Developing Student Metacognitive Skills Using Active Learning With Embedded Metacognition Instruction

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Abstract

The mismatch between high school and college learning environments creates a barrier to student success in STEM majors in college. The high school learning environment relies on surface learning in which skills such as re-reading and memorizing are sufficient for academic success. The college learning environment, particularly in STEM disciplines, requires deep learning supported by critical thinking and self-testing skills. Strong metacognitive skills can support students in the transition to college. We explored the impact of active learning with embedded metacognition instruction and practice on student metacognitive skills in one of eight sections of an undergraduate introductory biology course. Using a mixed methods concurrent triangulation approach we 1) developed a continuum of metacognitive monitoring, knowledge, and regulation, 2) explored the relationship between metacognitive skills and academic success and retention; and 3) assessed the impact of an active learning approach embedded with metacognition instruction relative to a lecture-based approach with no metacognition intervention on student metacognitive skills. We placed participants along the continuum of metacognitive monitoring, knowledge, and regulation that emerged from the qualitative analysis. Students with the weakest metacognitive skills at the end of the semester were at greatest risk for poor academic performance and attrition. Students who experienced active learning with embedded metacognition instruction ended the semester with stronger metacognitive skills relative to peers who experienced lecture-based instruction with no metacognition instruction. Embedding metacognition instruction and practice within the context of an active learning-based introductory biology course is a method to strengthen student metacognitive skills, most notably shifting students away from the weakest skills towards stronger skills. Since metacognitive skills are applicable across disciplines, this approach could be adopted in introductory courses across the STEM curriculum.

Introduction

Students entering college encounter fundamentally different learning expectations than they experienced in high school (Conley, 2007). Most pre-college learning is surface learning, i.e., reproduction of information or replication of a process, optimized so that students do well on standardized tests (Fanetti et al., 2010). College learning, however, requires deep mastery, analysis and critical thinking skills (Conley, 2003; McGuire, 2006; Nelson Laird et al., 2008; Newmann, 1996; Smith & Colby, 2007).

The difference in learning expectations is reflected in the different beliefs faculty and students hold about which learning strategies are important in college courses (Lynch, 2007). Students believe that rehearsal is more important while faculty emphasize deeper processing such as elaboration and critical thinking (Lynch, 2007). Both students and faculty note that the difference in academic culture between high school and college creates a barrier to academic success in college (Cherif & Wideen, 1992).

Introductory courses are often the first in which the mismatch in learning expectations between high school and college becomes evident. The learning strategies students used in high school are no longer sufficient to achieve academic success in college (Matt et al., 1991; Yip & Chung, 2005). Students unused to reflecting on their academic performance and learning strategies can struggle to regain their footing following an academic setback. Compounding the issue, grades received in introductory courses strongly influence student decisions to persist in a STEM major (Rask, 2010). Students can be "pushed out" by low grades in STEM courses and/or "pulled away" by high grades in non-STEM courses (Ost, 2010).

Faculty, particularly those teaching introductory courses, could support student success by teaching students both disciplinary content and the ways of thinking and learning to be successful in college (McGuire, 2015). Metacognitive skills are a good target because faculty do not need to be experts in metacognition to teach metacognitive skills (Hill et al., 2014), the skills are applicable across disciplines (Bransford et al., 2000), can be altered by training and practice (Hill et al., 2014; Wang et al., 1990), and can help students reach higher academic achievement (Cook et al., 2013; Hill et al., 2014; Wang et al., 1990).

Though the literature lacks a single definition of metacognition (Veenman et al., 2006), the term was originally defined by Flavell (1976) and is often discussed as having two key components: knowledge of cognition and regulation of cognition (Jacobs & Paris, 1987; Schraw, 1998). Knowledge of cognition broadly refers to what one knows about one's own learning. It can be divided into declarative knowledge (knowing about oneself as a learner), procedural knowledge (knowing how to use different strategies) and conditional knowledge (knowing why and when to use specific strategies) (Jacobs & Paris, 1987; Schraw, 1998). Regulation involves controlling one's own learning and involves three primary skills: planning, monitoring, and evaluation (Jacobs & Paris, 1987; Schraw, 1998).

Metacognition is an important student characteristic related to academic success (Sternberg, 1998; Wang et al., 1990). Metacognitive students plan, monitor, and evaluate their learning, which leads to improved learning performance (Schraw, 1998). We use the term "metacognitive skills" to reference the interdependent monitoring, knowledge and regulation components of metacognition. Monitoring and knowledge are prerequisites for selecting and using any particular strategy, i.e., regulating. Students with strong metacognitive skills evidence all three components while those with weaker metacognitive skills may lack one or more components.

Students enter introductory college courses with a range of metacognitive skills (Stanton et al., 2015). While almost all students in an introductory biology course were willing to reflect on exam performance and make changes to learning strategies to improve performance, the majority did not know which strategies would be most helpful and only half followed through with new strategies they planned to use (Stanton et al., 2015).

Similar to the majority of STEM classrooms in North America (Stains et al 2018), the introductory biology course at our institution was primarily lecture-based. In an effort to promote academic success of our students, we transformed one section of the course into an active learning, student-centered course (Armbruster et al., 2009; Knight & Wood, 2005). An active learning approach promotes student learning (Freeman et al., 2014) and reduces the achievement gap for some populations (Haak et al., 2011; Theobald et al., 2020).

Since the course is taken primarily by first semester college students, we further wanted to build student metacognitive skills to support the transition to the college learning environment. While active learning alone could promote metacognitive monitoring, knowledge, and regulation, we wanted students to intentionally engage with those components of metacognition as part of the course. We therefore utilized three principles outlined by Veenman et al. (2006): embedding metacognition instruction into course content, informing students about metacognition and the usefulness of metacognitive learning activities, and continuous practice with metacognitive skills throughout the course. We were interested in if and how well students monitored their learning, which learning strategies they were aware of and reported using, and if they regulated their learning behaviors during the semester.

Section type	Description	Number of sections	Number of enrolled students	Number of participating students	% participating	Intervention
Regular	All majors All class standings	6	346	246	71.7%	No
Enhanced	Primarily biology majors Weak pre-collegiate STEM preparation First semester college students	1	44	40	90.9%	Yes
Honors	Primarily biology majors Strong pre-collegiate academic performance First semester college students	1	41	25	61.0%	No

Three criteria were used to enroll students across the sections: major, pre-collegiate academic preparation, and status as a first semester college student. Participating students are those who completed both the pre- and post-MAI, consented for their survey responses to be included in the study, and provided sufficient responses to open-ended prompts to be assigned a location on the continuum of monitoring, knowledge, and regulation.

Table 1. Description of section types, number of students enrolled, and number participating in the study.

We used the quantitative Metacognitive Awareness Inventory (Schraw & Dennison, 1994) and responses to open-ended survey prompts to test the hypothesis that using an active learning approach with embedded metacognition instruction and practice would strengthen student metacognitive skills relative to a lecture-based approach with no metacognition instruction. A continuum of metacognitive monitoring, knowledge, and regulation emerged during the analysis. The continuum allowed us to further test the hypothesis that academic success and retention are associated with metacognitive skills as evidenced by continuum location.

Methods

We begin with a description of section types including a detailed description of the Enhanced section intervention. We then describe the collection and analysis of the quantitative and qualitative data, including a description of the continuum of metacognitive monitoring, knowledge, and regulation that emerged during the qualitative analysis. We conclude by describing the demographic and course data collected, calculation of z-scores and a description of the statistical analyses.

Section types

This research was declared exempt by the Institutional Review Board. A total of 431 students enrolled across eight sections of an introductory biology course at a private liberal arts institution. Three criteria were used to enroll students in each section type: major, pre-collegiate STEM academic performance, and status as a first semester college student. Any student could enroll in six "Regular" sections, academically high-achieving first semester college students majoring in biology could enroll in the one "Honors" section, and first semester college students who had completed few high school science courses and/or had weak academic performance in those courses were encouraged to enroll in the one "Enhanced" section (Table 1). Seven full-time faculty members taught the sections (one taught two Regular sections) using the same textbook, covering the same content, in the same order, at approximately the same pace. The six Regular and one Honors section were primarily lecture-based.

Three variables differed between the Enhanced section and the other sections in the study. The Enhanced section: (1) was taught by an instructor who did not simultaneously teach any of the Regular or Honors sections, (2) was the only section to include explicit instruction regarding metacognition, daily in-class activities related to content, and daily opportunities for monitoring and regulation of learning strategies, and (3) met for one additional contact hour per week to provide time for the in-class activities while maintaining the same pace as the lecture-based sections through course content. With the exception of learning about and discussing metacognition, the content of the Enhanced section was the same as the other sections. Students in the Enhanced section spent more time with content than students in the other sections, due to the active learning activities taking more class time than listening to a lecture. However, the time between introduction of content and assessment on that content was similar across all section types.

Description of Enhanced Section Intervention

The pedagogy of the Enhanced section was student-centered with the goal of promoting student learning and developing student metacognitive skills. The instructor made connections between course content, pedagogical approaches, and metacognitive skills explicit to students.

Students in the Enhanced section were taught about metacognition and offered time in class to monitor, evaluate, plan and adjust learning strategies. The course was adapted from primarily lecture-based to an active learning classroom (Knight & Wood, 2005) to facilitate student engagement with course material. Following each activity, the instructor asked students what the activity revealed that students had mastered and not yet mastered about a topic, what students learned from an activity, and what learning strategies students planned to use based on their experience with the activity. In this way, metacognition was part of the daily classroom experience (Pintrich, 2002). The first six class meetings included 10-15 minute discussions of concepts and data related to student learning and metacognitive skills (Supplementary Material) before moving into 40-45 minutes of course content. Students:

- Were introduced to the idea of active learning in the classroom and its impact on student learning using data from Knight and Wood (2005). They discussed what active learning in the classroom involves and generated a list of expectations for their classroom behavior.
- Participated in an exercise to demonstrate the importance of prior knowledge and the role of formative assessments for learning.
- Were introduced to the concept of metacognition and discussed how metacognition relates to their approaches to learning and their self-assessment of concept mastery.
- Were introduced to Bloom's Taxonomy (Anderson et al., 2001; Bloom et al., 1956) and brainstormed learning strategies targeting lower levels of Bloom's Taxonomy (Remember, Understand) versus higher levels of Bloom's Taxonomy (Apply, Analyze, Evaluate, Create).

- Learned about the fluid nature of intelligence using data from Aronson et al (2002).
- Read pages 3-7 of Make It Stick (Brown et al., 2014), discussed the reading in class, and generated categories of most and least productive learning strategies discussed in the reading.
- Read pages 3-14 of Mindset: The New Psychology of Success (Dweck, 2007), discussed the reading in class, and were verbally reminded to adopt a growth mindset throughout the course, particularly following exams.

Beyond discussions of learning and metacognition, each class session included at least one, and often multiple, in-class activities designed to engage students with course content while providing opportunities for reflection on learning. Activities included: strip sequences (Handelsman et al., 2007) of multi-step processes (e.g., action potentials, negative feedback cycles, muscle contraction, CO_2 transport in the blood, antidiuretic hormone action), drawing and labeling structures (e.g., digestive system) and processes (e.g., hormones released from or affecting different organs in the digestive system) on large whiteboards in class, and working in groups to complete worksheets interpreting data related to topics covered in class (e.g., endotherm and ectotherm body temperature regulation, evolution and reading phylogenetic trees, blood volume in the chambers of the heart).

Data Collection

Students in all section types completed the quantitative Metacognitive Awareness Inventory (MAI; Schraw & Dennison, 1994) and responded to open-ended prompts (Table 2) at the beginning and end of the semester. Students completed both assessment tools in the classroom, on paper, and were not given incentives to participate.

Quantitative Data

The MAI (Schraw & Dennison, 1994) consisted of 52 statements answered on a 5-point Likert scale (Almost never, Rarely, Sometimes, Often, Almost always). The MAI measures student "awareness" or knowledge of two factors: (1) knowledge of cognition which pertains to student knowledge of themselves, learning strategies, and the context in which strategies should be applied; (2) regulation of cognition which pertains to student knowledge of the ways in which they plan, use strategies, monitor, and evaluate their learning (Schraw & Dennison, 1994). The MAI provided a relatively rapid assessment of student knowledge of learning strategies and regulation, two of the components of "metacognitive skills" in which we were interested. Only students for whom we could collate completed pre- and post-MAI responses were included in MAI analyses (N=255).

Pre-course Prompts	**Monitoring**	**Knowledge**	**Regulation**
1. When was your last science course and what was it? (For example, biology, chemistry, biochemistry, environmental sciences)			
2. Thinking about that course, describe your approaches, techniques, and strategies for preparing for exams in the left column. Describe why you felt each one was helpful (or not) in the right column.		X	
3. If you could go back in time to the beginning of that course, what advice, if any, would you give yourself to help you be successful?		X	
4. What approaches, techniques, and strategies do you plan to use for ***this*** course (you may circle from the list you made above and also add more here)?		X	X*
Post-course Prompts			
Thinking about the biology course in which you were enrolled this semester: 1. In the left column, describe the approaches, techniques, and strategies you used to prepare for exams in this course. In the right column, describe why you felt each one was helpful (or not).		X	*X in conjunction with Pre-course prompt 4
2. Did you **change** approaches, techniques, or strategies during the course?	X		X
3. If so, why? If not, why not?	X		X
4. If you could go back in time to the beginning of this course, what advice, if any, would you give yourself to help you be successful?		X	

Table 2. Questionnaire prompts aligned with the monitoring, knowledge, and regulation attributes used to assign continuum location.

Qualitative Data

Participant responses were de-identified such that no personally identifying information or information regarding which section a participant was enrolled in was available to the coders. We used directed content qualitative analysis (Hsieh & Shannon, 2005) of participant responses to open-ended prompts to explore each participant's metacognitive skills, specifically looking for evidence of monitoring, awareness and use of strategies to be successful in the course, and adjustment of learning strategies during the semester.

Two undergraduates and one faculty member iteratively coded groups of ten responses. Initial coding was completed independently by each coder. We then met and arrived at a consensus on each code. As changes were made to the codebook during the consensus meetings, all previously-coded responses were re-assessed. After codes were assigned to all participants, a final assessment was conducted on all responses using the final codebook.

We used each student's responses to the pre- and post-course questionnaires to determine their placement along the continuum at the end of the semester. The pre-course questionnaire, completed in class at the beginning of the semester, articulated the student's learning plan for the course. The post-course questionnaire, completed in class at the end of the semester, allowed us to determine if students were following through with and/or adjusting their learning plan. Using the totality of a student's responses across the two questionnaires to assign a single continuum location at the end of the semester was necessary to determine if students were monitoring their learning strategies and academic performance, and if and how they were adjusting learning strategies during the semester.

We first looked for evidence of monitoring. We looked for evidence that participants reflected on and were open to adjusting their learning strategies over the course of the semester. Those with no evidence of reflection, who were not open to adjusting strategies, and those who were entirely externally reflecting (e.g., stating that their performance was the instructor's fault) were assigned a Not Monitoring code (Table 3).

If a participant indicated that they made no changes during the semester because their strategies worked for them we came to consensus on two codes. The first assumed that the participant performed well (defined as a score of $\geq 70\%$ on all exams) and therefore was accurately reflecting on their performance. The other assumed the participant performed poorly (defined as a score of $<70\%$

Category	Description	Examples
Not Monitoring	*Not reflecting on or willing to adjust approaches to learning* Student does not reflect on or consider making changes to their learning strategies. They are willing to continue doing what they have been doing even with lack of success in the course. Student may blame their instructor/outside factors for their lack of success. Student who reports not changing strategies because their strategies "worked" but received < 70% on exams - coded as Not Monitoring because the reflection on performance was inaccurate.	Not open to adjusting strategies: Student stated their approach was to "study the week of" and noted that this technique was "not helpful, too much info". They made no changes to their strategy during the semester due to "comfort" External reflection: In response to what advice they would give themselves to do better: "go on rate my professor and choose a new one" Double codes resolved as Not Monitoring: Student reports using "outline of chapter" because it was "helpful: easy structure to follow". Student did not make changes during the semester because "The strategy I used was already helpful". Initially double coded as Not Monitoring or Not Knowing. Double code resolved as Not Monitoring because the student scored <70% 3 of 4 exams which was evidence that the strategy was not helpful and the student was inaccurately reflecting. Student indicates on pre-course prompts that "doing practice problems" is helpful "to be able to get help in problem areas". Student reports using only "read textbook" and "flashcards" as strategies in the course. They report making no changes during the semester because "the approaches used were helpful and useful" Initially double coded as Not Monitoring or Not Regulating. Double code resolved as Not Monitoring because student scored <70% on all exams.
Not Knowing	*Reflects on and is open to adjusting approaches to learning, but does not know what strategies to use for success in the course* Student is open to adjusting their learning strategies, but either (1) does not articulate what they would change, (2) elects to do more of what they were already doing or (3) selects only learning strategies that support lower Bloom's levels of Remembering and Understanding.	Lists only passive strategies: "Went over the book, Re-read notes, Flashcards" and made no changes to strategies during the course because: "I don't really know how else to effectively study" Lists only passive strategies: "Reading textbook, revising [online] assignments, re-read notes in powerpoints" and made no changes to strategies during the course because "I have not been able to find any other effect (sic) strategies"
Not Regulating	*Reflects on and is open to adjusting approaches to learning, is aware of learning strategies that target higher Bloom's levels of Applying, Analyzing, Evaluating, or Creating but does not use the strategies* Student recognizes a need for change, selects learning strategies to help them with the challenges they face, but does not follow through with using the strategies. They know what learning strategies exist and when and why to use them, but do not follow through and use them.	Student plans to "test myself after understanding" on pre-course prompts but does not follow through with that strategy on the post-course prompts. While they recognized a need to change during the semester their change was to "Focused more on my notes since the tests are based on everything from the lecture" Student plans to "make diagrams/chart" because that "helps me visualize facts in an organized way" and then does not follow through with that plan.
Regulating	*Reflects on and is open to adjusting approaches to learning, is aware of learning strategies that target higher Bloom's levels of Applying, Analyzing, Evaluating, or Creating and reports using those strategies* Student recognizes the benefit of adjusting study habits, selects appropriate strategies, and follows through on those strategies. Student may drop ineffective strategies but must also use at least one strategy that targets higher Bloom's levels.	Student plans to "review info" as a strategy on the pre-course prompts. On post-course prompts student made a change to "drawing diagrams" to "understand processes" Student "changed approaches b/c there were topics that made more sense talking through [in a study group] than memorizing" Student reports "lots of practice problems"

Table 3. Descriptions of four categories that emerged along a continuum of monitoring, knowledge, and regulation.

Learning Strategies Targeting Lower Bloom's Levels (Remembering, Understanding)	Learning Strategies Targeting Higher Bloom's Levels (Applying, Analyzing, Evaluating, Creating)
Flashcards (if used for memorization)	Flashcards (if used to concept map or play games like Heads Up!)
Use of online textbook publisher content (used to review information, watch videos)	Use of online textbook publisher content (used to engage with material via interactive activities)
Study group (used to "get more opinions," have content explained to them by a peer, or simply to "study in a group")	Study group (used to explain or teach material to others)
Review quizzes, learning objectives or past exams to determine what will be on the next exam	Self-test using quizzes, learning objectives, or past exams to determine level of content mastery
Tutoring (tutor explains concepts to the student)	Tutoring (student explains concepts to the tutor)
Read, re-read, or review book, notes, or lecture slides	Create their own study guide
Re-write notes	Create diagrams or visuals
Highlight book or notes	Concept mapping
Attend Class	Teaching to others
Watch videos online	Reviewing mistakes made on past exams
Outline book or notes	
Quizlet (used as online flashcards for memorization)	

Table 4. Learning strategies categorized as targeting lower and higher Bloom's levels (Anderson et al 2001, Bloom et al 1956).

on at least one exam) and therefore was inaccurately reflecting on their performance. Only after achieving consensus on the two codes were exam scores checked to resolve the double code. This process avoided coders being biased by knowledge of individual participant academic performance while assigning codes. We selected 70% as "successful" exam performance because, despite differences in each participant's personal definition of success, 70% is the minimum score that students must achieve to receive credit for the course. Therefore, 70% was the minimum score a participant could reasonably be assumed to identify as successful.

The learning strategies participants planned to use, used, or gave themselves advice to use in retrospect were used to assess knowledge. A participant evidenced knowledge if they mentioned at least one learning strategy that targeted learning at Bloom's levels of Applying, Analyzing, Evaluating or Creating (Anderson et al., 2001; Bloom et al., 1956) (Table 4). We chose this criterion because, across sections, exam questions focused on application and prediction, making it highly unlikely that a student could earn $\geq$ 70% on exams using only learning strategies targeting Remembering and Understanding (Table 4). Participants with evidence of monitoring who reported on both the pre- and post-course prompts only strategies that targeted lower Bloom's levels of Remembering and Understanding were coded as Not Knowing (Table 3) because they provided no evidence that they were aware of learning strategies that promote the level of concept mastery required by the course.

If participants did not provide enough information to confidently determine what strategies they were using, we were conservative in our interpretation. For example, if a participant reported studying in a group but did not elaborate on what was happening in the group (e.g., were they simply studying in the same location as peers or were they quizzing and explaining material to others), we defaulted to the more conservative interpretation and considered it as targeting lower Bloom's levels (Table 4).

Regulation was assessed by (a) comparing answers to the final pre-course prompt that asked students to list strategies they planned to use in the current biology course to the post-course prompt asking students to list the strategies they actually used in the course and (b) using responses to post-course prompts about changes made during the semester and why participants chose to make changes or not (Table 2). Participants with evidence of monitoring and knowledge who reported using at least one strategy associated with higher Bloom's levels (Table 4) in the course were coded as Regulating (Table 3). If participants with evidence of monitoring and knowledge reported strategies associated with higher Bloom's levels (Table 4) on the pre-course prompts but indicated on the post-course prompts that they only used strategies associated with lower Bloom's levels, they were coded as Not Regulating since they were aware of higher level strategies but were not using them (Table 3). The Not Regulating category also included participants who dropped strategies and knew of, but did not use, strategies associated with higher Bloom's levels.

An important feature of the coding process was the assignment of continuum locations in a stepwise fashion. A participant had to show evidence of monitoring before evidence of knowledge was considered, and show evidence of monitoring and knowledge before evidence of regulation was considered.

Demographic and course data

Demographic (e.g., gender, identification as belonging to an historically underrepresented group in the sciences, major, status as a first semester college student), course (e.g., exam and course grades), and institutional data (e.g., major, college GPA, high school GPA, registration or graduation in subsequent semesters, grade in the subsequent course) were collected with each participant's informed consent. Most participants completed a math placement exam upon entering the university and these data were also obtained from the institution. Since the maximum college GPA was 4.0, an adjusted HSGPA (AHSGPA) of 4.0 was assigned to students with a HSGPA > 4.0. This prevented students with a HSGPA >4.0 who earned a college term GPA of 4.0 from appearing to be underperforming in college when they had actually performed as well as possible in college. Grades in the subsequent course were reported as letter grades and converted to numeric equivalents using the scale A=4.0, A-=3.7, B+=3.3, B=3.0, B-=2.7, C+=2.3, C=2.0, C-=1.7, D+=1.3, D=1.0, F=0.

The following groups were used to identify participants as belonging to an historically underrepresented minority (URM) group in the sciences: Black/Not Hispanic, Hispanic, Native American, Native Hawaiian/Pacific Islander). Participants who reported belonging to two or more groups (N=10) were excluded from URM analyses because we could not determine to which groups the students identified as belonging.

Z scores

Exam grades and percent score in lecture were converted to z scores for each section of the course. Z scores (also called Standard Scores) are useful when comparing different sets of data because they "standardize" the raw scores by computing how far away from the mean each raw score falls. If two sets of data (e.g., scores on exam 1 from two different sections) have different means and/or different amounts of variation, z scores allow comparison across the datasets by comparing how well each student did relative to the mean of their section. A student with a z score of 1 in Section A and a student with a z score of 1 in Section B both scored the same amount better on the exam, even if one section had a mean of 52% and the other had a mean of 70%. They are calculated as (x-u)/sigma where x is the student's score, u is the mean score of that population, and sigma is the standard deviation of that population.

Statistical Analyses

Change in MAI score from the beginning to the end of the semester and continuum location at the end of the semester were used to test the hypothesis that an active learning approach with embedded metacognition instruction and practice would strengthen student metacognitive skills relative to a lecture-based approach with no metacognition instruction. Academic performance in the current course, the subsequent course, and institutional retention data were used to test the hypothesis that academic success and retention are associated with metacognitive skills as evidenced by continuum location at the end of the semester.

All statistical tests were conducted in SPSS (v.25.0, 2017). Quantitative data were tested for normality prior to running statistical analyses. MAI data were normally distributed. MAI data were further tested for equal variances across section types given concerns about statistical power when both sample size and variances are unequal (Rusticus and Lovato 2014). Across section types, variances were equal (Levene's Test, p>0.05). Though MAI data are ordinal, either parametric or non-parametric tests can be used with ordinal data as there is little difference in the risk of Type I error between the two types of analyses (de Winter and Dodou 2010). Therefore, a two-factor mixed design ANOVA was used to determine the effects of section type (Regular, Honors, or Enhanced) and time (pre/post) on MAI scores. Only participating students with both a pre- and post-MAI score were used in the analysis (N=255).

The remainder of the quantitative data were either not normally distributed, and transforming the data did not result in normal distributions, or were ordinal or categorical. Thus, nonparametric tests were used for analyses of these variables. Kruskal-Wallis tests were used to compare differences in quantitative data across the section types. Significant Kruskal-Wallis tests were followed by Dunn tests with Bonferroni corrections for all pairwise comparisons. Chi-square and/or Fisher's Exact Tests were used to compare demographic data and metacognitive continuum location across section types. When conducting multiple pairwise comparisons using Chi-square or Fisher's Exact Tests, a sequential Bonferroni adjusted alpha was used to control for Type I error. A Wilcoxon signed-rank test was used to compare AHSGPA and college term GPA. Kendall tau-b correlations were used to evaluate the relationship between quantitative MAI scores and qualitative metacognitive continuum location. All participants were used in each analysis unless they were missing relevant data (e.g., if no SAT data were available, the participant was excluded from analyses using SAT data).

Results

Of the 431 students enrolled across all sections, 311 completed both the pre- and post-course questionnaires and consented to have their responses included in the study. Of those, 255 also had both pre- and post-course MAI responses. The discrepancy between number of consenting students and number of students with MAI responses was due to the inability to collate pre- and post-course MAI responses when student identification numbers were not entered, or were entered incorrectly, on MAI data sheets.

Participants were demographically similar across section types. Participants (N=311) across all three section types (Regular, Enhanced, and Honors) were similar with respect to gender and identification as belonging to a URM group (Gender: Chi-square: N=311 X^2=4.768 df=2 p=0.092; URM: Chi-square: N=290 X^2=1.406 df=2 p=0.495; Table 5).

The Regular sections served as a comparison group for the Enhanced section. Participants in the Regular and Enhanced sections were similar with respect to the proportion of biology majors (Table 5), AHSGPA and math placement exam scores (Figure 1A, 1B; AHSGPA: Dunn test with Bonferroni correction: adjusted p=0.220; math placement: Dunn test with Bonferroni correction: adjusted p=0.852). The Enhanced section had a higher percentage of first semester college students (Fisher's Exact Test: N=286 p<0.0001; Table 5), lower SAT scores (Dunn test with Bonferroni correction: adjusted p=0.039; Figure 1C), and weaker pre-collegiate STEM backgrounds (Table 1) relative to Regular sections.

The Honors section served as a high-achieving comparison group for the Enhanced section. Honors section participants had stronger prior academic achievement (Figure 1), MAI scores (Figure 2), and pre-collegiate STEM background relative to Enhanced section participants.

Impacts of the semester-long metacognition interventions

The semester-long metacognition intervention increased participants' metacognitive skills. Metacognitive skills were documented using the MAI and placement along the continuum of metacognitive monitoring, knowledge, and regulation. There was a main effect of section type (N=255 F(2, 252)=3.335 p=0.036). This main effect was driven by the Enhanced section having lower Pre-MAI scores relative to the Regular and Honors sections (Figure 2). There was a significant interaction

Variable	Regular	Enhanced	Honors	Statistical test, p (two-tailed)
# participants	246	40	25	
% Female	69.5%	77.5%	52%	Chi-square p=0.092
% URM	30.1%	28.2%	18.2%	Chi-square p=0.495
Biology majors *	51.2%[a]	70%[a,b]	80%[b]	Chi-square p=0.004
First semester college student *	67.5%[a]	100%[b]	100%[b]	Chi-square p<0.0001

Differences between sections were assessed using a sequential Bonferroni adjusted alpha applied to Chi-square or Fisher's Exact Tests on all pairwise comparisons. N=311 for all tests except for %URM in which N=290. Asterisks and letters indicate statistically significant pairwise comparisons (p < Bonferroni adjusted alpha).

Table 5. Participant characteristics across section type.

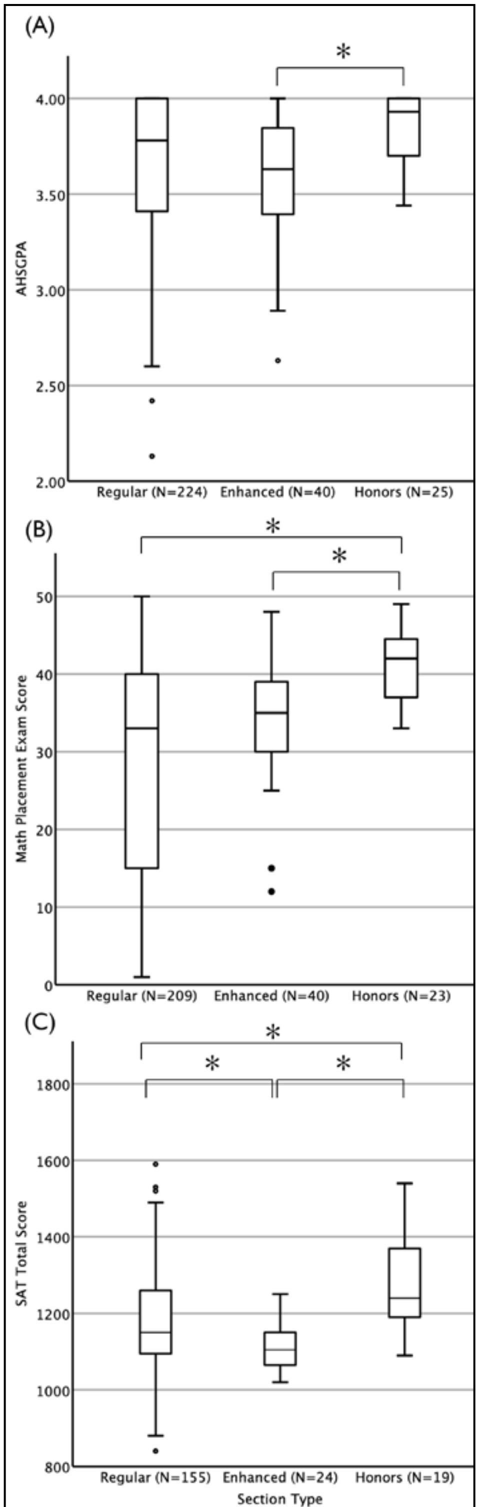

Figure 1. (A) Adjusted high school GPA (AHSGPA), (B) math placement exam score, and (C) SAT total score for participating students enrolled in the Regular, Enhanced, and Honors sections of a first semester introductory biology course. Students in the Enhanced section had lower AHSGPA (Kruskal-Wallis N=289 X^2=8.746 df=2 p=0.013), math placement exam (Kruskal-Wallis N=272 X^2=21.342 df=2 p<0.0001), and SAT scores (Kruskal-Wallis N=198 X^2=18.066 df=2 p<0.0001) relative to the other sections. Asterisks indicate statistically significant differences. N indicates number of participants in the analysis in each section.

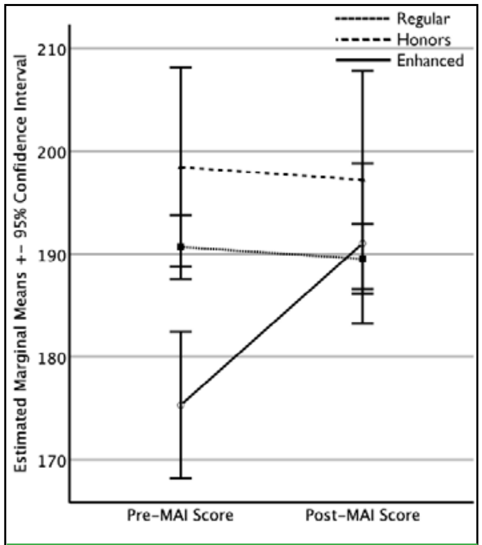

Figure 2. Estimated marginal means ± 95% confidence intervals of Pre- and Post-MAI scores across three section types: Regular no intervention, Honors no intervention, and Enhanced with intervention. There was a significant time*section type interaction (two-factor mixed design ANOVA N=255, F(2,252)=10.159 p<0.0001).

between section type and time of the semester (N=255 F(2, 252)=10.159 p<0.0001; Figure 2). The Regular and Honors sections (the two section types that did not receive an intervention) did not change over the semester while the Enhanced section increased by the end of the semester.

At the end of the semester, the distribution of students across the metacognitive continuum was shifted towards stronger skills in the Enhanced relative to the Regular sections (Chi-square, N=311, X^2=23.618, df=6, p=0.001; Chi-square pairwise comparison p<0.0001; Figure 3). The largest group of students in the Regular section were Not Knowing (37%), with 15.6% of students Not Monitoring. This is in contrast to the Enhanced section in which most students were Regulating (55%) with no Not Monitoring students at the end of the semester.

The distribution of students along the continuum in the Honors and Enhanced sections were statistically similar (Chi-square, N=311, X^2=23.618, df=6, p=0.001; Chi-square pairwise comparison p > Bonferroni adjusted alpha; Figure 3).

The quantitative and qualitative data were positively correlated. Post-MAI scores were positively correlated with metacognitive continuum location at the end of the semester (Figure 4; Kendall's tau-b=0.137 N=253 p=0.004). However, post-MAI scores overlapped across the four metacognitive categories (Figure 4).

Metacognitive skills, academic performance, and retention

Weak metacognitive skills translated to poor academic performance. Students with the weakest

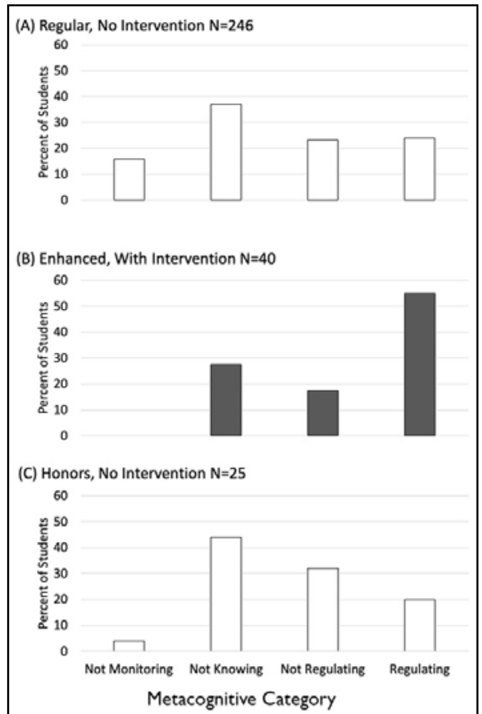

Figure 3. Distribution of students in each metacognitive category at the end of the semester. Shaded bars represent the intervention section. (A) Regular sections with no intervention, (B) Enhanced section with the semester-long intervention, (C) Honors section with no intervention. The distribution of students across the metacognitive categories in the Enhanced section was different than that in the Regular sections (Chi-square, N=311, X^2=23.618, df=6, p=0.001; Chi-square pairwise comparison p<0.0001). N indicates number of participants in the analysis in each section.

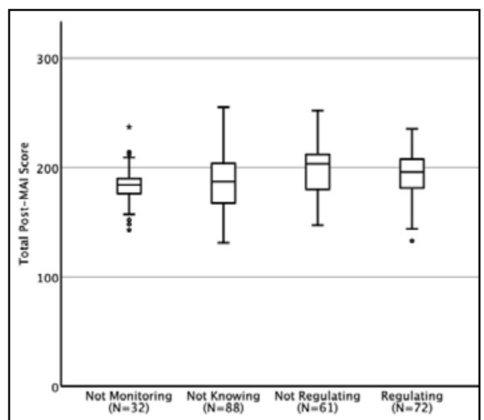

Figure 4. Post-MAI total scores of all participants who completed both the pre- and post-MAI relative to metacognitive category determined via qualitative coding. There is a positive correlation between total post-MAI score and metacognitive category (Kendall's tau-b =0.137 N=253 p=0.004). Overlap of MAI scores occurs across all metacognitive categories. N indicates number of participants in each metacognitive category in the analysis.

metacognitive skills at the end of the semester, those in the Not Monitoring category, had the lowest lecture percent z-scores relative to peers in the other categories (Kruskal-Wallis N=305 X^2=40.614 df=3 p<0.0001; Figure 5A). The majority of Not Monitoring students scored below the mean lecture percent in their section (35 of 39 or 89.7%). This is in contrast to the other categories in which 48.6% of Not Knowing, 36.6% of Not Regulating, and 29.8% of Regulating students scored below the mean lecture percent in their section.

Students ending the current course in the Not Monitoring category remained at risk of weak academic performance in the subsequent course. They earned significantly lower grades in the subsequent course relative to peers in other categories (Kruskal-Wallis N=170 X^2=10.675 df=3 p=0.014; Figure 5B).

Weak metacognitive skills were associated with academic underperformance relative to high school. While most participants' college academic performance was weaker than their high school performance, students who were Not Monitoring were most impacted. College term GPA was lower than AHSGPA for the majority (90.3%) of participants (Wilcoxon signed-rank test N=288 T= 905.500 p<0.0001). The mean drop in GPA from high school to college for all participants was 0.76 ± 0.63 points (mean ± SD). The drop in GPA among Not Monitoring students (1.04 ± 0.75 points; mean ± SD) was greater than that for their Not Regulating and Regulating peers (Figure 6; Kruskal-Wallis N=288 X^2 =15.889 df=3 p=0.001; Dunn tests with Bonferroni corrections, adjusted p ≤ 0.012).

Weak metacognitive skills were associated with low retention. Not Monitoring students were at greatest risk of attrition from the university having the lowest retention and graduation rates relative to peers in other categories (Table 6). Three semesters following the conclusion of this study, 55% of Not Monitoring students had graduated or continued to enroll at the university compared to an average of 81.4% of peers across the other three categories (Table 6; Chi-square N=311 X^2=14.188 df=3, p=0.003).

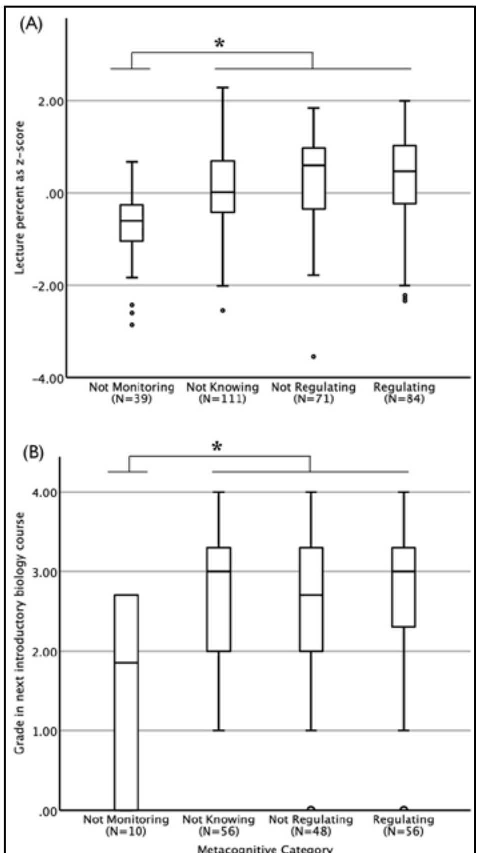

Figure 5. Not Monitoring students underperformed relative to peers in both the current course and the subsequent course. (A) Lecture percent transformed into z-score. Not Monitoring students scored the lowest of all metacognitive categories (Kruskal-Wallis N=305 X^2=40.614 df=3 p<0.0001). (B) Letter grade in the subsequent introductory biology course converted to a numeric equivalent. Not Monitoring students earned the lowest grades in the subsequent course (Kruskal-Wallis N=170 X^2=10.675 df=3 p=0.014). Asterisks indicate significance, N indicates number of participants in each metacognitive category in the analyses.

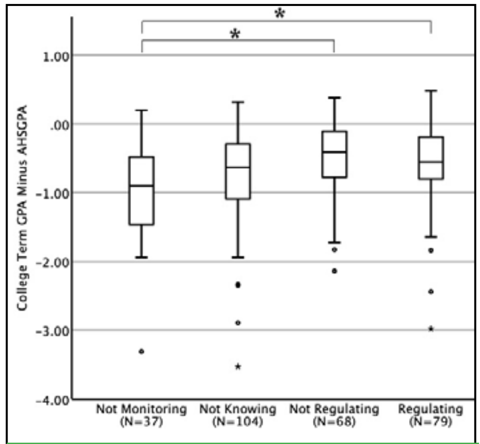

Figure 6. Difference between college term GPA and AHSGPA for students across a continuum of metacognitive development. The drop in GPA from high school to college was larger for Not Monitoring students relative to peers in the Not Regulating and Regulating categories (Kruskal-Wallis N=288 X^2=15.889 df=3 p=0.001; Dunn tests with Bonferroni correction adj. p ≤ 0.012). Asterisks indicate significance, N indicates number of participants in each metacognitive category in the analysis.

Metacognitive Continuum Location	N	Retention or graduation three semesters following the study
Not Monitoring	40	55.0%*
Not Knowing	113	79.6%
Not Regulating	72	83.3%
Regulating	86	81.4%

Retention/graduation was lower for Not Engaging students relative to each of the other categories (Chi-square, N=311, X^2=14.188, df=3, p=0.003; Fisher's Exact tests with sequential Bonferroni adjustments for all pairwise comparisons). Asterisk indicates statistically significant pairwise comparison (p < Bonferroni adjusted alpha).

Table 6. Retention or graduation within three semesters following the study.

Discussion

The mismatch in learning expectations between high school and college (Conley, 2007) creates a barrier to student success in college (Cherif & Wideen, 1992). We attempted to remove that barrier by embedding metacognition instruction and practice into an introductory biology course. A continuum of metacognitive monitoring, knowledge, and regulation emerged during analysis of student responses to open-ended prompts (Table 3). Using the continuum, we found that weak metacognitive skills were associated with lower academic performance and retention in the institution (Table 6). Embedding metacognitive skills instruction and practice in the course resulted in stronger student metacognitive skills by the end of the semester relative to sections that did not include a metacognition intervention (Figure 3).

Continuum of monitoring, knowledge, and regulation

The continuum of metacognitive monitoring, knowledge, and regulation that emerged from this work provides a framework around which to think about student metacognitive skills, identify specific skills to strengthen in individual students, and compare skills across populations of students. We posit that the continuum is broadly applicable across courses and contexts. While we used criteria for determining knowledge that were specific to this particular course (Table 4), as long as criteria are appropriate for the context and specified in advance, the continuum should be broadly applicable.

Metacognitive skills, academic performance, and retention

Most students experience a decrease in grade point average as they transition from high school to college (Elias & MacDonald, 2007; Matt et al., 1991; Wesley, 1994; Wintre et al., 2011; Yip & Chung, 2005), even those who were academically high achieving in high school (Balduf, 2009). The participants in this study were no exception. Of particular concern were students who ended the semester in the Not Monitoring category. They had the largest drop in GPA from high school to college (Figure 6), earned the lowest course grades (Figure 5A), lowest grades in the subsequent course (Figure 5B), and had the lowest retention and graduation rates (Table 6) relative to students with stronger metacognitive skills. It appears critical then to shift students out of the Not Monitoring category. The

Enhanced section, the only one to receive an intervention, was the only section that contained no Not Monitoring participants by the end of the semester (Figure 3). At minimum, active learning with embedded metacognition instruction can reduce the number of Not Monitoring students.

A caveat to interpretation of the weak academic performance of Not Monitoring participants is the process by which some participants were assigned a Not Monitoring code. While coders assigned codes blind to student grades, exam grades were the only evidence available to assess whether participants were accurately monitoring their academic performance. Participants originally assigned two codes and who demonstrated weak academic performance were ultimately assigned a Not Monitoring code, potentially creating an artificial relationship between codes and academic performance. However, we argue that the Not Monitoring code is the most appropriate for participants reporting making no changes to learning strategies because they were "doing well" or because their current strategies were "working" when they were not earning passing grades on exams.

Embedding metacognition instruction and practice in a course strengthens metacognitive skills

An intervention designed to support metacognitive skills development was effective at doing so. Most participants in the Regular sections ended the semester in the Not Knowing category (37%; Figure 3). These predominantly first semester college freshmen (Table 5) who were not explicitly taught learning strategies required for success in a college-level introductory biology course were unaware of those strategies. In contrast, first semester college freshmen who were explicitly taught metacognitive learning strategies and who were encouraged to reflect on and adjust learning strategies throughout the semester ended the semester with strong metacognitive skills (Figure 3). Indeed, the majority (55%) of participants in the Enhanced section ended the semester in the Regulating category, evidencing the strongest metacognitive skills (Figure 3).

Students with strong metacognitive skills, those who monitor and regulate their learning behaviors, are most likely to succeed in college (Holschuh, 2000; Robbins et al., 2004; Sebesta & Speth, 2017). Fortunately, the metacognitive skills associated with academic success in college can be taught and are not discipline-specific (Bransford et al., 2000; McGuire, 2015) having been taught across a variety of disciplines including chemistry (Cook et al., 2013; Dang et al., 2018), engineering (Vos & Graaff, 2004), law (Boyle, 2003; Gundlach & Santangelo, in press), mathematics (Schoenfeld, 1992), and the visual arts (van de Kamp et al., 2015). When taught about metacognition and specific metacognitive strategies, student grades (Biggs, 1988; Cook et al., 2013), self-evaluation skills (Dang et al., 2018) and metacognitive awareness (Hill et al., 2014) increased. Students also reported increased confidence and academic enjoyment (Zhao et al., 2014) and were more likely to use deep approaches to learning (Biggs, 1988). Embedding metacognition instruction and practice within a course is one approach to minimize the number of students with the weakest metacognitive skills while supporting development of stronger skills in more students.

Assessing metacognition

Measuring metacognitive skills is challenging given lack of a single definition and the complex nature of metacognition as a concept (Veenman et al., 2006; Zohar & Barzilai, 2013). This study employed a widely used quantitative instrument, the MAI (Schraw & Dennison, 1994), in conjunction with qualitative analysis of responses to open-ended prompts on questionnaires. The quantitative MAI provided snapshots of participant awareness of two components of metacognition, knowledge of cognition and regulation of cognition, at discrete time points at the beginning and end of the semester, allowing us to document an increase in MAI scores in the population enrolled in the Enhanced section (Figure 2).

The qualitative data provided more granular information about individual student metacognitive skills, allowing us to determine where each individual fell on a continuum of metacognitive monitoring, knowledge, and regulation. The qualitatively-derived continuum locations were positively correlated with quantitative post-MAI scores (Figure 4). However, the overlap in MAI scores across the four continuum locations meant that the MAI was not useful in determining where individual students fell along the continuum.

Another continuum, a continuum of metacognitive regulation, has also been proposed (Stanton et al., 2015). The two continua were developed in different ways. The current study used questionnaires asking students to reflect on performance across a semester whereas Stanton et al. (2015) asked students to reflect on specific exams. The current study also used a different lens, focusing on monitoring, knowledge, and regulation as interdependent components of "metacognitive skills," resulting in different criteria being used during the coding process. For example, Stanton et al. (2015) used dropping ineffective strategies as evidence for regulation and used alignment of self-identified exam challenges with proposed study strategies to determine knowledge. Despite these important differences, the continuum of metacognitive monitoring, knowledge, and regulation that emerged in the current study separates participants along similar lines as those that emerged in the work of Stanton et al (2015). This suggests that, whether asking students to reflect on specific exams (Stanton et al., 2015) or to reflect on performance across a semester-long course, and despite differences in approach, similar patterns in student metacognitive skills become evident.

Ideally we would be able to use the qualitative analysis to document shifts from one continuum location at the beginning to another at the end of the semester, as with the MAI data. However, because the coding process required use of both the pre- and post-course prompts together to assign a continuum location at the end of the semester, assigning two locations was not possible. We therefore developed a model representing four possibilities related to if and how skills could change throughout the semester (Figure 7). For simplicity the model is limited to a consideration of Enhanced and Regular participants.

Since Enhanced section participants had lower pre-course MAI (Figure 2) and SAT scores (Figure 1C), and a weaker pre-collegiate STEM background relative to Regular section participants (Table 1), we assumed Enhanced students had weaker skills than Regular section participants at the beginning of the semester. This assumption is based on the positive correlation between academic performance and metacognitive skills (Hammann & Stevens, 1998; Lynch, 2006; Pintrich & De Groot, 1990; Sawhney & Bansal, 2015; Schraw & Dennison, 1994; Welch et al., 2018; Young & Fry, 2008). However, the interpretation of the model remains the same even if Enhanced and Regular section participants began the semester with identical metacognitive skills.

In the first two cases, the intervention has no effect. Enhanced and Regular sections show the same pattern through time, either no change in metacognitive skills (Figure 7A) or both changing in a similar way over the course of the semester (Figure 7B). Even if Enhanced and Regular section participants begin the semester with similar skills, the data do not support either of these possibilities since Enhanced participants ended the semester with stronger skills than peers in the Regular sections (Figure 3).

In the other two cases, the intervention does have an effect. Either no change in skills occurs in the Regular sections while the intervention strengthens skills of Enhanced participants (Figure 7C), or, if metacognitive skills increase during the semester without an intervention, the intervention has greater impact than no intervention (Figure 7D). In either case, Enhanced section participants end the semester with stronger skills than Regular section participants (Figure 7C, 7D). The data support the final two possibilities (Figure 7C, 7D) with Enhanced participants evidencing stronger skills than peers in the Regular sections at the end of the semester (Figure 3). Even if Enhanced and Regular participants began the semester with identical skills, the data align with these two possibilities.

Limitations of this study

The study design was constrained by factors that warrant consideration when interpreting results. The study was done at one institution with one cohort of students. While the continuum that emerged from the study should be broadly applicable, the exact conditions under which it was developed are likely not replicable. This warrants

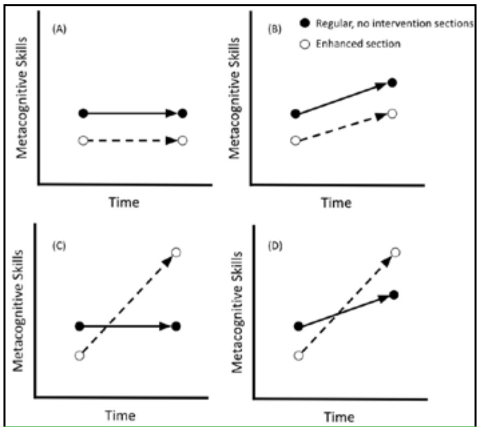

Figure 7. A model of four patterns of change in metacognitive skills from beginning to end of the semester for participants in Regular (closed symbols) and Enhanced (open symbols) sections. (A) Metacognitive skills remain constant through time. There is no effect of the intervention nor of taking a college level biology course or experiencing a semester of college on metacognitive skills. (B) Metacognitive skills increase in both section types during the semester. The intervention does not affect metacognitive skills. (C) Metacognitive skills remain constant with no intervention. With the intervention, metacognitive skills increase. (D) Metacognitive skills increase during the semester with no intervention. However, the intervention results in a greater increase in metacognitive skills relative to no intervention.

caution when interpreting results while simultaneously providing an opportunity to explore how applicable the continuum is across institution types, cohorts, and contexts.

Enrollment criteria used to register students in each section type resulted in non-equivalent groups of students across treatments. The multiple linear regression approach described by Theobald and Freeman (2014) to address the issue of nonequivalence was not appropriate in this study because the dependent variable, metacognitive continuum location, is ordinal. While nonequivalence of students across treatments creates a challenge to interpreting results, the way in which students were nonequivalent in this study can strengthen the interpretation. Since Enhanced participants, with weaker pre-collegiate STEM backgrounds and academic records relative to the Regular sections, ended the semester with stronger metacognitive skills relative to Regular section peers (Figure 3), it is likely the intervention had an effect.

The study design was further constrained by assignment of multiple instructors to the various sections with the Enhanced section instructor not teaching any of the Regular sections. Therefore, it is possible that results were due to an instructor effect that cannot be distinguished with the current study design. In addition, student-centered active learning increases student engagement, academic success (Armbruster et al. 2009), and retention (Braxton et al. 2008). The active learning format and addition of an extra contact hour each week to accommodate the active learning format in the Enhanced section differed from that of the other sections. These factors limit interpretation of study results since the impact of active learning, additional class time, and the explicit instruction and practice with metacognitive skills cannot be distinguished.

The constraints of this study highlight challenges faced when conducting discipline-based education research at this scale. While collecting data on the impacts of interventions is critical to inform pedagogical decisions, factors outside the control of the investigator, e.g., institution assignment of contact hours, enrollment criteria for different sections, and assignment of instructors to sections, can limit interpretation of results. Despite these limitations, results can be informative to others who may be interested in supporting student learning in similar ways.

Conclusions

Since most learning skills interventions work most of the time (Hattie et al., 1996), the question is not whether but *how* faculty should intervene to be most effective. The most successful learning skills interventions are those that are situated in the context in which instructors want them to be used, i.e., embedded within courses and content, and that promote active involvement of students in learning and metacognitive reflection (Hattie et al., 1996). Therefore, faculty interested in supporting development of student metacognitive skills should consider the approach used in this study of including both instruction in metacognition and opportunities to practice metacognitive skills in the classroom.

The approach we took of simultaneously transitioning to an active learning classroom and embedding metacognition instruction and practice in the course was time intensive. For those instructors already using an active learning approach, embedding explicit instruction and practice with metacognition is less time intensive. However, for those using a lecture-based approach, there are smaller-scale, less time intensive opportunities to support student metacognitive development (e.g., McGuire, 2015; Tanner, 2012). Even a one-class-session metacognition workshop improves student academic performance (Cook et al., 2013).

Including *how to learn* as part of introductory disciplinary courses is critical given that most students enter college with relatively weak metacognitive skills (Schraw, 1994; Stanton et al., 2015) and continue to rely on strategies that worked for them in high school that do not support academic success in college (Cao & Nietfeld, 2007). This presents a particular challenge for students intending to earn a STEM degree. If they underperform in introductory STEM courses they may be pushed out of a STEM major by poor grades in STEM courses and/or pulled away from a STEM major by higher grades in non-STEM courses (Ost, 2010). Whether pushed out or pulled away, the result is loss of many students from STEM careers (President's Council of Advisors on Science and Technology, 2012). Faculty have the power to mitigate these impacts by shifting the focus of introductory courses from solely content instruction to include teaching students how to learn (Barr & Tagg, 1995; Hill et al., 2014; McGuire, 2015). If students are to succeed in the college learning environment, it is incumbent that they be taught how to be successful in that environment. Embedding metacognitive skills instruction and practice in the classroom is a powerful tool to reach that goal.

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