed towards an activity that is a natural part of the problem-solving process (e.g. identifying areas of confusion) and would hopefully be perceived to be of benefit to them. Student perception of the task's value is an important factor in its successful implementation, since whether students appreciate the utility of an exercise is a large factor in determining whether they will put effort into it.

The range of positive student comments about the questionnaire also suggests that this reflective approach is helpful to some students. Student responses to surveys and interviews suggest that they perceived that completing the written questionnaire not only helped their conceptual understanding but also their computational understanding. For example, one student, in response to the interview question "Do you feel that you achieved a fuller understanding of the concept being tested by completing the questionnaires?" replied, "I'd say the little details, when doing computations, got down more, more processed, because I had to think of it, think about questions I had. More the small details." This observation suggests that students were aware of occasionally revising or rethinking their approach to solving problems computationally. This kind of computational metacognition inspired by a writing intervention is unique in the context of implementing writing-to-learn heuristics in a science class.

The correlation between grades in the course and students' perceived ability to formulate questions about tasks they were confused about suggests that the weakest students may not have benefited from the questionnaires because they did not know enough to begin to ask questions about the problems. The metacognitive coding data supports the notion that some students had difficulty identifying the source of their confusion, and therefore would likely find it difficult to articulate a specific question that would effectively support an improvement in their understanding. Perhaps such students would benefit more from a more targeted, scaffolded questionnaire that would guide them toward understanding the concepts well enough to ask more effective questions.

The lack of a clear overall pattern in how the metacognitive categories changed over time, either as a whole or for individual students, is not necessarily surprising, as these data were taken from a study in which no specific training was provided in how to improve metacognitive awareness. These results indicate that participating in the class activities was not enough to build metacognitive awareness over the course of the semester and suggest the need for and potential impact of an intervention that includes a training component in addition to a metacognitive writing prompt. The positive feedback we received from students suggests that a writing prompt that focuses student attention on identifying areas of confusion and formulating questions is valuable. Our future work will address how to best train students in the use of metacognitive writing prompts to maximize their lasting impact on student learning.

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