Enhancing Scientific Literacy in the Undergraduate Cell Biology Laboratory Classroom

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This paper describes the implementation of the Scientific Literacy in Cell Biology (SLCB) curriculum in an undergraduate biology laboratory course. The SLCB curriculum incorporated the reading and discussion of primary literature into hands-on and collaborative practical experiences. It was implemented in five stages over an 11-week period, during which students were also introduced to the theory and practice of common cell biology techniques. We report on the effectiveness of the course, as measured by pre- and post-course survey data probing students' content knowledge and their level of familiarity, confidence, and experience with different skills pertaining to analyzing (reading, interpreting, and discussing) primary literature. In the spring 2015 semester, 287 (72%) of the 396 students who were enrolled in the laboratory completed both the pre- and post-course survey. The average score on the content questions of the post-course survey was significantly higher ($p < 0.0001$) than the average score on the pre-course survey. Students reported that they gained greater familiarity, experience, and confidence in the skills that were measured. Our findings may aid in reforming higher-education science laboratory courses to better promote writing, reading, data processing, and presentation skills.

INTRODUCTION

Undergraduate biological sciences education has experienced a recent push toward providing students with laboratory-based experiences that more closely resemble the scientific research process (1, 4, 9). Handlesman et al. (9) coined the term “scientific teaching” to represent the importance of teaching science in a way that accurately reflects the rigor and dynamic nature of the discipline. A scientific teaching approach can better prepare students for careers in science by facilitating a more meaningful connection between theory and practice. Learning how various methodologies are currently used in scientific research allows students to make such meaningful connections (10, 11). Central to this goal is the reading and discussion of current primary literature, which serves to provide students with a model of the scientific process (3, 12). Also important is the use of collaborative, research-based projects that require both formal and informal communication and discussion of findings (4, 13).

In designing a laboratory-based curriculum for an intermediate-level cell biology course, we used a multi-pronged approach that incorporates both hands-on practical experiences and analysis (reading, interpretation, and discussion) of relevant primary literature. We will refer to this approach as the Scientific Literacy in Cell Biology (SLCB) curriculum. While there are many definitions of “scientific literacy” (e.g., 1, 2, 8), there is general agreement that scientific literacy includes skills pertaining to both conceptual understanding and the relationship between science and society (8).

Our interpretation of scientific literacy draws upon the skills that scientists and science educators regard as being most important for undergraduates to acquire, namely: data interpretation, experimental design, scientific writing, oral communication, critical analysis of primary literature, and collaborative work (5). Among these skills, our curriculum focuses on the combined use of primary literature and a collaborative laboratory project to enhance both the conceptual understanding and the learning experiences of undergraduate students in the cell biology laboratory classroom.

We deliberately chose primary literature that was engaging, appropriate for undergraduates, and directly applicable to the course curriculum. Collaborative, hands-on practical experiences were provided concurrently, in stages, over an 11-week period. Students were introduced to the theory and practice of common cell biology techniques and then given an opportunity to apply these techniques toward specific research goals in an end-of-semester, multi-week project on apoptosis and cancer. This project theme was inspired by DiBartolomeis and Moné (6), who reported the successful implementation of a multi-week project on apoptosis in a human leukemia cell line (HL60) in an advanced cell biology undergraduate course.
Intended audience

The SLCB curriculum was designed for a large (about 500 students), intermediate cell biology laboratory course that satisfies an upper-level laboratory course requirement for students in the biological sciences, biochemistry, and bioengineering; however, the SLCB curriculum can be implemented in any undergraduate laboratory course that has a prerequisite of introductory biology and introductory chemistry.

Prerequisite student knowledge

Our cell biology course included both a lecture and a laboratory component that were taken concurrently. The course had two prerequisites, a general biology course and a general chemistry course, both of which included corequisite laboratory components.

Learning time

Laboratory sessions met once each week for approximately three hours and were taught by either undergraduate or graduate teaching assistants. SLCB was implemented in five stages over an 11-week period, and was interspersed among weekly laboratory exercises covering a range of cell biology techniques. During this time, students spent the first half of the lab period discussing primary research articles and the second half conducting experiments. Brief descriptions of the various laboratory activities used can be found in Table A (Appendix 1).

Stage 1 (week 1) of the SLCB curriculum consisted of online tutorials introducing students to the fundamental features of primary and secondary scientific literature. This stage culminated in an online assessment that tested students’ comprehension of the basic concepts introduced in the readings/tutorials and students’ ability to apply these concepts to specific examples from the cell biology literature.

Stage 2 (week 2) involved reading a primary research article from the field of cell biology that would later be used by students as a model for organizing, writing, and presenting their own laboratory findings. The article was discussed in class, where groups of four students were randomly assigned sections of the article to present informally to the class.

Stage 3 (week 3) involved reading a second primary research article. Students were asked to both summarize this article in a graded essay and discuss the article in class (see Appendices 4, 5, and 7). This article built on the first article in that it addressed a similar research area, but incorporated further experimental investigations that required a higher level of technical and conceptual understanding.

During stage 4 (weeks 8 to 10), students worked in groups of four on a small-scale laboratory project. The goal of this stage was to give students an opportunity to apply the experimental techniques they had learned previously (during stages 1 to 3) toward a research area pertaining in some way to that of the primary research articles they had read.

Finally, during stage 5 (week 11), students presented results of their laboratory project in a formal PowerPoint-style presentation. This presentation required that students not only present and discuss their findings but that they also compare and contrast these findings with those of a third primary research article of their choosing that shared similar experimental objectives. Thus, the SLCB curriculum incorporated three primary research articles: the first two were chosen by the instructor, and the third was chosen by the students.

Learning objectives

Upon completion of the SLCB curriculum students should be able to:

1. Demonstrate conceptual understanding of various cell biology techniques typically performed in a laboratory setting
2. Identify characteristics of the scientific research process, as illustrated in primary literature
3. Process raw scientific data into a format appropriate for interpretation and presentation
4. Interpret, discuss, and analyze their own data in the context of relevant primary scientific literature

PROCEDURE

The SLCB curriculum was completed in five stages over 11 weeks of the semester. Please see Table A (Appendix 1) for a summary of the assignments and laboratory instruction topics implemented during each stage.

Materials

Sources of outside reading and primary literature. The reading assignments in stage 1 of SLCB were a compilation of online material taken from three sources:

a) A quick tutorial on primary and secondary sources in the sciences offered by the University at Albany, State University of New York: (http://library.albany.edu/infolit/prisci)
b) A video on the peer review process created by North Carolina State University: (“Peer Review in 5 Minutes,” www.youtube.com/watch?v=p-H187QJUJE)
c) Selected modules from the science education resource website Visionlearning (www.visionlearning.com/en/library/Process-of-Science/49/Understanding-Scientific-Journals-and-Articles/158/reading)

The primary research literature for stages 2 and 3 can be selected from any cell biology research journal. See “Faculty Instructions” for guidelines on choosing an appropriate article. The articles used in our cell biology course were chosen from the World Journal of Gastroenterology (14) and the International Journal of Cancer (7).
Student instructions

Written instructions for students can be found in Appendices 2 to 6, as listed below.

Stage 1:
Guided tutorial guidelines and readings (Appendix 2)
Online assessment questions (and key) for guided tutorial (Appendix 3)

Stage 2:
Primary research article reading guidelines (Appendix 4)
Primary research article #1 (14)

Stage 3:
Primary research article written summary guidelines (Appendix 5)
Primary research article #2 (7)

Stages 4 and 5:
Group oral presentation guidelines (Appendix 6)

Faculty instructions

Stage 1 preparations: Providing resources for reviewing primary and secondary literature. For stage 1 of SLCB, instructors should provide students with a guided tutorial that introduces and reviews key features of primary and secondary literature, particularly literature in the biological sciences. The resources provided to the students in our course included readings and online videos. To keep students engaged, we chose to provide “bite-sized” pieces of information taken from a variety of online sources, beginning with our own university library’s guide to primary sources. Following the tutorial, students took an online quiz that assessed their understanding of this material. The tutorial and assessment tools are provided in Appendices 2 and 3. These materials can be adapted for use in any similar introductory biology course.

Stage 2 preparations: Finding the right primary research article. Choosing a primary research article to be read in stage 2 of SLCB is not an easy task, especially since the article is assigned at the beginning of the course. A typical primary research article in the field of cell biology will have experimental goals that are aimed at discerning specific cellular pathways or events about which the reader is assumed to have a high level of understanding. At this point in an introductory cell biology course, however, it is unlikely that students have been exposed to the concepts underlying many experimental cell biology techniques. It is important to choose a paper appropriate to the students’ level of understanding.

Our stage 2 primary research article was chosen to meet three criteria: being engaging, accessible, and applicable (see Fig. 1). The article we chose focused on the relationship between nicotine and cancer progression (14). Since the SLCB was implemented in a laboratory course, we felt that it was also important that the chosen article include at least some experimental techniques that could potentially be used by students in their own laboratory investigations. The extent to which any given technique is feasible for students to replicate depends on available laboratory equipment.

Stage 3 preparations: Creating a primary literature curriculum arc. To build a learning progression from stage 2 to stage 3 it is beneficial to choose a second article that has some connection to the first. We chose a stage 3 article that had a similar experimental objective to that of the stage 2 article, but in which the investigation of the topic was deeper and involved more elaborate experimental techniques. By stage 3, our students had been exposed to a variety of concepts and processes in cell biology, and we expected them to have achieved a more sophisticated understanding of relevant topics and techniques. See Figure 1 for an overview of creating a primary literature reading curriculum arc in an SLCB curriculum.

Stage 4 preparations: Choosing a collaborative laboratory project. By this stage of the curriculum, students will have acquired skills in various experimental cell biology methods, as well as a general appreciation for the utility of such techniques in analyzing discrete cellular processes and/or characteristics. Furthermore, they will have had an opportunity to develop skills in the reading and analysis of primary research articles in a targeted area of cell biology (in our case, nicotine and cancer progression). We now want students to apply these combined skills to a specific research problem that can be investigated in the laboratory classroom and later presented and critically analyzed using relevant primary literature (see stage 5).

Given that the primary research articles we chose for stages 1 to 3 focused on nicotine-induced cancer progression, we decided to have students explore the topic of drug-induced cancer cell death (apoptosis). As previously mentioned, this project was inspired by a four-week project on apoptosis and cancer by DiBartolomeis and Moné (6), in which students examined the progression of apoptosis in drug-induced human leukemia cells (HL60) using cell biology techniques such as cell culturing, bright field and fluorescence microscopy, deoxyribonucleic acid (DNA) extraction and electrophoresis, and SDS PAGE (sodium dodecyl sulfate polyacrylamide gel electrophoresis) and Western blotting. Our version of this project lasted three weeks and included microscopy and SDS PAGE/Western blotting components similar to those implemented by DiBartolomeis and Moné. However, we also added the spectrophotometric determination of apoptotic enzyme activity, since spectrophotometry had been an integral component of the basic laboratory techniques students had used in stages 1 to 3 (see Appendix 9). Any number of
specific research areas could be chosen in this stage of the curriculum. However, in our experience, it is advantageous to choose a topic related to the research area(s) explored in the primary literature used in stages 1 to 3.

Stage 5 preparations: Directing students to choose an appropriate research article for their final presentation. Upon completion of the research project in stage 4, students are asked to choose their own primary research article for comparative analysis with their own project’s findings. This analysis is included in their formal presentation to their peers during stage 5. In our implementation of SLCB, the students chose an article within a narrow area of research that was relevant to the topic of their end-of-semester project on apoptosis and cancer. As this is the culminating assignment of the SLCB curriculum, instructors should aim to give students minimal guidance in choosing the article but should provide clear guidelines on how it should be presented. The article presentation guidelines we used can be found in Appendix 6.

Assigning students to groups. At the beginning of the cell biology laboratory course, students were permitted to choose their own groups of four to work with for the entire semester. Students worked individually on assignments in stages 1 to 3 and worked collaboratively within their lab groups for their apoptosis project and oral presentation during stages 4 and 5. Students were graded individually on all assignments except for the group oral presentation project at the end of the semester. They were encouraged to provide anonymous ratings for fellow group members on contributions to the group presentation using a scale of 1 to 4, with 4 indicating a significant contribution to the group and 1 indicating little to no contribution to the group. Students who received an average score below 3 from their group members had their group oral presentation grade reduced by up to 16%.

Suggestions for determining student learning

We assessed student learning on primary research article summaries, laboratory reports, and group project presentations using rubrics, as well as pre- and post-activity surveys. Rubrics used in each stage are provided in Appendices 3 and 7 to 10, as listed below.

Stage 1:
Online assessment questions (and key) for guided tutorial (Appendix 3)

Stage 2:
Sample rubric for grading in-class discussion of a primary research article (Appendix 7)

Stage 3:
Rubric for grading primary research article #2 written summary (Appendix 8)
Stage 5:
Rubric for grading group oral presentation (Appendix 9)
Post-lab assessment questions (and key) (Appendix 10)
The SLCB assignments described here were worth a total of 102 points. The breakdown of points awarded for each assignment is provided in Table 1.

Sample data: pre- and post-course surveys

During the first and last weeks of the course, students completed pre- and post-course surveys. The surveys were distributed through the online course management system (Canvas), and students were offered extra credit for completing both surveys. Each surveys consisted of four sections:

Section 1: Multiple-choice content questions about topics and skills taught in the course (15 on the pre-course survey and 18 on the post-course survey); 14 questions were identical on both surveys (see Appendix 10).

Section 2: Students’ reported level of familiarity with the structure of lab reports, structure of scientific papers, and process of preparing raw data for analysis in either biological (“biology”) or other scientific (“other”) disciplines using a 3-point scale (1 = no familiarity, 2 = some familiarity, 3 = substantial familiarity).

Section 3: Students’ reported level of experience with scientific writing, reading scientific literature, and data analysis using a 3-point scale (1 = no experience, 2 = some experience, 3 = substantial experience).

Section 4: Students’ reported level of confidence with scientific writing, reading scientific literature, and interpreting and presenting scientific data (1 = not confident, 2 = somewhat confident, 3 = very confident).

Safety issues

Safety issues relate only to the specific lab protocols and are not relevant to the course design that is described here.

DISCUSSION

Field testing

This experimental design was first implemented in spring 2014. Based on observation and data collection from this implementation, we made curricular and pedagogical revisions that were then implemented in the spring 2015 offering. Overall, 287 (72%) of the 396 students enrolled in the spring 2015 laboratory completed both the pre- and post-course survey. Demographics of the sample (54% female; 16% underrepresented minority students) were representative of the class as a whole.

Evidence of student learning

Our overarching goal was to determine whether students gained conceptual understanding of targeted experimental cell biology techniques (Learning objective 1), but also to increase students’ familiarity, experience, and confidence with scientific literacy skills such as reading, interpreting, discussing, and presenting data obtained from both published primary literature and from their own laboratory project experiments (learning objectives 2 to 4).

Conceptual understanding of targeted experimental cell biology techniques. The average overall score on the content questions of the post-course survey (58%) was significantly higher ($p < 0.0001$) than the average overall score on the pre-course survey (42%). For most questions, students improved their understanding (Fig. 2); however, students’ responses to question 5 showed no improvement. This was likely because the question dealt with a planned laboratory topic that was deleted from the curriculum for technical reasons. Also, no improvement was detected in students’ responses to question 6. In this case, the percentage of correct pre-course survey responses was already quite high (~80%), indicating that students may have acquired a good understanding of this topic from prior coursework.

| Assignment                                      | Type of Assignment | Maximum Points |
|-------------------------------------------------|--------------------|----------------|
| Online tutorials and assessments                 | Individual         | 14             |
| Primary research article #1 in-class discussion  | Individual         | 4              |
| Primary research article #2 written summary      | Individual         | 18             |
| Primary research article #2 in-class discussion  | Individual         | 6              |
| Laboratory report                                | Individual         | 35             |
| Group oral presentation (including student selection of primary research article #3) | Group              | 25             |

SLCB = scientific literacy in cell biology.
**Familiarity with scientific literacy skills.** Students’ familiarity with the structure of lab reports, the structure of scientific papers (learning objective 2), and the process of preparing raw data for analysis (learning objective 3) increased during the course (Fig. 3). Only 25% of the students came to the course having substantial familiarity with the proper structure and organization of a lab report in the biological sciences, and less than half reported substantial familiarity with characteristics of journal articles in biology (34% and 28%) or in other scientific fields (40% and 20%).

By the end of the course, most of the students reported that they had substantial familiarity with the structure and organization of lab reports (73%) and the characteristics of journal articles (structure and organization of primary research and difference between primary and secondary literature) in biology (68% and 77%, respectively). Fewer students reported that they had substantial familiarity with the characteristics of journal articles in other scientific disciplines (49% and 56%). This supports our assumption that the large gains by students in familiarity with journal articles were attributable to their experiences in this course rather than other science courses in which they were concurrently enrolled (e.g., physics, chemistry). Regarding familiarity with differences between raw and processed scientific data (a primary curricular goal of the course), most students came to the course with relatively low familiarity (no familiarity: 36%; some familiarity: 42%); however, by the end of the course, almost all students reported at least some familiarity with this concept (some familiarity: 36%; substantial familiarity: 59%).

**Experience with scientific literacy skills.** Fewer than a third (20% to 31%) of the students reported that they came to the course with substantial experience in any of the measured skills (Fig. 4). However, by the end of the course, most students reported that they had substantial experience in writing and reading in the biological sciences (≥65%), as well as processing, presenting, and discussing data (≥58%). As was the case with level of familiarity in other scientific fields, fewer students reported substantial experience in writing lab reports (40%) and reading and interpreting journal articles (50%) in other scientific fields.

**Confidence with scientific literacy skills.** Fewer than a third of the students reported that they came to the course feeling confident with writing, reading, or handling and presenting data (≤26%, Fig. 5). Encouragingly, at the end of the course, almost all students reported that they were at least somewhat confident in these skills (≥98%); however, only about half of them reported being very confident in these skills (45% to 56%).

**Student perceptions**

In the post-course survey, students were asked about the usefulness of primary research articles in understanding cell biology by rating their level of agreement with the statement, “Reading and discussing primary research articles in lab this semester was helpful towards my understanding of cell biology.” We were very encouraged that 80% of students either agreed or strongly agreed with this statement. Another encouraging finding was related to students’ responses to the open-ended post-course survey question, which prompted them to list two new techniques or concepts that they learned in lab. While many students simply took this opportunity to list various techniques they had conducted throughout the semester, others spoke more broadly about their lab experience, with comments such as, “Lab helped me grasp the big picture”; “Lab helped me...”
understand the logic behind what I did in each experiment/new method learned, instead of just performing what is written down”; and “I learned how to better understand and interpret primary research articles, and how to write a college level scientific paper.”

Possible modifications

We suggest that the SLCB curriculum can be applied to a variety of undergraduate biology laboratory courses. While the laboratory topics and primary literature implemented in our course were specific to an upper-level cell biology course, the basic approach could easily be adapted to other biology courses. An important component of the SLCB curriculum is the student assessments. We recommend that instructors use specific guiding questions, graded in-class discussions, and graded article summaries or other writing prompts to maximize student engagement with the primary literature. Instructors may also challenge students to make connections among the various primary research articles they are assigned by asking them to point out similarities and differences in experimental design, or to design their own hypothetical experiments to answer research questions similar to those in the articles.

Having students choose their own primary research article to present to their peers is an important final component to the SLCB curriculum. Although we did this as part of the three-week research project in which students chose an article related to their own findings, this assignment could instead be used for Journal Club presentations on research papers of students’ own choosing. Finally, one important modification to the pre/post survey questions given to students would be to include the Test of Scientific Literacy Skills developed by Gormally et al. (8).

CONCLUSION

We feel that the SLCB curriculum is an effective way to introduce biology students to important facets of the scientific process, and our post-course assessment data support this contention. Interestingly, our pre-course assessments show that upper-level students at a research-intensive university with a strong science program may have surprisingly limited experience with, and confidence in, fundamental scientific activities. This highlights the need for coordinated curriculum development and program-level assessment to ensure that students who complete a bachelor’s degree in science have the requisite skills for a successful career in science. We believe that our study may aid in reforming other higher-education science laboratory courses so that they too promote pertinent scientific literacy skills, such as writing, reading, data processing, and oral presentation, that ultimately enhance students’ conceptual understanding and ability to communicate.

SUPPLEMENTAL MATERIALS

Appendix 1: Table A. The organization of the SLCB curriculum
Appendix 2: Guided tutorial guidelines and readings
Appendix 3: Online assessment questions (and key) for guided tutorial
Appendix 4: Primary research article reading guidelines
Appendix 5: Primary research article written summary guidelines
Appendix 6: Group oral presentation guidelines
Appendix 7: Sample rubric for grading in-class discussion of a primary research article
Appendix 8: Rubric for grading primary research article #2 written summary
Appendix 9: Rubric for grading group oral presentation
Appendix 10: Post-lab assessment questions (and key)

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