Tips & Tools
DOI: https://doi.org/10.1128/jmbe.v21i1.2009
JMBE Journal of Microbiology & Biology Education

Advancing Metacognitive Practices in Experimental Design: A Suite of Worksheet-Based Activities To Promote Reflection and Discourse in Laboratory Contexts†

Thomas M. McCabe and Jeffrey T. Olimpo*
The University of Texas at El Paso, El Paso, TX 79968

INTRODUCTION

Recent efforts to reform postsecondary STEM laboratory education have resulted in the genesis of course-based undergraduate research experiences (CUREs). In contrast to expository and inquiry-based laboratory curricula, CUREs are designed to engage students in the authentic process of scientific discovery, from development of a novel research question to experimentation, data analysis, and dissemination (1, 2). Evidence within the biology education literature indicates that CUREs are effective at promoting students' acquisition of scientific reasoning skills, attitudes, motivations, and conceptual understanding in the discipline (3–7). Furthermore, CUREs have been shown to foster students' ability to "think like a scientist" and, in concert with the aforementioned outcomes, lead to increased student interest and persistence in STEM (8, 9).

Despite these findings, and an emphasis on scientific thinking, little attention has been afforded to explicitly developing students' metacognitive skills within research contexts, including CUREs. In its broadest sense, metacognition refers to "one's knowledge concerning one's own cognitive processes… [as well as] self-regulation—the ability to orchestrate one's learning—[and] the ability to reflect on one's own performance" (10, 11; as cited in 12). Within the laboratory arena, Dahlberg *et al.* (13) note that students engage in metacognitive practices via execution of the scientific method (see also, 12). In addition, Dahlberg and colleagues demonstrated that a brief metacognitive intervention implemented within a modular CURE at their institution was effective at advancing students' reflection and recalibration skills, suggesting that curricular activities can serve as a feasible method to address the need for developing metacognitive skills in STEM laboratory contexts. In considering this and other studies (e.g., 8, 14, 15), we contend that a greater emphasis on the multifaceted and dynamic nature of the scientific process is needed (e.g., troubleshooting; communication), as this more accurately reflects current advances in our understanding of the structure and benefits of CUREs and other similar research-driven opportunities (1, 16–18). Furthermore, while existing exercises (e.g., 13) require students to reflect on the actions and outcomes defining their research project, this is frequently done at the recall level (i.e., use of "*what…*" prompts), with limited, if any, opportunities for evaluation (i.e., use of "*why…*" and/or "*how…*" prompts). The Advancing Metacognitive Practices in Experimental Design (AMPED) exercises described in this article seek to address these concerns, offering a novel approach to engage students in metacognition within laboratory learning environments.

*Corresponding author. Mailing address: 500 W. University Ave., B226, Biology Bldg., The University of Texas at El Paso, El Paso, TX 79968. Phone: 915-747-6923. E-mail: jtolimpo@utep.edu.
Received: 18 October 2019, Accepted: 3 January 2020, Published: 30 April 2020
†Supplemental materials available at http://asmscience.org/jmbe

PROCEDURE

Developing AMPEDs

Congruent with Auchincloss and colleagues' (1) CURE framework, AMPED exercises were created to reflect the diversity of scientific practices that researchers commonly employ in the course of their professional lives. Exercise topics are presented in Table 1. In an effort to further ensure that AMPEDs could be implemented in an accessible manner, we elected to construct these activities as a series of worksheets containing, on average, four reflection prompts. AMPEDs described in this article (Appendix 1) consist of both general and course-specific prompts (see 19, for a description of the CURE at our institution), reflecting the fact that AMPEDs can be easily customized to address the individual needs of each instructor.

Implementing AMPEDs in the laboratory classroom

AMPED exercises are designed to be implemented in tandem with the introduction of the related topic within the laboratory course; as such, AMPEDs are distributed periodically throughout the entirety of the semester (Table 1). We encourage instructors to deploy AMPEDs in a manner conducive to their own instructional context. For instance, we used AMPED 1 as an icebreaker activity during class time to provide an opportunity for students (*N* = 18) to get to know each other while simultaneously discovering and discussing their strengths and weaknesses as a team (with non-assigned groups of four students per team). Subsequently, teams began to work collaboratively to identify possible research areas to explore in the course, which were then shared as part of a whole-class dialogue. Conversely, AMPED 3 ("Research Updates") was assigned weekly as homework and was used to initiate discussion at the start of the subsequent class session around the successes and challenges of engaging in the research process.

Importantly, two additional scaffolds were integrated into the course to support students' development of metacognitive skills. The first of these was the Individual Development Plan (IDP; 20), which we adapted for use with undergraduates and which students completed in the first week of the semester (Appendix 2). The IDP requires that students reflect on their goals for the semester, as well as their self-reported strengths and areas for growth associated with each goal, both individually and in concert with the course instructor. In our context, students were asked to revisit their IDP at the end of the semester in order to encourage them to reflect on their "evolution" as researchers over the course of the term. The second scaffold was weekly "PI meetings." These meetings were, in effect, office hours held outside of regular class meeting times and were designed to provide student teams with additional opportunities to converse with the instructors (*N* = 2) about any challenges the team might be experiencing (as identified, for instance, in AMPED 3), supplies/materials needed to effectively execute their project, and/or mechanisms for dissemination of their research findings.

CONCLUSIONS

Prior research demonstrates that metacognitive strategies, such as post-exam reflections, are effective at advancing students' awareness of their own learning approaches and enhancing students' ability to engage in self-regulated learning (12, 21, 22). Despite the critical importance of these outcomes, relatively few studies (e.g., 13) have sought to examine the use and impact of metacognitive practices in laboratory contexts. The AMPED exercises described herein seek to address this concern, offering a no-cost, adaptable mechanism to explicitly engage students in reflection and discussion around core elements of the scientific process, particularly within CUREs (1). One student enrolled in the Health Disparities CURE at our institution who completed the AMPEDs noted, for instance, that "knowing when to talk to the professors about roadblocks and how to overcome them is what challenged [their] group, and, in the end, was beneficial to [their] growth and research." A second student stated that "the weekly meetings and data analysis workshop (AMPED 4) were beneficial because [they] allowed [her] to ask questions and address errors in [her team's] data to reach [their] goal." While implemented within a CURE, we contend that AMPEDs can be employed in a diverse array of lower- and upper-division courses for majors and nonmajors alike, as they can easily be customized to meet the learning objectives of any research-intensive lecture or laboratory course with minimal investment of time and resources.

TABLE 1.
AMPED topics and implementation schedule.

AMPED Exercise	Topic	Implementation Schedule[a]
1	Collaboration and Goal-Setting	Week 1 (C)[b]
2	Developing Research Questions and Hypotheses	Week 2 (C)
3	Discovery, Implementation, and Iteration	Week 4 (HW)[c]
4	Data Analysis (Scientific Practices)	Week 11 (C)
5	Broader Relevance (Science Communication)	Week 14 (HW)
6	Broader Relevance (Community Engagement)	Week 15 (C)[d]

[a] The implementation schedule is aligned to a standard, 16-week semester.

[b] (C) = AMPED was completed in class during the laboratory session (total time required for implementation of in-class AMPEDs ranged from 60 to 90 minutes, dependent largely upon the duration of in-class discussion, within the context of a 180-minute laboratory session); (HW) = AMPED was assigned as homework, and student responses were discussed during the subsequent laboratory session (approximately 45 to 60 minutes of discussion per AMPED).

[c] AMPED 3 was distributed weekly throughout the semester beginning in week 4 and concluding in week 10.

[d] The Health Disparities CURE described in this article is offered as a two-course sequence as part of the BUILDing SCHOLARS Freshman Year Research Intensive Sequence (FYRIS; https://fyris.utep.edu) at The University of Texas at El Paso. As such, AMPED 6 was delivered at the end of the first semester in order to prime students for their work in the second semester (where the student population is retained between the two semesters).

MCCABE & OLIMPO: METACOGNITION IN THE LAB

SUPPLEMENTAL MATERIALS

Appendix 1: AMPED exercises
Appendix 2: Individual development plan

ACKNOWLEDGMENTS

Development of the AMPED exercises was part of a larger course reform initiative funded, in part, through a curriculum pilot grant awarded by The University of Texas at El Paso's BUILDing SCHOLARS initiative. BUILDing SCHOLARS is supported by the NIGMS/NIH under linked award numbers RL5GM118969, T4GM118971, and UL1GM118970. This study was approved by The University of Texas at El Paso's Institutional Review Board (IRB) under protocol #789648. The views expressed in this article are those of the authors and do not necessarily reflect the views of the NIGMS/NIH or its constituents. The authors declare that there are no conflicts of interest to report.

REFERENCES

1. Auchincloss LC, Laursen SL, Branchaw JL, Eagan K, Graham M, Hanauer DI, Lawrie G, McLinn CM, Pelaez N, Rowland S, Towns M, Trautmann NM, Varma-Nelson P, Weston TJ, Dolan EL. 2014. Assessment of course-based undergraduate research experiences: a meeting report. CBE Life Sci Educ 13:29–40.
2. Spell RM, Guinan JA, Miller KR, Beck CW. 2014. Redefining authentic research experiences in introductory biology laboratories and barriers to their implementation. CBE Life Sci Educ 13:102–110.
3. Brownell SE, Kloser MJ, Fukami T, Shavelson R. 2012. Undergraduate biology lab courses: comparing the impact of traditionally based "cookbook" and authentic research-based courses on student lab experiences. J Coll Sci Teach 41:36–45.
4. Jordan TC, Burnett SH, Carson S, Caruso SM, Clase K, DeJong RJ, Dennehy JJ, Denver DR, Dunbar D, Elgin SCR, Findley AM, Gissendanner CR, Golebiewska UP, Guild N, Hartzog GA, Grillo WH, Hollowell GP, Hughes LE, Johnson A, King RA, Lewis LO, Li W, Rosenzweig F, Rubin MR, Saha MS, Sandoz J, Shaffer CD, Taylor B, Temple L, Vazquez E, Ware VC, Barker LP, Bradley KW, Jacobs-Sera D, Pope WH, Russell DA, Cresawn SG, Lopatto D, Bailey CP, Hatfull GF. 2014. A broadly implementable research course in phage discovery and genomics for first-year undergraduate students. MBio 5:e01051-13.
5. Olimpo JT, Fisher GR, DeChenne-Peters SE. 2016. Development and evaluation of the *Tigriopus* course-based undergraduate research experience: impacts on students' content knowledge, attitudes, and motivation in a majors introductory biology course. CBE Life Sci Educ 15:ar72.
6. Fisher GR, Olimpo JT, McCabe TM, Pevey RS. 2018. The *Tigriopus* CURE—a course-based undergraduate research experience with concomitant supplemental instruction. J Microbiol Biol Educ 19(1):19.1.55. doi: 10.1128/jmbe.v19i1.1503.
7. Shuster MI, Curtiss J, Wright TF, Champion C, Sharifi M, Bosland J. 2019. Implementing and evaluating a course-based undergraduate research experience (CURE) at a Hispanic-serving institution. Int J Prob Learn 13:1–13.
8. Brownell SE, Hekmat-Scafe DS, Singla V, Seawell PC, Imam JFC, Eddy SL, Stearns T, Cyert MS. 2015. A high-enrollment course-based undergraduate research experience improves student conceptions of scientific thinking and ability to interpret data. CBE Life Sci Educ 14:ar21.
9. Rodenbusch SE, Hernandez PR, Simmons SL, Dolan EL. 2016. Early engagement in course-based research increases graduation rates and completion of science, engineering, and mathematics degrees. CBE Life Sci Educ 14:ar20.
10. Flavell JH. 1979. Metacognition and cognitive monitoring: a new area of cognitive–developmental inquiry. Am Psych 34:906.
11. National Research Council. 2000. How people learn: brain, mind, experience, and school. Washington, DC.
12. Tanner KD. 2012. Promoting student metacognition. CBE Life Sci Educ 11:113–120.
13. Dahlberg CL, Wiggins BL, Lee SR, Leaf DS, Lily LS, Jordt H, Johnson TJ. 2019. A short, course-based research module provides metacognitive benefits in the form of more sophisticated problem solving. J Coll Sci Teach 48:22–30.
14. Olimpo JT. 2015. The biology experimental design challenge: an interactive approach to enhance students' understanding of scientific inquiry in the context of an introductory biology course. J Microbiol Biol Educ 16:75.
15. Schwartz DL, Tsang JM, Blair KP. 2016. The ABCs of how we learn: 26 scientifically proven approaches, how they work, and when to use them. New York, NY.
16. National Academies of Science, Engineering, & Medicine. 2015. Integrating discovery-based research into the undergraduate curriculum: report of a convocation. Washington, DC.
17. Corwin LA, Runyon CR, Ghanem E, Sandy M, Clark G, Palmer GC, Reichler S, Rodenbusch SE, Dolan EL. 2018. Effects of discovery, iteration, and collaboration in laboratory courses on undergraduates' research career intentions fully mediated by student ownership. CBE Life Sci Educ 17:ar20.
18. Dolan EL. 2016. Course-based undergraduate research experiences: current knowledge and future directions. Paper commissioned for the Committee on Strengthening Research Experiences for Undergraduate STEM Students Board on Science Education, Division of Behavioral and Social Sciences and Education Board on Life Sciences, Division of Earth and Life Studies.
19. Olimpo JT, Apodaca J, Hernandez A, Paat YF. 2019. Disease and the environment: a health disparities CURE incorporating civic engagement education. Sci Educ Civic Engage Int J. https://new.seceij.net/articletype/disease-and-the-environment/.
20. Tsai JW, Vanderford NL, Muindi F. 2018. Optimizing the utility of the individual development plan for trainees in the biosciences. Nature Biotech 36:552–554.
21. Siegesmund A. 2017. Using self-assessment to develop metacognition and self-regulated learners. FEMS Microbiol Letters 364. https://doi.org/10.1093/femsle/fnx096.

22. Smith BA, Metzger K, Soneral P. 2019. Investigating introductory nonmajor biology students' self-regulated learning strategies through the implementation of a reflective-routine. J Coll Sci Teach 48:66–76.