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Variations in Students' Metacognitive Awareness: A Semester-Long Study in STEM Classrooms

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Abstract
To foster students' self-regulatory skills, metacognitive strategies have been widely encouraged in disciplinary teaching practices. Classroom research has shown that students encounter problems in transferring and applying learned concepts to different contexts, especially in STEM fields. However, differences through the use of metacognitive intervention have been observed across student levels and in students' class performance. This study aims to understand the variations in students' metacognitive awareness across class levels and disciplines in STEM fields. To assess students' basic level of metacognition, we administered the Metacognitive Awareness Inventory (MAI) assessment at the beginning and end of the semester in multiple STEM classrooms. Our results showed that natural growth of overall metacognitive awareness is not significant in all students, suggesting the need for targeted interventions. STEM disciplines and student academic levels are factors leading to the significant differences in students' developing metacognitive skills. Within the same discipline, biology, our findings revealed a substantial variance of metacognition between entry-level and upper-level students, primarily centered around metacognitive knowledge, indicating the critical necessity to enhance entry-level students' cognition-related knowledge early on in their academic journey.

Keywords
metacognitive awareness, STEM disciplines, class levels, content learning

Introduction

Metacognition, often referred to as "thinking about thinking," plays a crucial role in enhancing undergraduate students' learning outcomes and academic performance across various disciplinary contexts. Based on metacognition theories, metacognitive skills can be sorted into two complementary processes: 1) the knowledge of cognition and 2) the regulation of cognition (Baker, 1991; Brown, 1987; Jacobs & Paris, 1987; Schraw & Moshman, 1995). The knowledge of cognition is also known as knowing about thinking, or metacognitive knowledge, which is considered to include three aspects: declarative knowledge, procedural knowledge, and conditional knowledge. The regulation of cognition, also called metacognitive regulation, refers to the self-directed regulation of the learner's own learning process (Schraw, 1998). It is usually described in terms of three critical skills: planning, monitoring, and evaluating. Previous research has indicated correlations between metacognition, motivation, and strategic behavior (Hammann & Stevens, 1998). Specifically, metacognitive skills enable students to regulate their cognitive processes effectively, leading to improved learning experiences and class performances (Brown, 1987), although the required frequency of effective metacognitive reflection for significant improvement remains unclear (Knight et al., 2022). By engaging in metacognitive strategies, students can become more self-aware of their strengths and weaknesses, identify areas for improvement, and adapt their study approaches accordingly (Jacobs & Paris, 1987). Moreover, metacognition facilitates deeper levels of understanding by encouraging students to reflect on their learning strategies and make connections between new information and prior knowledge (Schraw & Moshman, 1995) as well as to improve the transfer and durability of scientific concepts (Georghiades, 2000). Metacognition has also been linked to increased motivation and engagement in academic tasks, as students who possess higher levels of metacognitive skills are more likely to set challenging goals, persist in the face of difficulties, and employ effective learning strategies (Baker, 1991, Schraw et al., 2006).

STEM education in the U.S. faces a number of challenges, including low student enrollment and a high attrition rate, especially in the first two years of post-secondary education (Chen & Soldner, 2013; Correll et al., 1997; Marra et al., 2012; Schuetz & Schuetz, 2005). Recent studies have consistently highlighted the difficulties students encounter in STEM subjects from introductory biology to upper-level engineering courses (Dye & Stanton, 2017; Erlin & Fitriani, 2019; Sebesta & Speth, 2017). One notable difficulty is the application of learned concepts to different contexts, as highlighted by Georghiades (2000) and Cao & Nietfeld (2007). This challenge is particularly prominent in introductory biology courses, where students have limited self-regulated learning skills but must manage the simultaneous demands of acquiring foundational knowledge and developing as learners (Sebesta & Speth, 2017). In upper-division biology classes, for example, students had challenges evaluating their study strategies and changing the ineffective ones (Dye & Stanton, 2017). Similarly, in engineering programs, both academic factors (e.g., curriculum complexity, ineffective instructional approaches, and insufficient academic supports) and non-academic factors (e.g., lack of belonging in engineering) contribute to difficulties in student learning and eventually lead to low retention rates (Marra et al., 2012). To this end, these challenges underscore the importance of fostering metacognitive skills among undergraduate students to enhance their ability to navigate the complexities of STEM disciplines effectively (Tanner, 2012).

There have been considerable evidence-based instructional strategies, practices, and programs developed to improve student interest, success, and persistence in STEM programs, including high-impact practices (McDaniel & Van Jura, 2020), academic support programs (Huvard et al., 2020; Leoni et al., 2023; Otero, 2015), and pedagogical support for faculty (Sithole et al., 2017). Many introductory biology classes, for example, have integrated active-learning strategies which have been demonstrated to lead to increased engagement and higher levels of content learning (Deslauriers et al. 2019; Freeman et al. 2014; Haak et al. 2011; Lee et al., 2019; McNeal et al., 2020). However, students may not always be able to accurately gauge this increased learning, especially early in their academic careers. Moreover, the ways in which students interact with course material impacts both their content learning and their feelings about learning, such as their feelings of enjoyment, confidence, or instructor effectiveness (Deslauriers et al. 2019). As such, metacognitive strategies are widely recognized as effective tools for enhancing learning outcomes, despite challenges that persist in their application, particularly in STEM disciplines. These challenges stem from the complexities inherent in transferring learned concepts across different contexts and levels of proficiency (Sithole et al., 2017). In addition, the fast-paced nature of the classes often necessitates rapid mastery of new concepts and skills, leaving little time or support for students for deep reflection or to process their planned change of learning strategies even after they recognize the need for change (Stanton et al., 2015). In this regard, understanding variations in students' metacognitive awareness becomes imperative for informing instructional practices and promoting effective learning strategies.

In this study, we aimed to explore how undergraduate students' natural metacognitive skills grow and change in a one-semester STEM course. Our goal is to examine the influencing factors of metacognition growth to provide valuable insights into how students' metacognitive skills vary and to provide meaningful instructional implications for STEM instructors when coupling metacognition activities to class activities. Specifically, we seek to address the following research questions:

1. How does the average of students' metacognitive awareness change over one semester of STEM learning?
2. Are there differences in metacognitive awareness among students based on class levels and disciplines?

Methodology

Participants

During the Spring semester of 2022, a total of 809 undergraduate students majoring in science and engineering participated in the study. All participants were enrolled at the same research-intensive R1 public university in the U.S., as classified by the Carnegie Classification of Institutions of Higher Education. The total participants represented, on average, about 70% of the entire enrollment in the courses in this study. The distribution of participants across course levels was as follows: 614 students in the lower-level Introductory Biology courses BIOL1000, 139 students in the upper-level General Microbiology courses BIOL3000, and 56 students in the upper-level engineering classes INDY3000 (comprised of Deterministic Operations Research, INSY 3410 and Probability and Statistics, STAT 3610). All classes were taught by different instructors. The study included students from diverse academic backgrounds and levels of expertise to capture a comprehensive understanding of metacognitive awareness across different STEM disciplines (biology and engineering) and course levels (lower-level and upper-level).

Data Collection

To measure students' metacognitive awareness levels, we employed the Metacognitive Awareness Inventory (MAI) developed by Schraw and Dennison (1994). The MAI, comprising 52 items, was utilized to comprehensively evaluate students' metacognitive skills into two dimensions of metacognition: knowledge about cognition and regulation of cognition (see Table 1).

Knowledge about cognition (i.e., metacognitive knowledge) is students' understanding of themselves and their learning processes. All declarative, procedural, and conditional types of knowledge are essential for developing students' conceptual knowledge. Higher scores on this dimension represent students who are adept at assessing their mastery of skills and concepts, as well as predicting their study needs. In contrast, regulation of cognition refers to the metacognitive regulation strategies learners employ to control their learning, including activities such as goal setting, strategy selection, progress monitoring, strategy adjustment, and evaluation of the learning process. Students who score highly on this dimension demonstrate proficiency in identifying learning objectives, selecting appropriate strategies, monitoring their progress, adjusting strategies as needed, and evaluating their learning process.

Table 1

Dimensions and Categories of Metacognitive Awareness Inventory (MAI)

Dimensions	Categories	Abbreviation	Number of Items	Example Item
Knowledge about Cognition (metacognitive knowledge)	Declarative Knowledge	DK	5	I am good at organizing information.
	Procedural Knowledge	PK	4	I am aware of study strategies I use.
	Conditional Knowledge	CK	4	I know when each strategy I use will be useful.
Regulation of Cognition (metacognitive regulation)	Planning	P	7	I ask myself questions about the material before I begin.
	Information Management Strategies	IMS	5	I focus on the meaning of new information.

Comprehension Monitoring	CM	6	I ask myself periodically if I am meeting my goals.
Debugging Strategies	DS	5	I change strategies when I fail to understand.
Evaluating	E	7	I summarize what I've learned after I finish.

The MAI assessment survey administrations have been declared exempt by the researchers' institutional IRBs (Protocol#: 21-345 EX 2108).

Data Analyses

First, we conducted a two-way ANOVA to understand whether there was a difference in students' MAI scores based on measurement time (pre- and post-semester), class levels (i.e., BIOL1000 and BIOL3000), and disciplines (i.e., BIOL and INDY). Second, we conducted a two-way multivariate analysis of variance (MANOVA) to understand whether there were differences in students' MAI scores across eight categories based on measurement time (pre- and post-semester), class levels (i.e., BIOL1000 and BIOL3000) and disciplines (i.e., BIOL and INDY). Third, to investigate whether class levels and disciplines are influencing factors impacting students' metacognitive awareness in learning STEM classes, we conducted two sets of one-way MANOVAs for both the pre- and post-semester data sets. When there were nine significant interaction effects, we performed Post-hoc Bonferroni multiple comparisons to determine whether differences between means existed. All analyses were performed using SPSS version 26.0.

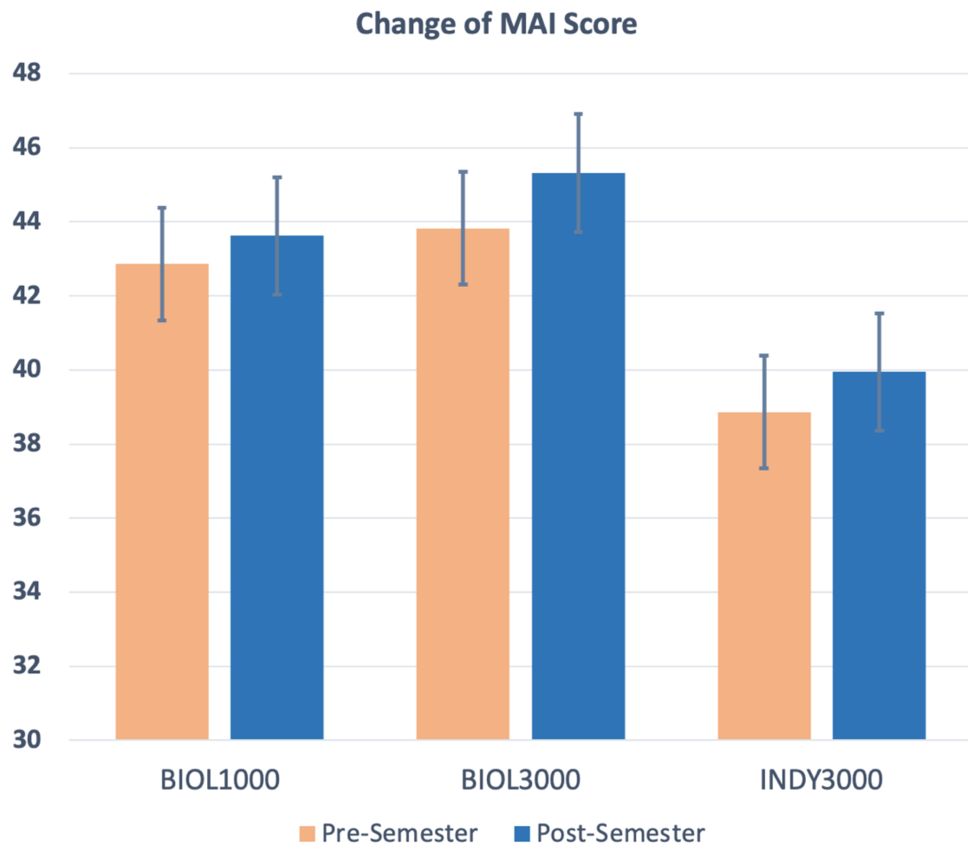
Results

The Overall Growth of Metacognition is Not Significant

To measure students' natural growth within one semester of study in STEM courses, we calculated the changes in overall MAI scores by comparing the pre-semester and post-semester scores. The results showed no significant difference in MAI scores across disciplines (biology and engineering) and levels of classes (lower and upper): $F(2, 1673) = .257$, $p = .773$, partial $\eta 2 = .00$ (see Figure 1). Specifically, the mean scores for BIOL1000, BIOL3000, and INDY3000 courses in the pre-semester were 42.86, 43.63, and 43.83; while at the end of the semester (post-semester), they were 45.32, 38.86, and 39.95, respectively. To further display any differences across the eight categories of metacognitive awareness in the MAI assessment, we conducted a two-way MANOVA, which showed no significant difference in MAI scores (including the eight categories and the overall MAI score) among all disciplines and levels of classes: $F(16, 3332) = 4.046$, $p = .693$; Wilks' $\Lambda = .992$, partial $\eta 2 = .004$.

Figure 1

Comparison of Pre-Semester and Post-Semester Overall MAI Scores Across Disciplines and Class Levels



Note. The y-axis represents the MAI score; x-axis represents three classes. Error bars show 95% confidence intervals.

Disciplinary Content as an Influencing Factor

To investigate whether class level and discipline are influencing factors that impact students' metacognitive awareness in STEM classes, we used the same instrument to collect data pre- and post-semester. Both overall MAI and category breakdown scores are shown in Tables 2 and 3.

Table 2

Student MAI Scores from Different Disciplines Pre- and Post-Semester

	Metacognitive Knowledge			Metacognitive Regulation					Overall
	DK	PK	CK	P	IMS	CM	DS	E	MAI Overall
Pre-semester									
BIOL3000 (N=166)	6.93***	3.57	4.51***	5.49***	8.36 ***	5.83***	4.76*	4.37**	43.83***
INDY3000 (N=65)	6.15	3.38	4.08	4.60	7.34	4.98	4.58	3.74	38.86
Post-semester									
BIOL3000 (N=139)	7.02*	3.66**	4.57***	5.78***	8.76***	6.04***	4.67**	4.81***	45.32***
INDY3000 (N=56)	6.46	3.29	4.11	4.86	7.66	5.20	4.32	4.05	39.95

Note. N: number of participants. DK: declarative knowledge; PK: procedural knowledge; CK: conditional knowledge; P: Planning; IMS: information management strategies; CM: comprehension monitoring; DS: debugging strategies; E: Evaluation; MAI Overall: Overall scores of Metacognitive Awareness Inventory.

*$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Comparing biology students with engineering students at the same class level (i.e., BIOL3000 and INDY3000), engineering students exhibited significantly lower overall MAI scores than biology students at both the beginning ($M_{\text{BIOL}} = 43.83$, $M_{\text{INDE}} = 38.86$, $p < .001$) and end of the semester ($M_{\text{BIOL}} = 45.32$, $M_{\text{INDE}} = 39.95$, $p < .001$) (Table 2). Specifically, when examining the category breakdown data, the significantly lower scores for engineering students were observed in all categories of metacognitive awareness except for procedure knowledge (PK) at the beginning of the semester. At the end of the semester, engineering students had significantly lower scores in all categories (see Table 2).

Discrepancy in Academic Levels within the Same Discipline

We also compared the students' metacognitive awareness in the same discipline but from different class levels. Compared with the upper-level class BIOL3000, students in the lower-level class BIOL1000 had significantly lower levels of declarative knowledge (DK) ($M_{\text{BIOL1000}} = 6.58$, $M_{\text{BIOL3000}} = 6.93$, $p <.05$), procedural knowledge (PK) ($M_{\text{BIOL1000}} = 3.41$, $M_{\text{BIOL3000}} = 3.57$, $p <.05$), and debugging strategies (DS) ($M_{\text{BIOL1000}} = 4.57$, $M_{\text{BIOL3000}} = 4.76$, $p <.01$) at the beginning of the semester, although the difference in their overall MAI scores was not statistically significant (see

Table 3). However, at the end of the semester, students in upper-level class exhibited significantly higher overall MAI scores than those in lower-level class ($M_{BIOL1000} = 43.62$, $M_{BIOL3000} = 45.32$, $p < .05$). By examining the breakdown data, we observed that a significant discrepancy occurred in all three categories of knowledge about cognition dimension, including declarative (DK) ($M_{BIOL1000} = 6.66$, $M_{BIOL3000} = 7.02$, $p < .05$), procedural (PK) ($M_{BIOL1000} = 3.50$, $M_{BIOL3000} = 3.66$, $p < .05$), and conditional knowledge (CK) ($M_{BIOL1000} = 4.37$, $M_{BIOL3000} = 4.57$, $p < .05$), but not in any categories of metacognitive regulation (see Table 3).

Table 3

Student MAI Scores from Different Class Levels Pre- and Post-Semester

	Metacognitive Knowledge			Metacognitive Regulation					Overall
	DK	PK	CK	P	IMS	CM	DS	E	MAI Overall
Pre-semester									
BIOL1000 (N=639)	6.58*	3.41*	4.36	5.48	8.31	5.74	4.57**	4.40	42.86
BIOL3000 (N=166)	6.93	3.57	4.51	5.49	8.36	5.83	4.76	4.37	43.83
Post-semester									
BIOL1000 (N=614)	6.66*	3.50*	4.37*	5.62	8.45	5.87	4.53	4.62	43.62*
BIOL3000 (N=139)	7.02	3.66	4.57	5.78	8.76	6.04	4.67	4.81	45.32

Note. N: number of participants. DK: declarative knowledge; PK: procedural knowledge; CK: conditional knowledge; P: Planning; IMS: information management strategies; CM: comprehension monitoring; DS: debugging strategies; E: Evaluation; MAI Overall: Overall scores of Metacognitive Awareness Inventory.

*$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Discussion

Metacognition and Disciplinary Attributes

Our results found that the natural growth of overall metacognitive awareness is not significant in all STEM classes. This might be impacted by the different nature of STEM disciplines, students' prior knowledge and preparation, and different instructional approaches.

The disciplinary discrepancy, specifically between biology and engineering, has been examined to be a factor leading to the significant difference in developing metacognitive skills among students at similar academic levels in our study. The inherent natures of biology and engineering courses diverge significantly in terms of content, resulting in potentially significant variations in student learning. Biology courses often involve memorization, understanding key terms, and grasping complex processes to make connections across multiple scales (e.g., molecular, cellular, organismal, exosystemic) within the natural world. Many students experience cognitive overload when they are exposed to complex terminologies, hindering their progression to higher order thinking practices (Feldon et al., 2018). In contrast, engineering classes emphasize analytical thinking and problem-solving over memorization to create practical solutions for real-world challenges, requiring more complex quantitative and analytical skills for which students are typically underprepared in their high schools (Astin & Astin, 1992). Consequently, students may struggle with constructing their cognitive models in different ways and in different disciplines (Dauer et al., 2019; Ifenthaler et al., 2011; Seel, 2017), impacting the specific metacognitive skills required for effective learning. Our study showed that students in the engineering course had significantly lower levels of metacognitive regulation compared to students in the same-level biology course. This provides instructors insights to design embedded metacognitive activities to specifically help engineering students improve their self-directed regulation of their learning process.

In addition to the discrepancies in disciplinary content and student learning approaches, instructional methods and students' prior knowledge also play significant roles in shaping students' metacognitive development. With the national call for educational reform aimed at enhancing the quality and quantity of STEM graduates (Association for the Advancement of Science, 2011; PCAST, 2012), extensive research on best practices has emphasized the efficacy of active learning strategies (Freeman et al., 2014; Theobald et al., 2020). However, the diversity in instructional practices has been noted to result in varying student outcomes (Martella et al., 2021). While active learning strategies have proven effective in tackling discipline-specific challenges, like reducing cognitive overload in introductory biology courses (Abeysekera & Dawson, 2014; Barral et al., 2018), their success hinges on students' engagement and perceptions of the material. As such, students' prior knowledge and their awareness of learning obstacles can significantly influence their learning outcomes (Astin & Astin, 1992; Stanton et al., 2015). Previous research has highlighted the need for alignment between students' perceived challenges in learning and their adaptation of study strategies (Cao & Nietfeld, 2007), underscoring the importance of pedagogical support in nurturing metacognitive skills.

Hence, it is necessary to consider a range of classroom dynamics and contextual factors to cultivate an effective and inclusive learning environment. With the proposed continuum of student metacognitive regulation serving as a valuable framework for understanding the observed variations in introductory courses (Stanton et al., 2015), our findings also provide foundational insights into recognizing the variation of students' metacognitive skills in biology and engineering classes.

Metacognition and Academic Level

Various prior studies have explored the differences in metacognitive skills among students at different academic levels, with no definitive consensus on a direct positive or negative correlation between students' academic standing and their metacognitive skill development (Akin, 2016; Garzon et al., 2020; Harding et al., 2019). Our findings revealed a substantial variance in Metacognitive Awareness Inventory (MAI) scores between entry-level and upper-level students, primarily centered around metacognitive knowledge, encompassing declarative, procedural, and conditional knowledge in both pre- and post-semesters. This indicates the critical necessity to enhance entry-level students' cognition-related knowledge early on in their academic journey.

Different from metacognitive regulation skills that pertain to the actions taken during learning, such as planning, monitoring, debugging, and evaluating, metacognitive knowledge focuses on learners' comprehension of their own learning processes, effective learning strategies employed, and when, why, and how to utilize these. Previous research has identified similar issues in biology classes, where students reported employing various study strategies without a clear understanding of their effectiveness for their learning outcomes (Ewell et al., 2023; Stanton et al., 2015; Stanton et al., 2021a).

Therefore, by acknowledging the challenges faced by entry-level students, instructors can employ certain strategies—like practice quizzes and concept mapping—during teaching sessions to afford students the chance to practice these strategies and comprehend their efficacy. Providing students with opportunities to engage with and receive feedback on these strategies can enhance their awareness of their effectiveness and further improve their overall learning experiences (Stanton et al., 2021a).

Implications for Teaching and Learning

Deeper-level instructional interventions such as metacognitive interventions have been widely advocated for given their demonstrated effectiveness across multiple disciplines (Dorji, 2023; Huvard et al., 2020; Osterhage et al., 2019; Steiner, 2016; Zhong et al., 2024). The effectiveness of metacognitive strategies can vary depending on the alignment between the nature of the discipline and the strategies being utilized. Even when used with the same metacognitive framework intervention, different instructors provided students with different experiences, leading to variations in students' improvements in metacognitive skills (unpublished data). Therefore, the infusion of metacognition into classroom practices has been strongly recommended and implemented in STEM disciplines (Lee et al., 2019; Tanner, 2012; Zhong et al., 2025).

Classroom instructors should recognize the diversity of learners within STEM classes and adapt instructional approaches to accommodate different levels of metacognitive development (Stanton et al., 2015). This may involve providing explicit instruction on metacognitive strategies, offering opportunities for self-reflection and peer feedback, and scaffolding the development of these skills over time (Tanner, 2012). In particular, those evidence-based instructional designs that can provide a frequent assessment with constructive feedback on students' metacognitive processes, such as self-testing, exam grade prediction and reflection, built-in confidence questions, and muddiest point group activities, are strongly recommended (Knight et al., 2022; Rodriguez et al., 2018; Zhong et al., 2025). In addition, our results specifically addresse the importance of improving student's different regulatory skills in learning STEM content based on the significant discrepancy across disciplines.

Conclusion

In conclusion, we found that the natural growth of overall metacognitive awareness is not significant in all STEM classes in our study. Both disciplinary attributes and student academic levels are influencing factors leading to the metacognitive variation. Therefore, we strongly recommend STEM instructors embed metacognitive interventions into instructional practices by emphasizing the importance of tailored metacognitive interventions based on factors such as class level and discipline. The Evidence-Based Teaching Guide to Student Metacognition (Stanton et al., 2021b) offers instructors detailed strategies categorized as enhancing metacognitive knowledge or metacognitive regulation. Our investigation into variations in students' metacognitive awareness provides valuable insights that can guide instructional practices and foster self-regulatory skills in STEM classrooms.

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