Engaging Biology Undergraduates in the Scientific Process Through Writing a Theoretical Research Proposal

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Abstract: It has been suggested that research experiences are an important element that should be included in all undergraduate Biology curricula. This is a difficult suggestion to accommodate due to issues with cost, space and time. We addressed this challenge through development of a capstone project in which Biology majors work in groups to develop novel theoretical research proposals with guidance from a faculty mentor. Though students are not directly working at the bench, they are being mentored in aspects of the scientific process such as synthesizing information from the literature, asking novel research questions, constructing logical aims, designing experiments and writing scientifically. Since this project began, we have mentored 417 students in proposal writing and have assessed their experiences through pre- and post-surveys. Students have made gains in several areas, but most notably in their ability to pose novel questions and develop an experimental plan, and in the number of professional relationships they have with faculty members. Most faculty feel positively about mentoring these projects. In our view, this approach allows programs to engage a large number of students in the scientific process, and could be adapted for use in a variety of different university or college environments.

Key words: undergraduates, capstone, Biology, proposal, grant, research, writing, experimental design.

INTRODUCTION

Reports from the National Research Council (NRC) and American Association for the Advancement of Science (AAAS) have made suggestions indicating how Biology undergraduate education should be reformed to meet the changing needs of students (National Research Council 2003; Woodin, Carter et al. 2010; American Association for the Advancement of Science 2011). A common theme has emerged from these studies, suggesting that students should be given opportunities to engage in scientific research (Lewis et al. 2003; Woodin et al. 2010). Indeed, a number of studies have demonstrated the benefits of undergraduate research, including personal and professional gains such as increased confidence, ability to think like a scientist, and gains in communication and organizational skills (Seymour et al. 2004; Hunter et al. 2009; Junge et al. 2010; Laursen et al. 2010; Lopatto 2006; Lopatto 2007). While some institutions can provide opportunities for all Biology majors to conduct independent research, this is a challenge at many institutions due to issues of space, cost and availability of faculty mentors. As a result, many programs need to employ creative approaches to allow students to experience research.

In developing approaches to provide students with a genuine research experience, it is essential to reflect on the types of skills students gain through research. Based on several studies that have evaluated the benefits of undergraduate research, the best supported benefits include an increase in self-confidence, understanding of science and the research process, ability to apply knowledge and skills, communication skills, and ability to work independently (Laursen et al. 2010; Lopatto 2004; Russell et al. 2007; Seymour et al. 2004). While data generation and analysis are certainly critical parts of science, they are not the only things that scientists do. In fact, scientists devote a good deal of their time to designing novel research questions, devising well controlled experimental strategies to address these questions, and writing proposals to secure funding for their research. In light of this, we developed a year-long proposal writing project to engage Biology majors in developing theoretical research proposals similar to the research plan component of an NIH grant, with guidance from a faculty mentor. One benefit of using this type of approach is that it does not require costly equipment, reagents or lab space.

While the use of a research proposal as a training tool for undergraduate students is not novel, an assessment of what students learn from this type of approach has not been carefully documented in the literature (Wolfson et al. 1996; Hunter 1998; Rammelsberg 1999; Oh et al. 2005; Schepmann & Hughes 2006; Blair et al. 2007; Colabroy 2011). In fact, a recent article reviewing the literature on writing-to-learn in science education has called for evaluating the impact of writing-to-learn practices (Reynolds et al. 2012). Here, we detail the structure of the proposal writing project we utilized to teach our students and provide data from assessments conducted to evaluate this project over a three year period.

Institutional Background

Drexel University is a private, urban, comprehensive research university. The Biology

Table 1. Timeline of theoretical research proposal related activities in the capstone course series.

Student Timeline	Week	Instructor Timeline
	1	Lecture on guidelines, designing a research question and doing a careful literature search.
	3	Lecture on managing references.
Mini-proposals due	5	Lecture on research ethics. Grade proposals.
	6	Match student groups with mentors.
Expanded mini-proposals due	10	Grade proposals. Review feedback from mentors and students.
	11	Lecture on specific aims and scientific writing. Address any group issues.
Specific aims due	13	Grade specific aims. Meet with individual student groups to discuss progress.
Background due	16	Grade background sections.
Abstract, background and specific aims due	20	Grade proposals. Review feedback from mentors and students.
	21	Lecture on experimental design. Address any group issues.
Experimental design due	23	Grade experimental design.
Draft of complete proposal due	26	Grade proposals.
Final proposal due	28	Grade final proposals and choose award winners.*

*The top three proposals are selected after review by both course instructors, and students from these groups earn a small prize at a ceremony for the senior students and their faculty mentors.

Department is part of the College of Arts and Sciences, and is currently home to 770 undergraduate Biology majors. At present, there are 15 tenure-track, research intensive faculty in the department, and 8 full-time teaching faculty.

Drexel employs the quarter system, with four 10-week terms per year. Most students take at least four courses per term. The quarter system is one approach in place to support Drexel's cooperative education (co-op) program. Students who choose to participate in co-op benefit from at least six months of full-time professional employment. Notably, only about 52% of all Biology majors participate in the co-op program.

METHODS

Course Structure

The proposal writing project is completed as part of the Seminar in Biological Sciences course series, which is a 3-course sequence (10 weeks per term) intended for senior undergraduate Biology majors. Each course in the sequence is worth two credits. In each of the three courses of the Seminar in Biological Sciences series, the class meets once a week for 110 minutes. Course sessions include lectures on project related topics (see Table 1), scientific seminars, career panels, and small group discussions (not shown). The courses in the Seminar in Biological Sciences series are directed by the authors, who serve as "course instructors." These instructors run the day-to-day aspects of the courses, instruct students about the basics of proposal design, grade assignments, and manage group issues.

Project Description

This project requires students to identify a novel research question of interest supported by relevant and current background information, and develop a proposal that justifies the research question, establishes aims to address that question, and describes specifically how those aims will be addressed experimentally. These proposals are written in self-selected teams of five students, with support from faculty mentors. We have chosen to use a group approach to allow students to benefit from collaborative group study (Oh et al. 2005; Petress 2004). Note that "faculty mentors" are distinct from course instructors, though both course instructors also serve as faculty mentors each year. Faculty mentors meet with student groups on a regular basis outside of class (usually once a week) to provide feedback and guidance on proposal development.

This project is intended to challenge students to further develop skills that they have obtained throughout their undergraduate career and to acquire additional skills (see Table 2). In class, students are given lectures on researching the literature, developing research questions, managing references, planning ethical experiments, designing specific aims, writing scientifically, and devising sound experimental strategies. Students are also provided

Table 2. Learning outcomes for the capstone research project.

Through the development of a theoretical research proposal, students will:
1. Demonstrate a strong understanding of biological concepts
2. Improve their critical thinking and problem solving skills
3. Gain experience with critically reading and reviewing the scientific literature in a specific area of interest
4. Further develop and enrich their skills in scientific written communication
5. Begin to learn about grant writing
6. Exercise their time management skills in planning and submitting each stage of the proposal
7. Build on their abilities to work as effective team members
8. Develop a relationship with a faculty mentor who will oversee group progress and provide helpful insight into the field of interest

with detailed descriptions of project-related assignments, and with the overall learning goals for the project.

The timeline of assignments and course instructor responsibilities with regards to the project are outlined in Table 1. In brief, the first 10 weeks are initially focused on identifying topics of interest. Project selection and matching of faculty mentors with specific groups are based upon "mini-proposal" submissions. Each group submits three mini-proposals that each include a novel research question supported by brief background and justification sections sufficient to allow a reader to understand the relevance and context of the question. Students are permitted to choose any biological topic of interest as the focus for these proposals. Course instructors choose one of these proposals for further development based on extent of initial proposal development, quality and originality of the ideas, and suitability of matching with faculty mentor interests. Course instructors then match selected proposals with faculty mentors. Working with their mentors, student groups then refine their research question, identify additional sources to support their ideas, and begin to expand their background section to support their research question. The second 10 weeks are focused on continuing to expand the background and justification of the proposal and devising three specific aims to address the overall research question. The last 10 weeks are focused on experimental design. The final submission includes an abstract, background section, research question, justification, brief description of specific aims, experimental design section, and at least 20 references.

As has been discussed elsewhere, it is essential to ensure consistency in grading when evaluating assignments of this type (Oh et al. 2005). As a result, we have developed rubrics to aid in our evaluation of student assignments. In addition, while each assignment is graded by one of the two instructors, all graded assignments are discussed by both instructors to further ensure consistency in grading, similar to what has been previously described (Oh et al. 2005).

Assessing Student Outcomes

From the 2009-10 academic year through the 2011-12 academic year, the project was assessed using a pretest/posttest student self-assessment design. Embedded in both pre- and post-project surveys were the same series of questions about the project. Most of these questions utilized a 5-point Likert scale to assess student comfort level with project related skill sets. All Likert scale options were defined with written labels to clarify each choice. An additional question asking about the number of faculty whom students felt understood their career goals used multiple choice responses. In the 2010-11 academic year, a Likert scale question was added to both the pre and post-project surveys regarding student comfort level with understanding laboratory techniques described in the literature. In addition, a multiple choice question was added to the post-project survey in 2011 to clarify the role that this project played in increasing the number of faculty that students believe understand their career goals.

Surveys were posted on the course learning management system. While the surveys were anonymous, it was possible to observe whether a student completed the survey. Students who had not completed the survey were contacted by email to encourage compliance. Of all possible students who could have responded, 88% complied with submitting the pre-project survey (270 out of 307 students who engaged in the project between the 2009-10 and 2011-12 academic years), and 89% of students complied with submitting the post-project survey (274 out of 307 possible students).

Assessing The Faculty Experience

Faculty were asked to complete a survey on their experiences with mentoring these projects. All faculty who had ever served as mentors for this project were surveyed once in 2012. This survey primarily used multiple choice questions with choices directed at addressing specific issues, including number of mentored groups, whether faculty benefited from interacting with these student groups, overall experience with the student groups, how this project has affected the number of students the faculty member interacted with, and whether the faculty felt that students met project learning goals. Faculty were also given the opportunity to provide additional comments. The survey was developed using Qualtrics (www.qualtrics.com). Responses were anonymous. Of all mentors engaged in the project in the 2011-12 academic year, 67% complied with completing the survey.

RESULTS

Since the 2008-9 academic year, 417 students have participated in this project in 81 distinct groups, and 21 faculty have served as mentors. Of the faculty involved, 13 have served as mentors for all four years that the project has run. Additional faculty who began mentoring in subsequent years have also mentored consistently. Only one faculty member stopped participating in this project as a result of leaving the university.

Table 3. Faculty perceptions of the benefits and negative aspects of mentoring student groups.

Benefit or Negative Aspect	% Response
I find it rewarding to teach students	75%
I find it rewarding to work closely with students	67%
I find it rewarding to work closely with students on this type of intellectual project	75%
I enjoyed talking with undergraduates about an area of research that was of interest to me	50%
Working with my student groups made me aware of a paper relevant to my research that I had not previously seen	8%
Working with my student groups was intellectually stimulating	67%
I developed new teaching strategies as a result of my interactions with a student group	8%
I enjoyed mentoring the students about career related issues in addition to mentoring them about their project	42%
The time investment was high	8%

When developing the project, we felt that it was important to allow students to choose the focus area for their own work to encourage student engagement, as has been described (Lewis et al. 2003). As a result, our student projects are quite varied in topic, for example, understanding viruses, basic cell biology, aspects of epigenetics, the underlying mechanisms of disease, organismal physiology, evolution, and effects of environmental changes on ecosystems. One challenge this approach raises is that it sometimes requires faculty to mentor groups on topics outside their area of expertise. Of note, faculty who responded to the survey generally had a positive experience (Figure 1), despite the time and effort required. The majority of responding faculty found it rewarding and intellectually stimulating to interact with students in this way, and few found the time investment to be high (Table 3).

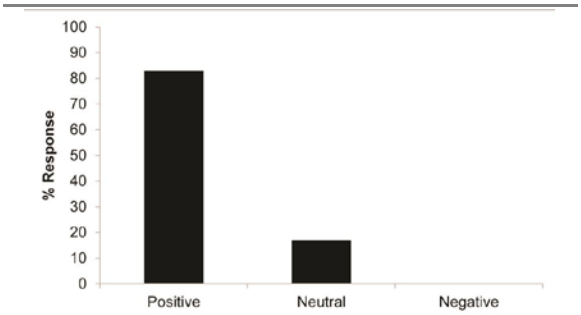

Fig. 1 . Faculty perception of their overall experience with mentoring student groups. Faculty indicated their average overall experience working with student proposal writing groups using a Likert scale ranging from 1 (Very Positive) to 5 (Very Negative). Data are reported as the percentage of faculty who chose positive, neutral or negative responses.

One additional benefit of this approach is that it provides students with another mentor with whom to discuss career related issues. A number of mentors indicated that they enjoyed this aspect of working with student groups (Table 3). As well, the number of students who feel as though they have at least one faculty member who knows their career goals increased by 14.7% by the end of the project (Figure 2A). Because it is possible that this change in student relationships with faculty could be due to factors outside of the senior project, on the 2011 and 2012 surveys we asked students whether the project was the reason why more faculty know them well. A majority (62%) reported that this was at least one of the reasons for the increased connection with faculty (data not shown). As well, the majority of faculty surveyed indicated that they have made more connections with senior undergraduates as a result of this project (Figure 2B).

In considering what students have learned through the use of this project, we asked students to self-assess their comfort level with intended project learning outcomes (Table 4). While students exhibited learning gains in all areas studied, the greatest gains were seen in their ability to design and develop an experimental research plan, and to propose a novel research question. Statistically significant gains were also seen in scientific writing, reading the scientific literature and conducting a literature search in Biology. At the end of the project, of the assessed outcomes, students were most comfortable with conducting a literature search in Biology, reading the Biology primary literature, scientific writing, and working as part of a group.

Table 4. Mean responses of student comfort level ± SD with important aspects of the proposal writing project.

	Mean Scores Pre-Project	Mean Scores Post-Project
Ability to work as part of a group	4.02 ± 0.07	4.12 ± 0.12
Conducting a literature search in biology	4.02 ± 0.23	4.45 ± 0.07*
Reading the biological primary literature	3.91 ± 0.16	4.28 ± 0.15*
Understanding techniques described in the biological literature#	3.81 ± 0.10	3.87 ± 0.22
Analyzing and synthesizing information in multiple primary research articles	3.74 ± 0.08	4.07 ± 0.21
Scientific writing	3.87 ± 0.10	4.25 ± 0.03*
Proposing a novel research question	3.31 ± 0.18	3.76 ± 0.02*
Designing and developing an experimental research plan	3.32 ± 0.12	3.80 ± 0.03*

Data were collected from pre and post project surveys from 2009-2012. Responses were on a scale of 1 (very uncomfortable) to 5 (very comfortable). #This question was added to the survey in 2010. *Two sample t-test, $p<0.05$.

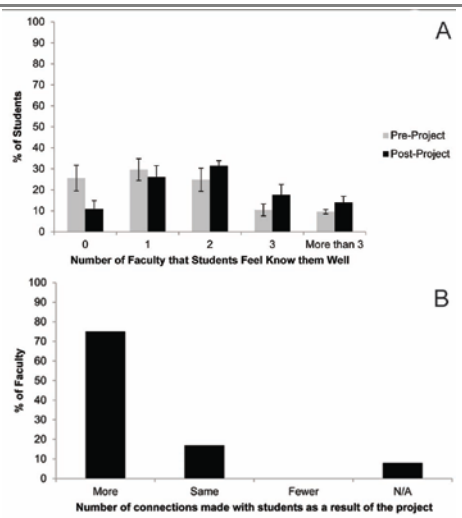

Fig. 2. Connections made between senior undergraduate students and faculty. (A) Students were asked to report the number of faculty that knew them well and understand their career goals on pre and post-project surveys given from 2009-2011. (B) Faculty reported the relative increase or decrease in number of connections they made with senior undergraduates since the inception of the project.

The majority of faculty agreed that students made gains with conducting a literature search, reading the literature, analyzing and synthesizing information from multiple articles, scientific writing, proposing a novel research question and designing and developing an experimental research plan (Table 5). Interestingly, while a majority of faculty indicated that they thought students gained knowledge in understanding techniques in the literature, there was no significant change to the students' perception of their comfort with this skill.

DISCUSSION

Through the implementation of this project, we have been successful in providing 417 students with a type of research experience that has been generally well received by both faculty and students. Notably, with the number of department faculty we have, space limitations, and costs, we would not have been able to accommodate this number of students in traditional undergraduate research experiences. While students do not engage in bench work through this project, they certainly engage in scientific thought processes, namely designing novel research questions, justifying their ideas logically, and devising experimental aims to address their research question. Thus, we have provided all of our graduating Biology majors with an opportunity to engage in a type of research experience through this project.

Students gained comfort with a variety of skills through this project. The skills with the most gains included the ability to propose a novel research question and the ability to design and develop an experimental research plan. Because these skills are not formally taught elsewhere in the curriculum, it is not surprising that students felt least comfortable with these skills at the beginning of the project. Importantly, though, this project allows students to gain competence in these areas. The skill sets in which students had the highest confidence level at the end of the project included the ability to conduct a literature search in Biology, read the Biology primary literature, write scientifically, and work as part of a group. Because these skills are taught in a variety of contexts throughout the Drexel Biology curriculum, it is not surprising that students ended the project feeling most comfortable with these skills. What is notable is that despite learning about these skill sets elsewhere in the curriculum, this project still had an effect on student learning in these areas.

The areas where students had the least gains were in their ability to work as part of a group, and in their ability to understand techniques described in the literature. Because Biology majors engage in group work extensively throughout their undergraduate career, this is a skill set that students have experience with prior to the project. Therefore, it is not surprising that students do not appear to make significant additional gains as a result of this project. However, the finding that students do not make

Table 5. Faculty perceptions of student learning gains. Faculty were asked to select the learning gains in which they saw student improvement as a result of the project, from this list.

Skill	% Response
Ability to work as part of a group	33%
Conducting a literature search in biology	83%
Reading the biological primary literature	75%
Understanding techniques described in the biological literature	83%
Analyzing and synthesizing information in multiple primary research articles	75%
Scientific writing	75%
Proposing a novel research question	75%
Designing and developing an experimental research plan	83%
Professional networking	8%
Creative thinking	58%
Critical thinking	58%
Ethical reasoning	8%
Self-directed learning	58%

Table 6. Suggestions for establishing this project.

Mentoring	*Approach:* • Supply mentors that provide feedback on proposal development. *Benefits:* • Regular meetings with mentors enable significant progress. • Provides another opportunity for student:faculty connections. *Strategies that Work:* • Allow mentors to focus solely on discussing proposal content and development. • Establish guidelines for effective interactions with mentors. • Ask mentors to evaluate their groups once per term, allowing instructors to address emerging issues.
Group Work	*Approach:* • Have students work together in groups of five students. *Benefits:* • Group work has cognitive and affective benefits (Petress, 2004). • Larger numbers of students can be mentored by using this approach. *Strategies that Work:* • Consider group size (Petress, 2004). Larger groups have more issues with group dynamics. Smaller groups may need additional mentoring to complete the project effectively. • Ask students to consider common issues of incompatibility during group formation, such as: times they are available to work together, group work style, and topics of interest. • Ask students to evaluate the efforts of their group members once per term, allowing instructors to address emerging issues.
Grading	*Approach:* • Establish a system in which assignments meeting stated requirements earn a grade in the A range. *Benefits:* • Emphasizes a focus on the quality of the product generated instead of on numeric grades. • Acknowledges student effort. • Avoids discouraging groups that struggle with the difficult process of grant writing. *Strategies that Work:* • Use a four-point scale: Unsatisfactory – does not meet requirements; Good- has significant issues with the writing, logic and/or scientific approach; Very Good – has an issue with one of these elements; Excellent – excels in all aspects of proposal writing. • Though most students earn grades in the A range, a majority become exceptionally invested, going beyond expectations for the project.

significant gains in their ability to understand techniques was a surprising result. As course instructors and mentors who have worked closely with a number of student groups, we have both seen firsthand that students learn a lot about experimental approaches through this project. Our faculty colleagues seem to agree, in that 83% reported that they believed students made gains in their ability to understand techniques (Table 5). One possible explanation for this student outcome may be that it is a metacognitive issue. Students' initial perception, that they are at least comfortable with understanding techniques, may change as they are asked to make use of these techniques in their aims and experimental design. By the end of the project, we believe students have gained skills in their ability to understand techniques, but by acquiring these skills, they gain a much clearer perspective of what they know and do not know. Another possibility is that the students' perception of their understanding of techniques does not change throughout the year because of a belief that the only way to learn techniques is by gaining hands-on experience. We may be able to better understand this outcome by asking one or more follow-up questions about their understanding of techniques on a future survey.

It also came as a surprise to us that so many students felt as though no faculty knew them well at the beginning of the senior year (Figure 2A). This is problematic from a programmatic perspective, because the success of a program depends on students' ability to find employment or to enroll in a professional school program. If students do not have a faculty member that they can confidently ask for a reference, it is unclear whether they will be successful in achieving these goals. While it is undoubtedly important that students make an effort to develop relationships with faculty, a program must also provide opportunities for students to work closely with faculty. This is a challenge in programs that have a medium to high student:faculty ratio. These data suggest that this project is one mechanism that can help to address this challenge. By the end of the senior year, the number of students reporting that no faculty member knew them well declined significantly, and the majority of students indicated that this project was at least one of the reasons why that was the case.

While we describe the use of this project in the Biology Department at Drexel, we believe the format of this project could be used in a variety of departments and institutions. Though Drexel is on the quarter system, this project took place over 30 weeks,

and could be adapted for use in a semester school by adjusting to two 15-week terms. The format of a proposal utilizing a research question and specific aims is certainly not specific to Biology. As a result, this format should be generalizable to use in other disciplines. We have found that there are some factors that are useful to consider when implementing this type of project, and we outline these in Table 6. Most importantly, over the past four years we have observed a high level of engagement from students participating in this project. It is common to see students talking enthusiastically about their project with their peers and the faculty, and we believe this level of engagement is one of the best aspects of this project.

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