Fostering Metacognitive Awareness in Introductory Biology: A Lesson on Protein Structure

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Abstract

In many introductory biology classes, active-learning strategies are used to enhance students' levels of content learning. However, students are not typically able to accurately gauge this increased learning, especially early in their academic careers. This lesson focuses on protein structure, a foundational yet challenging concept in introductory biology, and integrates metacognitive activities to help students assess their content knowledge and learning processes. Our goals are to increase students' metacognitive awareness and foster their self-regulatory learning skills over the course of the semester. The lesson was implemented at three universities for two semesters with six lecture classes in total. Students participated in a variety of activities, including worksheets, reflective writings, small-group discussions, and clicker questions. To assess students' content learning, we used pre- and post-intervention content-based assessments on the topic. To measure students' levels of metacognitive awareness and to foster their metacognitive reflection, we used built-in confidence questions following each content question for both pre- and post-assessments. Analyses of reflection assignments and survey data revealed that students developed skills in monitoring their learning and valued the opportunity to cultivate metacognitive skills in their early years of college. Our results also indicate that embedding metacognitive activities into class interventions is an effective strategy to improve students' learning gains and awareness in learning challenging content.

Primary Image: A small group was working on the metacognitive assignment facilitated by a learning assistant in one of our active learning classrooms.

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Learning Goals

Students will:

◊ learn to identify their own learning goals and, in turn, be able to plan, monitor, and reflect on their own learning.

◊ improve their self-regulatory skills and become more independent learners.

◊ apply their metacognitive skills to an overall content learning process.

Learning Objectives

Students will be able to:

◊ Learning Objectives for Metacognitive Skills:

- » think, reflect on, document, and present their learning goals in the topic.
- » identify what they know and what they do not know in specific topics or activities.
- » summarize their learning process and examine where they can improve after the topic.

◊ Learning Objectives for the Re-Designed Module "Protein Structure":

- » recognize and/or diagram the basic structure and R-group properties of an amino acid.
- » describe the four levels of protein structure and diagram simple examples of each (in ribbon form).
- » identify peptide bonds and describe how they are formed or broken.
- » discuss the structural basis for the dynamic properties of macromolecules and predict the effects of changes in dynamic properties that might result from the alteration of a primary sequence.

INTRODUCTION

College-level introductory biology courses pose unique challenges to students as they are often required to learn biological content at a breadth and depth that they may not have previously encountered, while simultaneously transitioning into adult learners. Consequently, students' development as learners is key to success in the courses (1). Metacognition stands out as a valuable strategy to help learners to meet these demands (2–4).

According to metacognition theories (3–6), metacognitive skills can be interpreted as two complementary processes: (i) knowledge of cognition and (ii) regulation of cognition. Knowledge of cognition is also known as knowing about thinking, which is considered to include three aspects: declarative knowledge, procedural knowledge, and conditional knowledge (7). Regulation of cognition involves the self-directed management of the learner's own learning process. It is usually described in terms of three critical skills—planning, monitoring, and evaluating (2, 7). Lacking a grasp of the metacognitive approach can lead to challenges such as an inability to apply learned concepts to new contexts and faster forgetting of acquired knowledge (8). Therefore, improving metacognitive skills is expected to facilitate the development of introductory biology students as adult learners.

Active learning strategies have been integrated in many introductory biology classes, demonstrating the effectiveness of enhancing students' higher levels of content learning (9–12). Stanton *et al*. provided an overview of how instructors can foster metacognition to support student learning. Among other strategies, they emphasized promoting social metacognition during group work, when students share ideas with peers and potentially evaluate ideas shared by peers (13). Other instructors focused on fostering students' metacognition skills by infusing activities of an authentic research experience in a pre-majors introductory cell and molecular biology lab (14). However, as highlighted in the study by Deslauriers and coworkers (11), students may not always be able to accurately gauge this increased learning, especially early in their academic careers. Moreover, this study demonstrated that the way in which students interact with course material impacts both their content learning and their feelings about learning. Factors such as student enjoyment, confidence, and perceptions of instructor effectiveness may all be impacted (11).

Protein structure and function are foundational concepts in biology and biochemistry, yet they pose significant challenges for student comprehension (15–20). Students often struggle to organize the primary structure into the secondary structure and to visualize protein structures due to their complexity and the transition from 2D representations in textbooks to 3D models (15). Freshman students in particular face difficulties with amino acid and protein structures, as they are introduced to these topics early in their academic journey without adequate cognitive preparation for college-level contexts. Addressing these challenges has gained increasing attention among teaching faculty, especially following curriculum recommendations from The American Society for Biochemistry and Molecular Biology emphasizing the importance of teaching protein structure (21). There have been many strategies and practices designed to improve student understanding of protein structure and function, including drawing secondary structures with a more explicit explanation of bonding interactions (15), incorporating a molecular visualization exercise (18, 19) and external representation (16), and using a simple paper-folding activity to model 3D structures (20). However, most of these strategies were developed for small upper-level classes or lab courses with hands-on materials, and there is a lack of published classroom practices incorporating metacognitive components into the teaching of protein structure in introductory biology lecture courses. Therefore, in this study we developed a lesson that couples metacognition activities to class activities focusing on protein structure for introductory biology students.

The class intervention was implemented in three different institutions over two semesters, Fall 2021 and Spring 2022. The activities, ranging from individual- to group-level, are designed for students to better judge their content knowledge/gaps as well as the process they are applying while learning content. To assess students' content learning, we used pre- and post-intervention content-based assessments on the topic. To measure students' levels of metacognitive awareness and to foster their metacognitive reflection, we used built-in confidence questions following each content question for both pre- and post-assessments. We hypothesized that intervention during the semester can lead to content learning gains, increased metacognitive awareness and skills, and greater likelihood of application and retention of the course content.

Intended Audience

The intervention was designed for the majors' introductory biology course. The majority of the student population consisted of first-year undergraduate science majors, with the class size ranging from 200 to 300 students.

Required Learning Time

Each course was taught in a 15-week semester, and the intervention has been implemented in both 50-min and 75-min class period formats. Instructors can adjust the class time, placement of activities, and pace depending on the topic and context (Table 1). The module requires students to answer pre- and post-quiz questions individually and requires time for group discussion activities.

Prerequisite Student Knowledge

The lesson is designed for the first year of college-level introductory biology. Students should have some basic knowledge about biological systems, biological organisms, and chemical bonds relevant to biological molecules before implementing the topic of protein structure. For example, students should have learned about covalent, ionic, and hydrogen bonds. In addition, students should know the major categories of biological molecules, including carbohydrates, lipids, proteins, and nucleic acids.

Prerequisite Teacher Knowledge

To better implement this lesson, we suggest that instructors should have teaching experience with freshman-level introductory biology courses with training in either student-centered course design or any active learning-based pedagogical practices. Instructors will want to have a good introduction to metacognitive concepts, reasoning, and approaches (Supporting File S1). We recommend instructors read the Tanner article (2) that we used to inform our module design.

SCIENTIFIC TEACHING THEMES

Active Learning

All metacognitive activities in the lesson are designed for the student-centered, active learning classroom (2). While our lesson may not align with lecture-only classes, its metacognitive activities are well-suited for instructors seeking to transform lectures into active learning experiences. The intervention engages students in the following aspects: (a) students take low-stakes pre- and post-assessments with content quizzes (Supporting Files S2, S3); (b) students work collaboratively in either fixed or random groups; (c) students fill out worksheets individually before presenting their work to peers (Supporting Files S4, S5); (d) students attend short lectures with built-in student response system questions to engage students in class; and (e) students complete reflective writing prompts in the pre- and post-assessments, which are used to foster students' self-regulatory metacognitive skills (Supporting Files S2, S3). During class, the instructors called on groups randomly to share the outcome of the activities. Some worksheets are designed to allow students to work in groups but to submit them individually for grading or for participation credit (Supporting Files S4, S5).

Assessment

There are two assessments designed to measure student learning. The assessment surveys have been declared exempt by the researchers' institutional IRBs (Protocol#: 21-345 EX 2108).

1. To measure students' learning outcomes and retention of course content, we wrote a content question set for both pre- and post-quizzes which contained the five same questions (at least 3 of 5 were Bloom's mid-level or higher). These are used to assess student content knowledge/gaps and the process they are applying to learn content after either an individual- or group-level activity followed by the reflection questions in the post-assessment (2).
2. To measure students' levels of metacognitive awareness and foster their metacognitive reflection, we included confidence-level questions following each content question in both pre- and post-assessments.

Inclusive Teaching

Activities in the lesson, especially the higher-order problems, are designed as small group work (22). Instructors who implemented the lesson in large classrooms (over 100 students) were able to utilize Learning Assistants or Teaching Assistants to facilitate small group work. Moreover, instructors asked students to submit their worksheets individually (in-person or online through their LMS) after group discussions to create opportunities for all students to participate in the activity. The pre- and post-assessments in the form of quizzes are low stakes (credit for completion) (Supporting Files S2, S3) and allow students to switch their focus from grades to their own learning processes. All activities for these modules were implemented in a way that allowed students who were unable to attend class to still practice, complete, and receive credit for the activity.

LESSON PLAN

Initially, a short introductory video about metacognition and its benefits was made available to the classes before the metacognitive module (Supporting File S1). After watching the video, guided follow-up or student reflection was implemented in the lesson. For example, students discussed the following questions on the course LMS:

1. What is one thing about metacognition that you learned in this video?
2. What is one metacognitive question you could ask yourself as it relates to our biology class?

Overall, this activity seeks to increase students' awareness of metacognition in the learning cycle. The lesson's design consists of the following three aspects, with a framework of design and selected metacognitive questions listed in Tanner (2):

1. **Pre-assessments** are used to assess students' prior knowledge. They are designed with both content and metacognitive questions (level of confidence for each question's answer) in the form of an individual quiz. To set a baseline for measuring gains, we had students take this assessment before we began the module. A majority of the content questions target higher-order thinking skills in Bloom's taxonomy. The pre-quiz has 12 questions in total with 5 content questions, each followed by a confidence-level question, as well as two reflection questions at the end (Supporting File S2). In the pre-quiz file (Supporting File S2), we also highlighted the Bloom's level for each content question. Three of the five involve the higher-order thinking level of analysis. Two are lower-order questions targeting either understanding or applying.
2. **A common content-based activity** targeted student metacognitive monitoring during in-class practice and was designed to help students identify points of confusion. The activity can be implemented individually or in groups. In the protein structure module, we designed higher-order activities such as creating a 3-amino acid oligopeptide and characterizing the molecules. These activities address common struggles with determining protein folding due to the polarity of functional groups carried in each amino acid unit and the complexity of transitioning from 2D representations in textbooks to 3D models (Supporting Files S4, S5). Both content-based activities were designed to promote students' learning, retention, and higher-order thinking.
3. In **post-assessments**, the same pre-assessment quiz is used to assess students' content learning retrospectively along with their confidence level. Students worked on the quiz individually. The post-quiz has 12 questions in total with 5 of the same content questions as the pre-quiz. Each are followed by a confidence question, and there are two reflection questions at the end (Supporting File S3).

The comprehensive teaching timeline, including the designs and estimated durations mentioned above, is outlined in Table 1. While we focus on the metacognitive design for protein structure as a challenging topic within this teaching module, the entire framework described in the lesson plan is adaptable to a variety of subjects and classroom settings.

TEACHING DISCUSSION

As ample previous research has reported, college students, particularly in STEM disciplines that require critical thinking and deep learning, commonly lack skills related to metacognition and reflection (1–3, 9, 23).

During the class discussion, we observed that students were able to clearly mark what they knew and what they did not know with our instruction. The activity helps them monitor their learning, especially in a challenging topic. In the reflective writing prompts, students who engaged in this lesson showed their appreciation for the opportunity to cultivate metacognitive skills when studying science in their early years of college.

Although all our classroom interventions were done in large classrooms for introductory biology courses, the lesson can be easily adapted to different levels or sizes of biology classes. For example, the protein structure module can also be used in classes on genetics, cell and molecular biology, microbiology, biochemistry, and more. On a smaller scale, instructors can integrate the metacognitive reflection prompts into their own class designs. For example, when instructors build their quiz questions, it may be useful to address student confidence levels by simply adding one question from our pre- and post-assessments, "How confident are you about your answer to the question?" (2). Some other simple metacognitive reflection prompts, such as the fill in the blank question "Before this course, I thought 'protein structure' meant… Now I think it is..." and the short-answer question "What do you think was the instructor's goal in having you learn about this topic?", can also be directly used (2).

Ensuring that students can understand and monitor their learning, including discussing ideas shared by peers, is a teaching practice that can foster students' metacognition (13). This lesson used protein structure as an illustrative example to demonstrate how instructors can integrate metacognitive strategies into introductory biology content. A long-term primary goal of this lesson is to empower students to transfer their learning and skills from this lesson to future learning processes.

In this teaching module, students demonstrated significantly higher knowledge and confidence in the post-test compared to the pre-test for all instructors ($p < 0.001$), except for the quiz score for Instructor 1 ($p = 0.056$), as seen in Figure 1. Instructor 1 was the "control" for this module (*i.e.,* Instructor 1 did not include the metacognition class activity). Our data show that students did not perform as well as they expected relative to their confidence level at the end of the module in this control group. However, the metacognition intervention helped all treatment groups to show significant improvement in both content understanding and confidence (Figure 1). This suggests that metacognitive activities help students better grasp challenging content. Without metacognitive activities, students

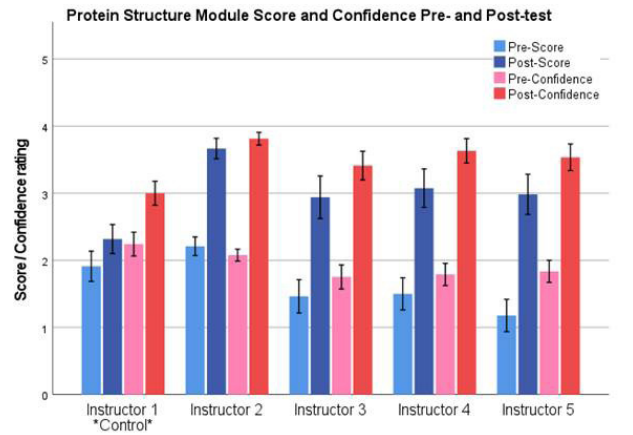

Figure 1. Average quiz scores and reported student confidence levels for the module pre- and post-test. Students demonstrated significantly higher knowledge and confidence levels in the post-test compared to the pre-test for all instructors' classes ($p < 0.001$), except for the quiz score for Instructor 1 who served as the control group ($p = 0.056$). Error bars show the 95% confidence intervals. The p values listed are a paired comparison of the pre-test to post-test values for each instructor's class for knowledge level and separate analyses for confidence.

may overestimate their understanding. In contrast, the treatment groups with metacognitive activities not only showed improved performance but also had confidence levels that more accurately reflected their knowledge, indicating better self-assessment abilities due to metacognitive activities. Therefore, we infer that the class intervention with embedded metacognitive activities is an effective strategy to improve students' learning gains and awareness in learning challenging content. Instructors should note the discrepancy between students' confidence and actual performance, as higher confidence levels did not always align with better performance. Moreover, our study provides valuable insights for instructors to implement a more tailored instructional approach where metacognitive activities are specifically embedded to address known areas of difficulty within the subject matter.

Student comments and reflection statements provided positive feedback on the value of the class activities in supporting content learning. In open-ended comments, students volunteered that the in-class activities helped them organize and apply their knowledge. Reflection statements later in the semester revealed that students were thinking about and discussing the process of learning in this class.

The strategies employed by instructors, as well as classroom discourse and classroom management, can influence student perceptions and awareness (24). Our study recognized that different instructors may have supported their students in various ways, even when utilizing the same module framework. However, our results indicated similar gains among students in terms of their content knowledge and confidence levels. Moreover, this activity not only supports student growth but also provides feedback to instructors as they develop awareness of building metacognitive skills. As such, our experiences suggest that instructors can better integrate metacognitive activities into their classes by considering the class pace and promoting student team-based learning.

SUPPORTING MATERIALS

- S1. Metacognition in intro bio – Metacognition Introduction
- S2. Metacognition in intro bio – Protein Structure Pre-Quiz
- S3. Metacognition in intro bio – Protein Structure Post-Quiz
- S4. Metacognition in intro bio – Protein Structure Oligopeptide Activity with Key
- S5. Metacognition in intro bio – Protein Structure Amino Acids Activity with Key

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Table 1. Teaching timeline.

Activity	Description	Estimated Time	Notes
Introductory video	Have students watch the short introductory video to metacognition (Supporting File S1).	4 min	The video can be released prior to the first metacognition class as an out-of-class assignment. Class discussion (in-person or asynchronous online) can be guided as a follow-up reflection.
Pre-assessment	Students complete a content-based quiz with 5 questions plus confidence questions (individually).	10 min	Supporting File S2.
Pre-class reading	Materials include chapter slides and/or textbook reading assignment.	30–60 min	Instructors can assign any preparation assignments as homework to students to help them prepare for the class.
Introductory lecture	Instructors can use their own slides to introduce amino acid structure and the four levels of protein structure.	10–30 min	Instructors are advised to break the content into pieces and lecture in each class before or after the class activities.
Content-based activity with a reflection	Students complete: 1. Oligopeptide activity with reflections. 2. Amino acids and protein structure activity.	15 min each	These are group activities. Instructors can implement them in one or two class periods. Supporting Files S4 and S5.
Post-assessment	Students complete the post-assessment.	10 min	Supporting File S3.

REFERENCES

1. Sebesta AJ, Speth EB. 2017. How should I study for the exam? Self-regulated learning strategies and achievement in introductory biology. CBE Life Sci Educ 16:ar30. doi:10.1187/cbe.16-09-0269.
2. Tanner KD. 2012. Promoting student metacognition. CBE Life Sci Educ 11:113–120. doi:10.1187/cbe.12-03-0033.
3. Brown A. 1987. Metacognition, executive control, self-regulation, and other more mysterious mechanisms, p 65–116. *In* Weinert F, Kluwe R (ed), Metacognition, motivation, and understanding. Erlbaum, Hillsdale, NJ.
4. Baker L. 1991. Metacognition, reading, and science education, p 2–13. *In* Santa CM, Alvermann DE (ed), Science learning: Processes and applications. International Reading Association, Newark, DE.
5. Jacobs JE, Paris SG. 1987. Children's metacognition about reading: Issues in definition, measurement, and instruction. Educ Psychol 22:255–278. doi:10.1080/00461520.1987.9653052.
6. Schraw G, Moshman D. 1995. Metacognitive theories. Dep Educ Psychol Fac Publ 40. https://digitalcommons.unl.edu/edpsychpapers/40
7. Schraw G. 1998. Promoting general metacognitive awareness. Instr Sci 26:113–125. doi:10.1023/A:1003044231033.
8. Georghiades P. 2000. Beyond conceptual change learning in science education: Focusing on transfer, durability and metacognition. Educ Res 42:119–139. doi:10.1080/001318800363773.
9. Haak DC, HilleRisLambers J, Pitre E, Freeman S. 2011. Increased structure and active learning reduce the achievement gap in introductory biology. Science 332:1213–1216. doi:10.1126/science.1204820.
10. Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP. 2014. Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci 111:8410–8415. doi:10.1073/pnas.1319030111.
11. Deslauriers L, McCarty LS, Miller K, Callaghan K, Kestin G. 2019. Measuring actual learning versus feeling of learning in response to being actively engaged in the classroom. Proc Natl Acad Sci 116:19251–19257. doi:10.1073/pnas.1821936116.
12. Vandegrift EVH, Cavanagh AJ. 2019. Building student literacy and metacognition through reading science in the news. CourseSource 6. doi:10.24918/cs.2019.37.
13. Stanton JD, Sebesta AJ, Dunlosky J. 2021. Fostering metacognition to support student learning and performance. CBE Life Sci Educ 20:fe3. doi:10.1187/cbe.20-12-0289.
14. Lee SR, Dahlberg CL, Wiggins BL. 2019. A short laboratory module to help infuse metacognition during an introductory course-based research experience. CourseSource 6. doi:10.24918/cs.2019.20.
15. Harle M, Towns MH. 2013. Students' understanding of primary and secondary protein structure: Drawing secondary protein structure reveals student understanding better than simple recognition of structures. Biochem Mol Biol Educ 41:369–376. doi:10.1002/bmb.20719.
16. Harle M, Towns MH. 2012. Students' understanding of external representations of the potassium ion channel protein, part I: Affordances and limitations of ribbon diagrams, vines, and hydrophobic/polar representations. Biochem Mol Biol Educ 40:349–356. doi:10.1002/bmb.20641.
17. Harle M, Towns MH. 2012. Students' understanding of external representations of the potassium ion channel protein, part II: Structure–function relationships and fragmented knowledge. Biochem Mol Biol Educ 40:357–363. doi:10.1002/bmb.20620.
18. Terrell CR, Listenberger LL. 2017. Using molecular visualization to explore protein structure and function and enhance student facility with computational tools. Biochem Mol Biol Educ 45:318–328. doi:10.1002/bmb.21040.
19. White B, Kim S, Sherman K, Weber N. 2002. Evaluation of molecular visualization software for teaching protein structure differing outcomes from lecture and lab: Differing outcomes from lecture and lab. Biochem Mol Biol Educ 30:130–136. doi:10.1002/bmb.2002.494030020026.
20. Pikaart M. 2011. The turn of the screw: An exercise in protein secondary structure. Biochem Mol Biol Educ 39:221–225. doi:10.1002/bmb.20487.
21. Voet JG, Bell E, Boyer R, Boyle J, O'Leary M, Zimmerman JK. 2003. Recommended curriculum for a program in biochemistry and molecular biology. Biochem Mol Biol Educ 31:161–162. doi:10.1002/bmb.2003.494031030223.
22. Ambrose SA, Bridges MW, DiPietro M, Lovett MC, Norman MK. 2010. How learning works: Seven research-based principles for smart teaching. Jossey Bass, San Francisco, CA.
23. Stanton JD, Neider XN, Gallegos IJ, Clark NC. 2015. Differences in metacognitive regulation in introductory biology students: When prompts are not enough. CBE Life Sci Educ 14:ar15. doi:10.1187/cbe.14-08-0135.
24. DeMonbrun M, Finelli CJ, Prince M, Borrego M, Shekhar P, Henderson C, Waters C. 2017. Creating an instrument to measure student response to instructional practices. J Eng Educ 106:273–298. doi:10.1002/jee.20162.