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Engaging Early-Career Students in Research Using a Tiered Mentoring Model

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Abstract

Incorporating research into undergraduate curricula, especially at an early stage, has been linked to improved critical thinking, intellectual independence, and student retention. This results in a graduating population more ready to enter the workforce or graduate school. Similarly, mentoring has been linked to enhanced self-efficacy, persistence, and desire to pursue graduate studies. We have designed two linked courses that engage second-year undergraduate students in developing self-directed research projects, proposal writing. These courses also serve to nucleate relationships with graduate student mentors enrolled in the companion course. Early-career undergraduate students, with no previous research experience, receive formal training in the process of scientific research from a faculty process mentor while working with a graduate student content mentor to develop an independent research project and write a proposal and embed themselves in an active research group. Undergraduate students may elect to submit their proposals for funding to continue the project, either as part of the upper division research course required for graduation or independently. Graduate students enrolled in the companion course gain experience in mentoring through formal training and actively mentoring early-career undergraduates. This chapter presents both the model and early assessment of our integrated approach to engaging early career undergraduates in developing and funding independent research projects with the support of empowering mentoring relationships.

1. Introduction

Engaging in undergraduate research as been shown to increase confidence, intellectual independence, and intrinsic motivation to learn, in addition to gains in research and critical thinking skills, clarification of career choices, and creating a more sophisticated understanding of the process of scientific research (1–11). Potentially even more impactful are early undergraduate research experiences, which have been shown to influence student attitudes about science, shape career choices, and increase retention in STEM (12). Longer-term research experiences lead to the development of higher-order scientific thinking skills, greater independence, and students taking more ownership of their projects (4, 5). Research experiences are especially influential for traditionally underrepresented students (10, 11). In

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many departments, undergraduate research experience has become a degree requirement and is often a requirement for graduate school admission (13). Because of the benefits, the landmark Boyer report recommends that universities make undergraduate research experiences standard for all students (14).

However, there are challenges inherent to implementing methods that provide a meaningful research experience for each undergraduate student (2, 9, 15–17). Finite faculty resources limit the number of students that can be provided meaningful experiences, especially if more students are engaged in research for a larger fraction of their undergraduate careers (18), and when faculty directly mentor undergraduate research projects (17). This is especially the case when engaging less experienced students who require more mentor effort to become productive researchers (15). Thus balancing these tensions is the challenge of engaging early-career undergraduates in meaningful research on a large scale.

Course-based models have recently emerged as an efficient way to engage large numbers of students in research with similar learning outcomes to the traditional research lab-based experiences (12, 19–22). Course-based research experiences have also been reported as more inclusive for underrepresented groups may not be aware of research opportunities and may be less likely to be selected or self-select for the more traditional research experiences (7). Students may also value these course-based experiences because they allow them to complete a research experience with the same finite time commitment as required for a typical lab-based course (22).

Effective mentoring is another critical component that has been linked to students' learning gains during research experiences, creation of scientific identities, and retention in STEM (10, 11, 23). Tiered mentoring effectively reduces the faculty effort required and is already routine, either formally or informally, in many research groups. Principle investigators interact with postdocs who, in turn, take on daily mentoring and interaction with graduate students and, sometimes, undergraduates. Hutchison and Atwood describe a tiered mentoring system for recruiting early career students into their research laboratory to work with graduate students. Benefits to undergraduate researchers identified include: developing fundamental research skills, authorship on presentations and publications, as well as knowledge of how a research lab functions, the importance of selecting of realistic goals, and the improved ability to integrate research and course material (24). Dolan and Johnson (2010) further explored these faculty-graduate student-undergraduate researcher relationships and note that graduate students and postdocs are perceived as being more accessible than faculty. The primary role of the faculty is to initiate mentor pairs, establish the tone of mentoring relationships and serve as a mentor and role model. They state that "*Postgraduates are likely to have unique and important effects on undergraduate protégés*," highlighting the importance of near-peer mentoring (15). Peer mentoring and developing cohorts strengthens students' sense of a learning community and builds links within this community, which are critical to persistence in STEM, especially for underrepresented groups (25, 26).

2. Approach

2.1. Motivation

In this chapter, we describe a course-based model using tiered mentoring to facilitate early career undergraduate research. The model described is a hybrid of similar programs (17, 19, 24, 27) adapted to suit our needs. The Department of Chemistry and Biochemistry at the University of Alaska Fairbanks is relatively small with 15 faculty, ~1 postdoc, ~12 graduate students, and about 12 undergraduate degrees are conferred annually. For years, 1–2 semesters enrollment in a junior/senior-level research course has been part of the graduation requirements and the benefits of early entry into research are widely recognized by faculty. However, efforts to facilitate undergraduate research experiences for earlier career students have been stymied by finite faculty resources as many faculty directly supervise undergraduate research projects.

Our goals in developing a research course for early career students were to: 1) facilitate early-career student entry into independent research, 2) improve student readiness in terms of productivity and outcomes in the required junior/senior level research course, and 3) make research experiences available for more students without increasing the load on faculty. We defined the early career target population as being students who have taken one lab course after general chemistry (usually either organic or analytical).

2.2. Strategy

In order to accomplish these goals, we created a pair of courses that complement the existing 400-level course (Figure 1), a 200-level Introduction to Chemical Research, targeting early career students, and a companion 600-level Mentoring in Chemistry course for graduate students [syllabi available on the course website (28)]. The classroom setting allows for the systematic scaffolding of research project development and formal training in scientific ethics, which are often not explicitly taught despite being essential for good science (29). Graduate students also benefit from systemizing their knowledge of research practices and gain both formal mentoring training and experience.

Throughout the semester undergraduate students are guided through systematic development independent research projects and proposal writing with the mentorship of graduate students. Upon successful completion of the course, undergraduate students will have developed an independent research proposal targeting a specific funding opportunity available on campus. These proposals can be submitted, if the student desires to continue the project, and the research would then be performed the following semester.

In this model, there are two faculty involved in directly or indirectly mentoring both the graduate student and early-career undergraduates enrolled in the courses (Figure 2). The course instructor serves as the “process mentor,” guiding both students through systemizing the process of doing research and, in the case of the graduate student, in mentoring. The class-based, one-to-many knowledge transfer minimizes the faculty time required to convey broadly applicable material. The faculty advisors of graduate students enrolled are the “content mentors,” whose time with students is focused project-specific skills. The faculty “content mentor” may or may not interact directly with the undergraduate student, depending on the norms in the research group.

The graduate student (or post-doc) enrolled in the course is both a mentor to the undergraduate students with whom they work, and also as a mentee of both the course instructor and their faculty advisor. Graduate students provide support for both the content and the process to their undergraduate mentees. They attend the undergraduate lectures and “labs” with their mentees, which allows them to offer maximum support to their mentees. In this way, the course structure provides a specified time for mentors and mentees to work together in a concerted manner, shortens the feedback loop, and facilitates critical discussion and skill transfer. Graduate students are not encouraged to meet with mentees outside of class hours, so the lab time is when students work together, which helps to manage both undergraduate and graduate student expectations of the course.

Graduate students also participate in a weekly mentoring discussion groups based on the Entering Mentoring curriculum (30) adapted to directly integrate with the undergraduate course. Thus, the graduate students receive formal instruction and support in mentoring the undergraduates from the course plus a venue to discuss challenges and celebrate milestones achieved with their mentees. This discussion-based course builds peer support between the mentors and gives them freedom to explore ideas and challenges away from the undergraduate students.

The undergraduate student receives the benefits of making connections with three potential mentors during the development of their research project (two faculty and one graduate student). The most important of which is their graduate student mentor, who guides both the content and process of developing their research project. This gives the undergraduates the opportunity to not only have the support of their peers in their course, but also imbed themselves into an active research group by attending group meetings and working in an active research lab.

2.3. Introduction to Chemical Research

In Introduction to Chemical Research, the undergraduate and graduate students participate together in 1 hr. lecture and 3 hrs. lab per week. Lectures incorporate active learning and small group activities, generally mentor-mentee groups, as well as whole class discussion. Topics at the beginning of the semester focus on developing a research project because students need to get started as early as possible in order to write a fundable proposal by the end of the semester. During this project development stage of the course, “lab” time is dedicated to the mentor-mentee pairs working in a focused manner on developing their research proposal based on whatever topic was covered in lecture (Figure 3). Lecture topics include: available undergraduate funding opportunities, surveying primary literature, stating testable hypotheses, experimental design, and other required proposal components (budget, figures, etc.). For much of the semester, “lab” time occurs in the computer lab creating dedicated time for mentors and mentees to work together crafting their research project. Mentors and mentees sit side-by-side performing literature searches, discussing ideas, planning experiments, etc. Milestone assignments, due throughout the semester, focus on developing materials that can be directly incorporated into the final proposal (i.e. literature review, testable hypotheses, project goals, and experimental plan). There is extensive revision of written work incorporating several cycles of revisions based on feedback from their graduate student mentor, the course instructor, and their peers. Later in the semester, while proposals are being reviewed and revised, formal discussions of ethical and philosophical aspects of science, guided by the course textbook, *On Being a Scientist* (31), are conducted.

2.4. Introduction to Mentoring Chemical Research

In Mentoring Chemical Research, graduate students are expected to systemize, refine, and articulate their approach to mentoring students in all phases of an independent research project. Students attend and actively mentor undergraduates during the Introduction to Chemical Research lectures and "labs," receive professional development at weekly mentoring discussion groups, and develop and deliver portions of the undergraduate course.

The mentoring discussion group, based on the Entering Mentoring curriculum (30), is also a venue used to discuss topics and situations specific to Introduction to Chemical Research. These sessions included discussing case studies, reflecting on their motivations for mentoring, articulating a mentoring philosophy, and examining elements of good mentoring. The course also develops strategies for recognizing and resolving challenging situations in positive ways, exploring resources and tools available facilitate clear communication, and fostering strong relationships.

Graduate students also develop and deliver two pieces of content as part of Mentoring Chemical Research, a lecture that they deliver to the class and a lab rotation activity for undergraduates. Students select a lecture topic and develop materials, including required active learning activities, over the course of several weeks with the support of the course instructor prior to delivery to the class. The instructor meets with students two weeks prior to delivery to discuss a detailed outline of the lecture time and again one week prior to review instructional materials. This ensures that students are properly supported, deliver a quality product, and have a positive learning experience while realizing the large amount of work involved in developing good instructional materials. At the beginning of the semester, graduate students are also asked to develop a lab rotation, in which they take a few undergraduate students in their research lab to participate in a 3-hour experiment. The graduate students are encouraged to use instrumentation and incorporate as many aspects of the research lifecycle as possible so undergraduates can get some exposure to what the process of doing research in a particular area is like prior to being paired with a mentor.

Benefits to graduate students enrolled in this course include refining their understanding of scientific research, developing mentoring skills with the formal support and structure of a course environment, and contributing to the professional development of maturing colleagues. These mentoring relationships have the potential to last beyond the semester, be intrinsically rewarding and generate results for the graduate student's thesis project. Additionally, students gain instructional experience that can help them clarify the next steps in their own career trajectory and build their CVs. The course instructor also interacts with each graduate student extensively and provides written comments to each graduate student at the conclusion of the course detailing their work and progress, which can later serve as the basis of letters of recommendation.

2.5. Challenges

2.5.1. Misaligned Research Interests—Mentees are strongly encouraged to work in a content area aligned with their graduate student mentor's expertise, but may not always want to. One good way to address this issue is to recruit graduate students who have interests that are well aligned with the interests of undergraduates enrolled. Undergraduate interests are easily assessed by emailing enrolled students prior to the beginning of the semester to inquire about their interests. Most undergraduates who have limited research experience are usually flexible about their area of research. However, if the undergraduate student is determined to investigate a question outside of their mentor's expertise, it is essential that they engage a content mentor outside of the course. Perhaps this is a faculty member who would like to work with a student but who does not have a graduate student working on the project who wants to enroll in the graduate course. The graduate student mentor role then becomes facilitating the undergraduate's project development in concert with the external content mentor's input. However, this is not an ideal situation because the feedback loop is generally too large for optimal progression and should be avoided.

2.5.2. Recruiting Graduate Students—Recruiting graduate students is much more challenging than recruiting undergraduates, partly because they are a smaller population and partly because the benefits of participation are less clear for graduate students. I believe the ideal ratio is 2 undergraduates in Introduction to Chemical Research per graduate student enrolled in Mentoring Chemical Research. That way the undergraduates can support each other and each student gets ample attention from the mentor without overwhelming the graduate students. Actively recruiting graduate students several months in advance is critical to having good ratios and good alignment of interests at the beginning of the course. I talk to graduate students I believe would be good mentors individually and point out the benefits of the course. I also mention if one of the undergraduate students enrolled has closely aligned interests. It is also good to have a few graduate students or post-docs willing to step in at the last minute, if needed, to address changing undergraduate enrollment.

3. Assessment

The following assessment is based on the analysis of the 2015 and 2016 offerings of the courses, which had a combine enrollment of 11 undergraduates and 6 mentors (5 graduate students and 1 postdoctoral fellow).

3.1. Introduction to Chemical Research

Both qualitative and quantitative data have been collected to assess the effectiveness of this course model. As stated on the syllabus, the desired learning outcomes of the Introduction to Chemical Research include:

1. Provide formal training in research ethics, the scientific method, and experimental design.

2. Increase student research skills by developing an independent research project, performing preliminary experiments, and writing a proposal.

3. Improve student readiness for Chemical Research in terms of productivity, and outcomes.

Overall students really enjoyed this course with 100% agreeing or strongly agreeing with the statement “I like the Introduction to Research course” and 91% agreeing that “I would recommend this course to my peers.” Less formally, there was a lot of interest in the course from enrolled students and from the upper division Chemical Research course, which were both taught by the same instructor in Spring 2015. Below are a few representative quotes from enrolled students that capture the essence of the course:

> “This class is an introduction to a whole new world... Having our own project seemed liberating and encouraged me to learn and succeed.”
>
> “I actually felt like I was part of a team effort. I felt like I was contributing to the field as a whole, in a tiny way.”
>
> “Lab time was very effective, although it was not a typical lab”
>
> “This class was excellent… there was a lot of information targeted to a part of chemistry that is not taught in any other class this information is extremely helpful, almost do I dare say essential. Suggestion: make it a core requirement for CHEM.”

3.1.1. Formal Training in Research Skills—Student competence was assessed using a 15-item questionnaire delivered at the end of the semester in which students were requested to rank themselves on a scale of 0 to 5 (low to high) at the beginning (retrospective-pre) and end (post) of the course. Mentors also responded to the same questionnaire, evaluating their mentees competence at the beginning and end of the course. Items in the survey are listed below followed by the figure abbreviation in parentheses:

1. The nature of science and research *(NatSci)*
2. Developing a research project *(DevProj)*
3. General research skills *(GenRes)*
4. Searching literature *(LitSea)*
5. Reading journal articles *(Read)*
6. Using reference management software *(RefMgr)*
7. Developing a hypothesis *(Hypothesis)*
8. Developing and writing procedures *(Procedure)*
9. Keeping laboratory records *(Records)*
10. Writing a proposal *(Proposal)*
11. Working collaboratively with your mentor *(Collaborate)*
12. Familiarity with job duties of a researcher and graduate student *(Grad)*

13. Receiving feedback from your mentor *(Feedback)*

14. Providing feedback to a peer *(PeerRev)*

15. Presenting a research project *(Presenting)*

In order to account for the nested data (questionnaire item nested in time, nested in ranker, nested in student), a random intercept multilevel model was applied using the *nlme* package in R (version 3.4.1)..

Averaging all items and time points, the analysis indicates that students and mentors do not report statistically different levels of competence, $F(1,10)$, = .00001 p, < 0.998. This indicates that the mentee's self perceptions of learning gains generally agreed with the mentor's observations. These results contrast with previous results, where researchers found that faculty observed total learning gains were nearly twice those of undergraduate mentees and the only category with students' self-perceived learning gains were higher than faculty perception by even a small margin, was "skills" (3).

Examining student overall competence gains by combining all questionnaire items in Figure 4, regardless or ranker, indicates the initial average competence was 2.0 with an average gain of 1.7 (t(21 = 14.29, p. < .000). Thus, participation in the course increases perceived student competence, which adds credence to unanimous student agreement with the statement "I learned new skills and developed a research project."

Item by item analysis at the two time points indicates a much greater spread in the incoming level of student competency level, as judged by averaged student and mentor evaluations (Figure 5). However by the end of the course, the spread of individual competency indicators is much less. This is interpreted to indicate that whatever readiness level students arrive with in each category, they are able to increase competency in all areas to a similar level of mastery. Items with the lowest initial competencies (e.g., reference management software, records keeping, and proposal writing) improve the most over the course of the semester and items with higher initial competency levels improve, but to a lesser degree (F(14, 558) = 3.10, p. < .001). Simultaneous analysis (e.g., the 3-way interaction) of student competencies, ranker, and time did not yield statistically significant results.

3.1.2. Develop Independent Research Projects—Increasing student research skills by developing an independent research project, performing preliminary experiments and writing a proposal was a central course goal and motivation for developing the course. All students who successfully complete this course write proposals formatted for the internal University of Alaska Fairbanks RFP most appropriate to their research. Of the 11 students who have completed the course, 7 have submitted proposals and all of those have been awarded funding through several different competitive processes. The average funding rate for undergraduate proposals to these calls is ~50%, it is quite noteworthy that all 7 proposal submitted have been funded.

As one mentor noted of their mentee's development throughout the proposal development process:

"Through a few rounds of edits, I observed a significant improvement in the way he articulates/coveys information and intent in his writing. I think he had experience reading research articles before, but hadn't gone into [the] specifics of hypothesis driven [research]… The deeper we dove into the science, the better he was able to articulate his questions. His understanding of the subject matter really came through in his writing"

This quote highlights the degree of scientific maturation instigated by engaging students in undergraduate research.

3.1.3. Student Readiness for Chemical Research—One of the main departmental motivations for developing a course and facilitating earlier student entry into research was to improve the quality of projects performed as part of the 400-level Chemical Research course, a graduation requirement. Because of the short time (1–2 semesters) most students devote to fulfilling this requirement, students rely heavily on mentor support for project ideas, research design, and data analysis. Faculty perception is that there is simply no time for students to make mistakes or struggle or research problem solutions themselves if they are to complete their projects successfully within the allowed timeframe. There was simply not adequate time for students to develop higher-order scientific thinking skills and become *proficient technicians*, let alone become *knowledge producers* in the terminology of Feldman *et al.* (4, 5). The general consensus amongst faculty was that earlier student engagement in research would encourage students to take ownership of their projects, be more likely to present or publish their work and gain more research skills and confidence in their abilities.

All students who have completed the course agree "I feel more prepared for CHEM 488 [Chemical Research]." At the end of the first course offering, 50% of students planned to take Chemical Research the following semester, although only 25% actually enrolled. Student tracking has proved to be challenging, but it is clear that several student projects conceived in Introduction to Chemical Research have been carried forward in collaboration with their mentors, and, in many cases, independent funding.

Overall, this course has been successful in training undergraduates in the process of doing research as well as in supporting undergraduates to develop fundable, independent research projects. The mentoring relationships with graduate students were critical to the success of this course in terms of student experiences and faculty effort. Many undergraduates reported that working with their mentor was not only a highlight of the course, but also critical to their success in learning new skills and successful project development.

3.2. Mentoring Chemical Research

The graduate course focuses primarily on professional development for the graduate students. Specifically, the goals for Mentoring Chemical Research course were:

1. Receive formal mentoring training and experience within a structured course environment.
2. Design and deliver instructional units, including a lab experiment and a 1-hr lecture on a course topic of their choosing with instructor support.

Graduate students also benefited from attending the Introduction to Chemical Research because it gave them the opportunity to refine and articulate their understanding of the process of designing and executing a research project. All students agreed with the statement "this course has refined my own research skills." Below are several quotes from graduate students expressing the impact of this course on their own research skills:

> "I learned a number of things about the scientific process and mentoring skills."

> "I've had to go back to some basic concepts in order to teach and this has strengthened/tightened up my knowledge base."

3.2.1. Formal Mentoring Training and Experience—The success of the formal mentoring training can be judged by the unanimous agreement with the statement "I learned new skills as a result of working with my mentee and the mentoring discussion group." Several graduate students also responded to a prompt about their favorite thing about the course as being the mentoring discussions, demonstrating the value students place on these peer interactions. One student put it:

> "I really enjoyed discussing strategies with my peers. I think by talking through problems and bouncing ideas off each other we improve our mentoring efficacy."

This highlights the value of the peer mentoring and cohort development in the discussion group, which has been previously recognized (26).

Students also highly value the experience of mentoring undergraduate students. Many of the comments on the end of semester evaluation related to how many useful tools they learned and that it gave them much greater confidence in their mentoring abilities. As one student shared, "*this was a great first-time mentoring experience that I felt taught me a lot about catering to different mentees.*" Another student comment revealed the importance of the dedicated lab time to their experience:

> "I think the course and lab times were effectively spent, and I especially likedtheflexibilityoftheuseoflabtimesforimportanttasksandteaching/mentoring"

These results point to the value of integrating the Mentoring Chemical Research, focused on building mentoring skills and developing an identity as an mentor, with the Introduction to Chemical Research, where the mentors can directly practice their mentoring in a supported, structured environment.

3.2.2. Instructional Materials—By all accounts, developing and delivering the lab rotations and lectures were valuable experiences for the graduate students and they all produced very high quality materials. The time devoted to the content in student-delivered lectures were ranked as "about right," a similar assessment as for most of the instructor-delivered content. The class was also asked to provide feedback to the graduate students on their lectures, which was overwhelmingly positive.

Graduate students also highly valued the experience of developing instructional materials, especially the lecture, which one student voluntarily identified as their favorite assignment. Several students, noted that the most surprising benefit of the course was "*practicing* *lecturing*," and "*greatly increased teaching and mentoring skills*." All students strongly agreed that preparing and delivering a lecture should remain a graded portion of the course. I hope that these experiences developing instructional materials will help graduate students evaluate their next career step analogously to the way research experiences influence and clarify undergraduate career choices (1, 3).

3.3. Nucleating Lasting Mentoring Relationships

Although not explicitly stated as a goal for either course, it was hoped that some of the mentoring relationships initiated in these courses would persist beyond the semester. Effective mentoring has been linked to improved research outcomes, as well as creation of scientific identities, and retention in STEM (10, 11, 23). Thus, we hoped to initiate mentoring relationships in which both parties saw the mutual value and that would formally or informally persist, regardless of if the research project also continued.

The mentoring relationships were clearly valued by both the graduate and undergraduate students, as was expressed informally throughout the semester and beyond. More measurable was the unanimous agreement of graduate students with the statement "I liked working with my mentee," and that 63% reported plans to continue working with their mentee at the end of the semester. All mentors evaluated their mentee's performance as either excellent or above average, indicating that these experiences were perceived to be of high quality.

In reality, roughly 50% of the mentoring relationships persisted beyond the course and research projects facilitated the continuation most, but not all, of these relationships. As summarized by this student, who responded to a prompt on the best part of their research experience was "*the relationship formed with the mentor*."

4. Conclusions

The paired-course model described here uses a unique tiered mentoring approach to foster early career undergraduate engagement in developing independent research projects. Both qualitative and quantitative measures indicate that undergraduates increased their scientific research skills and developed fundable projects. Graduate students also refined their understanding of the process of developing a research project in addition to developing mentoring skills with the support of formal training in a peer discussion group. The empowering mentoring relationships nucleated in this course are clearly valued by both the graduate and undergraduate students as indicated by their persistence beyond the course. All together, this course-based model efficiently facilitates the professional development of both undergraduate and graduate students involved.

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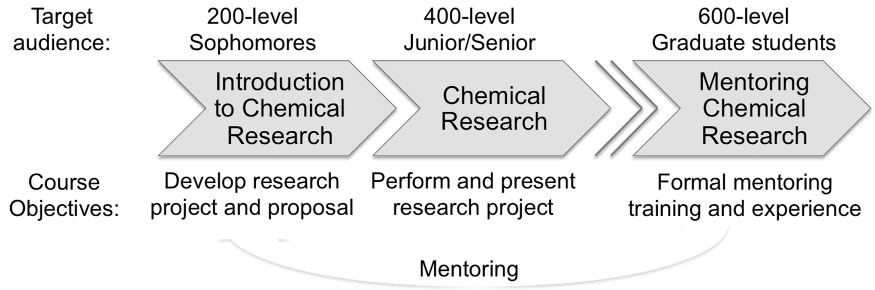

Figure 1.

Course progression, demonstrating how the paired courses surround and support the research course targeting advanced undergraduates, which is a graduation requirement.

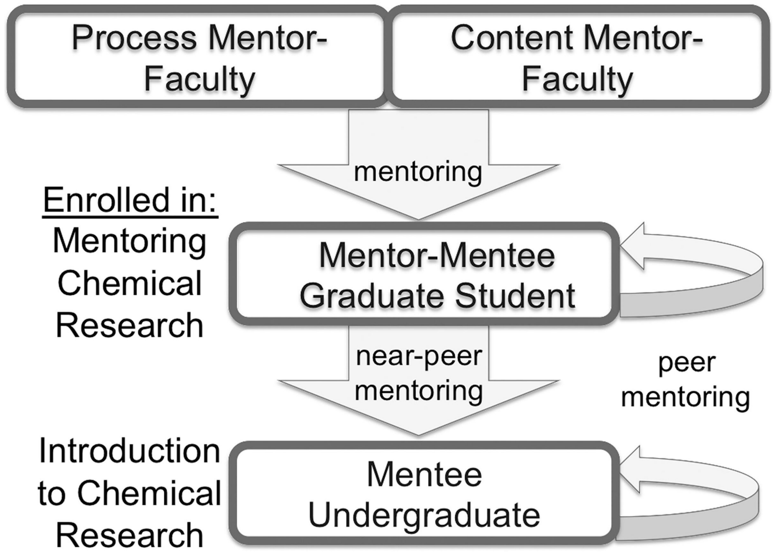

Figure 2.

Theoretical framework of tiered mentoring model as applied in these paired early-career undergraduate introduction to research and graduate-level mentoring courses.

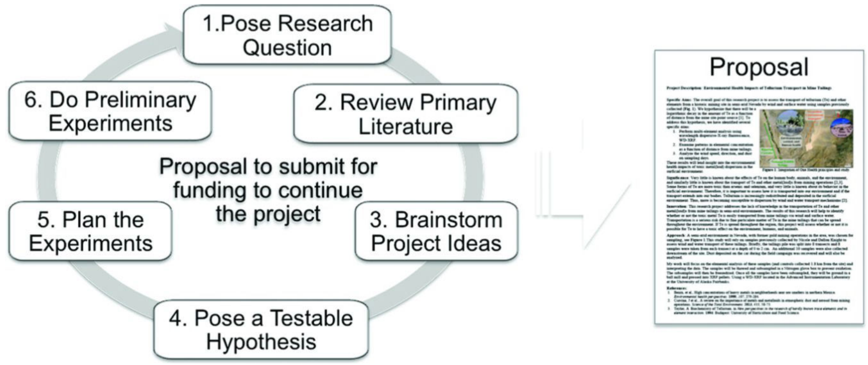

Figure 3.

Undergraduate students engage in and drive all aspects of developing a research project, which are covered in lecture and lab. The final course outcome is a proposal that can be submitted for funding to continue the project.

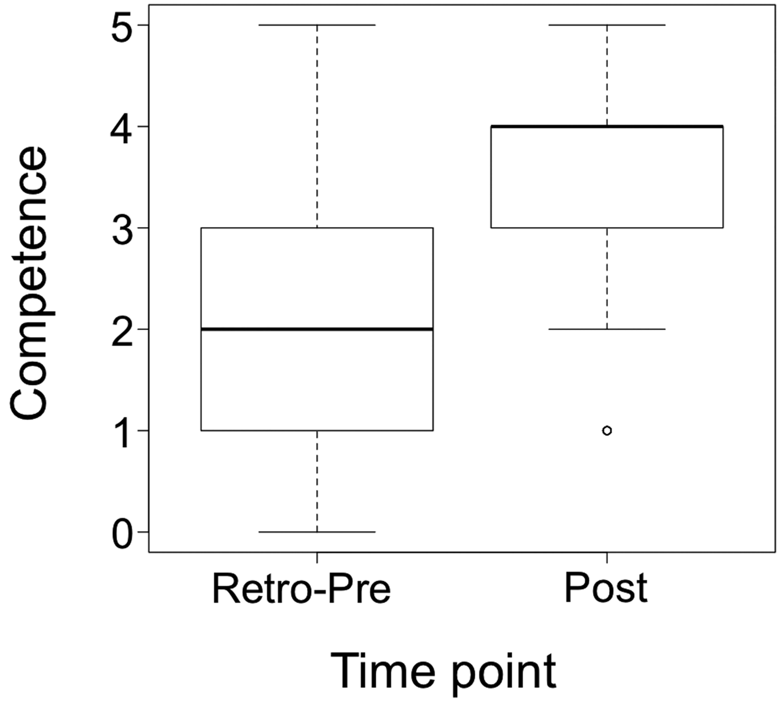

Figure 4.
Student perceived competence increases substantially throughout the semester. This plot averages all student competence questionnaire items reported by both the student and mentor.

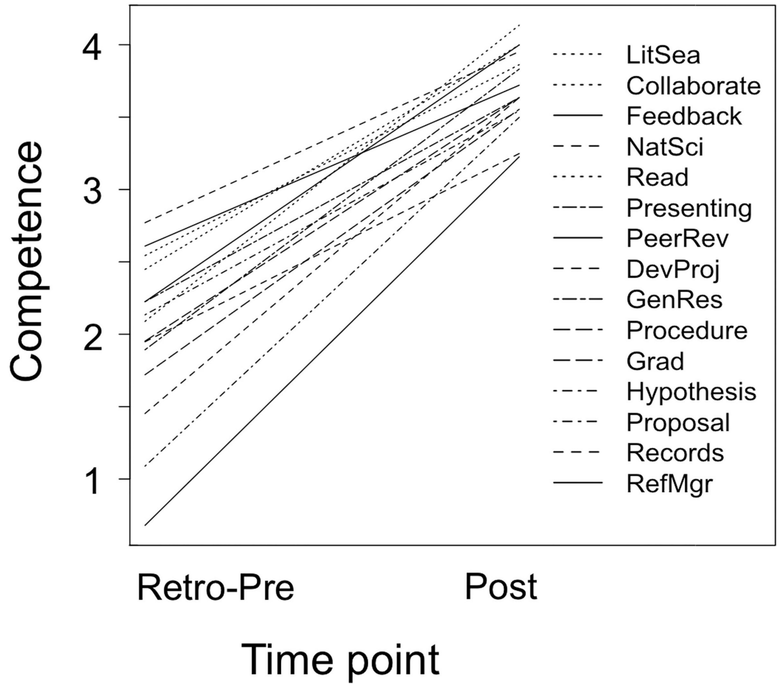

Figure 5.

Individual competence items ranked by the student and mentor increase substantially throughout the semester. However, the items with the lowest initial competency increase the most while items with higher initial competency increase less over the course of the semester. Items are listed in the legend in the order that they appear in the graph at the post time point. Item abbreviations are listed at the beginning of section 3.1.1.