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Semester-Long Course-Based Research Project in Second-Semester Organic Chemistry: Synthesizing Potential Lead Compounds for the Treatment of a Neglected Tropical Disease

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A Semester-Long Course-Based Research Project in Second-Semester Organic Chemistry: Synthesizing Potential Lead Compounds for the Treatment of a Neglected Tropical Disease

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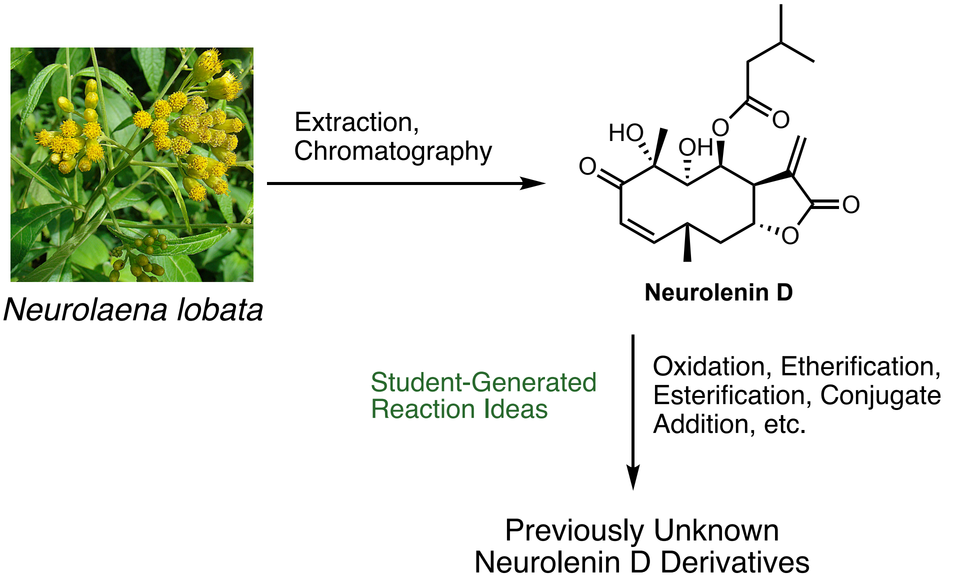
ABSTRACT

A semester-long research project for second-semester Organic Chemistry lab sections was developed. Student projects were based on preliminary data from faculty research that suggested the natural product neurolenin B to be a treatment for lymphatic filariasis. Students isolated neurolenins from the Central American plant *Neurolaena lobata* and proposed syntheses of previously unknown analogs using reactions learned in first- and second-semester Organic Chemistry. Using literature-based procedures, students ran reactions on neurolenins and analyzed their results by TLC and NMR spectroscopy. The semester culminated with a public poster session and final report using the *Organic Letters* template. Students in a total of five lab sections over three different semesters of the class completed this pilot course and 15 sections in the same time span conducted traditional lab experiments. Qualitative and quantitative assessment data were collected to demonstrate the efficacy of the course. Students did not self-select into the pilot sections, were demographically similar to those in the traditional lab sections, and performed at the same level in the lecture portion of the course. Survey results from all students (traditional and pilot) were compared and the students in the pilot sections showed higher levels of self-reported topic understanding, general motivation, and interest in organic chemistry.

ABSTRACT GRAPHIC



KEYWORDS

Second-Year Undergraduate, Organic Chemistry, Inquiry-Based/Discovery Learning, Testing/Assessment, Natural Products, Student-Centered Learning, Undergraduate Research

INTRODUCTION

Undergraduate research is one of the most powerful pedagogical tools to educate and inspire students, especially those from diverse backgrounds.[1] Many science faculty do an excellent job working one-on-one or with small groups of students on independent projects in their research labs.[2] Research students are often third- or fourth-year students who are selected by faculty members because of top performances in advanced classes. Providing a meaningful undergraduate research experience for students enrolled in introductory courses is a more challenging prospect.[3] However, this is the time in students' educational paths when a research experience could be valuable for a variety of reasons. It is known that early research increases student persistence in STEM disciplines.[4] Repetitive exposure to research over an extended period during undergraduate education has measurable benefits.[5] Early exposure to research fosters student ownership over the material.[6] Additionally, required course-based research was shown to foster student diversity in senior research experiences.[7]

Guided inquiry and discovery-based labs are excellent examples of implementing research-type problems in introductory courses. These activities allow students freedom to experiment and even fail while trying to answer interesting questions. They are an important stepping-stone on the path from “cookbook” experiments to independent research. Incorporating actual research into undergraduate laboratory courses is a pedagogical advance aimed at improving students’ learning and exposing more students to research.[8] Course-based undergraduate research experiences (CUREs) vary from introductory to advanced classes, from modules over several weeks to a full semester, and from community colleges to liberal arts colleges to research universities.[9] Hallmarks of these types of courses include setting the research question in context, providing a true sense of discovery where neither students nor instructors know the outcome of experiments, fostering student ownership over the research experience, and providing opportunities for experimental iteration.[9-10] Furthermore, CUREs promote scientific communication among students and between students, instructors, and other scientists, and usually incorporate presentations to an external audience, often via a poster session.[9a]

A variety of CUREs have been developed for differing levels of chemistry labs, from high schools through advanced undergraduate classes.[11] Some CUREs focus on pieces of a much larger, often national, research project[11] and others are tailored to the research of the faculty member teaching the course.[12] Implementation has ranged from large enrollment introductory classes[11, 13] to smaller individual lab sections,[12a, 12b] or majors only courses,[14] and includes various chemistry subdisciplines.[9-12] Assessment results are generally very positive and rely on students' attitudes and perception of their learning.[11-14]

Focusing on undergraduate organic chemistry classes, there are a variety of inquiry-based and simulated research experiences for introductory[15] and advanced courses.[16] In recent years, several examples of CUREs have been reported and illustrate the viability and effectiveness as an educational tool for introductory organic chemistry education.[12, 17] Considering students' limited laboratory experience, course design for introductory labs is a major challenge. Additionally, the time constraints of lab courses and the number of students enrolled in the course pose potential obstacles. Courses previously described focus on using a multicomponent reaction to make tetrahydropyrans,[12c] developing green chemistry alternatives to traditional reactions,[17b] synthesizing metalloprotease peptide inhibitors,[12b] using solid-phase combinatorial chemistry to synthesize aromatic oligoamides,[12a] and designing and synthesizing peptides with antimicrobial activity.[17a]

The challenges and previous successes of CUREs for organic labs were inspiration to design a CURE-based Organic Chemistry lab that exposed students to research in a second-semester Organic Chemistry course. There were two main goals for the course design. The first initiative was to design a course that provided a genuine independent research experience closely related to current faculty research in the department. A second goal was to compare student outcomes from a CURE based lab experience versus a traditional topic-based lab course. These aims led to specific research questions: What will students gain from the research experience? How will students perform in the lecture portion of the course? How will student results impact independent research in faculty research labs? Answers to these questions could motivate instructors at other institutions to adopt similar semester-long research experiments in Organic Chemistry teaching labs.

COURSE BACKGROUND AND DESIGN

Smith College is a primarily undergraduate institution for women with 2,500 students, and more than 40% declare a major in the sciences. The chemistry sequence involves one semester of either General or Advanced General Chemistry followed by first-semester Organic Chemistry. Students are co-enrolled in lecture and lab as one course for the General and Organic Chemistry classes. First-semester Organic Chemistry covers an introduction to organic compounds, followed by spectroscopy, then carbonyl and alkene reactions. Topics in second-semester Organic Chemistry include substitution and elimination reactions, oxidation reactions, radical reactions, carbonyl α-substitution reactions, cycloaddition and electrocyclic reactions, aromaticity, and reactions of benzene. Most students in second-semester Organic Chemistry are first-semester second-year students. Typically, 80-110 students are enrolled in two sections of lecture and there are seven lab sections with enrollment capped at 16 students. Over three different semesters, a semester-long research project was piloted in one or two of the lab sections per semester. The remaining lab sections followed a traditional lab curriculum focused on conducting experiments on topics closely linked to lecture content. The traditional lab experiments were well documented (detailed procedures/instructions) and had known outcomes. Overall, there were five pilot lab sections and 15 traditional lab sections, providing robust numbers for comparison between student outcomes. To avoid self-selection issues, students were not notified in advance about the research-based lab sections. All the lab sections were given the same course code making them undistinguishable to students during course registration. Analysis of the demographics of enrolled students in the pilot sections vs the traditional sections verified proper similarity to enable comparisons, see Table 1.

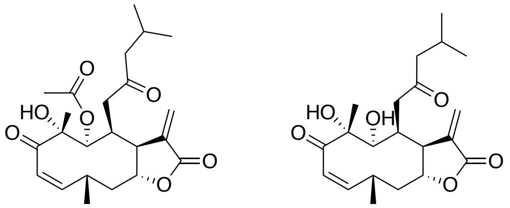
Table 1: Student Demographic Data in the Pilot Labs Compared with the Traditional Labs

	Students, %, by Lab Section	
Demographic Parameter	Pilot Lab (n=62)[a]	Traditional Lab (N=185)[a]
First Generation[b] Students	17	23
International Students	14	16
Students of Color[c]	50	40
White Students	35	44
Students Offered a Pell Grant[d]	26	25
Second-Year Students	76	72

a) No significant differences were found between pilot and traditional lab students for each of the demographic measures (Chi-square test, p-values > 0.05). b) First generation is defined as neither parent having a bachelor's degree. c) Students of color include U.S. residents whose heritage is Asian American, African American, Native American, Hispanic/Latinx, and Hawaiian/Pacific Islander. d) A Pell Grant is need-based federal financial aid to help undergraduate students from low-income families pay for college tuition.

PROJECT BACKGROUND

The research idea originated as an undergraduate honors thesis project with the broad aim of addressing neglected tropical diseases.[18] The focus was on identifying new treatments for lymphatic filariasis, a disease that afflicts over 120 million people in tropical areas of Africa, Asia, and the Americas.[19] Extracts of the Central American plant *Neurolaena lobata* have demonstrated antifliarial activity,[20] and the goal was to identify the molecule responsible for this bioactivity. Following literature precedent,[21] impure samples of neurolenin B and D (Figure 1) were isolated, and the former showed promising antifilarial activity in an assay that measured the killing of lymphatic filarial parasites in culture.[22]



Neurolenin B

Neurolenin D

Figure 1: Structures of Neurolenin B and D

RESEARCH PLAN

To build on the exciting bioactivity of neurolenin B, the project goal for the second-semester Organic Chemistry lab course was to produce analogs of neurolenin. There are no literature reports of the synthesis of neurolenin analogs, and generation of new molecules would subsequently enable evaluation of their biological activity. This potential for bioactivity provided a good way to introduce students to some ideas and motivations within the field of medicinal chemistry. In first-semester Organic Chemistry, students spend more than half of the course studying carbonyl and alkene reactions, so they are well positioned to propose reactions to modify neurolenins. Considering the allotted three hours of lab time per week a course timeline was developed (Table 2). Isolation and purification took four weeks (see Supporting Information for details). Students prepared for the proposal in week five and then presented their proposed reactions to the class in week six. The next six weeks were spent carrying out the proposed reactions. Finally, a group poster session presented to the broader Smith science community was held in week 13.

Table 2: Week-by-Week Outline of the Laboratory Course Components

Week	Experiment	Additional Details
1	Soxhlet Extraction	Introduction to course and overview of research project
2	Charcoal Purification	Extra time in lab was used to train students in Scifinder Scholar.
3	Column Chromatography	Purification of crude extraction mixture to yield impure neurolenin D
4	NMR spectroscopy	Proposal ideas were turned in and instructor assigned a project from student ideas.
5	Analysis of NMR spectra	Proposal drafts were turned in.
6	Proposal Symposium	Students turned in final proposals and presented a short talk on proposals.
7-12	Independent research projects	Poster drafts were due in week 12.
13	Poster session	Paper drafts due and final paper due two weeks after.

IMPLEMENTATION

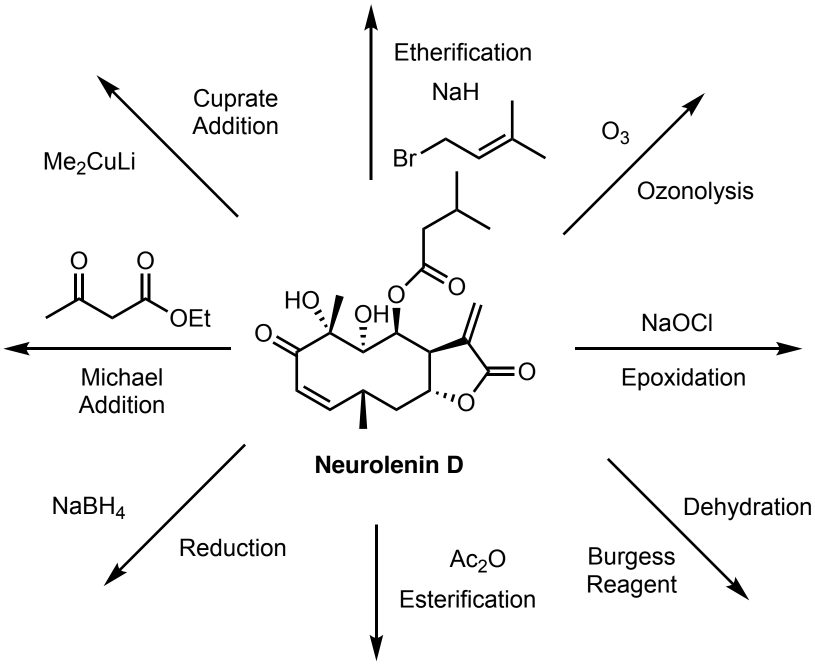
The initial lab meeting began with an introduction to the project and a demonstration of how to use a Soxhlet extractor. Students chose a partner and then the project pairs set to work extracting crushed, dried leaves of *Neurolaena lobata* with methylene chloride. After student extractions were set-up, the instructor provided a seminar style overview of the project focusing on the latest research findings. The next three weeks consisted of charcoal filtrations, flash column chromatography, and NMR spectroscopy. Except for the lab devoted to column chromatography, there were significant blocks of time when students were not actively conducting experiments. These breaks provided the necessary time to discuss experimental techniques, database searching, and potential project ideas. The extra discussion time in the early weeks of the course were a critical component of the course design.

During the second lab session, students were introduced to SciFinder Scholar and the Web of Science to help them find literature precedent for the proposals. The instructor taught strategies for efficient substructure searching, for example using a substituted cyclohexenone as a structural stand-in for the conjugated enone in neurolenin. Students were also instructed to search for cited references after a lead paper was identified to check the reproducibility of an experimental procedure.[23]

The first semester Organic Chemistry lab provided useful introductions to NMR, TLC, and standard techniques; however, students had much to learn to succeed in this lab. They had to quickly learn flash column chromatography to successfully isolate approximately 150 mg of neurolenin D from 200 mg of crude material. Students were introduced to flash chromatography by three different methods. Prior to the second lab session, students were given a three-page handout detailing the experimental steps (see Supporting Information) and were asked to watch the MIT OpenCourseWare Digital Technique Video on column chromatography.[24] (Students also used other helpful MIT videos for first exposure or review of common techniques like refluxing a reaction, TLC analysis, reaction work-up, rotary evaporation, and recrystallization.) During the second lab session, the instructor prepared a column according to the handout instructions. This gave students an example of exactly what to do in the next lab session and provided an opportunity to ask questions about the procedure. The students successfully completed the chromatographic purification to separate neurolenin B from neurolenin D,[25] but other impurities present were observed in the NMR spectra (see Supporting Information). Despite the impurities, the students continued with the project.[26]

During weeks two and three, each group proposed three possible reactions of neurolenin D based on first- and second-semester Organic Chemistry reactions. (The extraction and purification yielded significant amounts of neurolenin D (>100 mg) and only small amounts of neurolenin B (<10 mg), so efforts focused on the former.) The instructor reviewed student ideas with each group during the lab sections and ultimately approved one reaction per group. Groups were advised against hazardous reagents, complicated experimental conditions, or reactions being investigated by other students. Weeks four and five were spent refining proposals, finalizing literature procedures, and locating or ordering reagents. Thus, by the end of week five, all groups had selected different reactions, many from first-semester Organic Chemistry and some from second-semester Organic Chemistry.

The student pairs submitted proposals (see Supporting Information for an example) and presented their proposed reactions in week six as part of a class “symposium” on their research ideas. After each presentation, there was time to ask the presenters questions. This was a great way for the students to learn about the diverse chemistry that would be happening during the second half of the semester. Additionally, students gained experience preparing a presentation to communicate their research ideas. Examples of some experiments conducted in the course are highlighted in Scheme 1 (examples from all sections taught are included in the Supporting Information, Figures S1-S5). The students proposed a variety of reactions: Michael addition, cuprate addition, etherification, ozonolysis, epoxidation, dehydration, esterification, and reduction are just a few examples.



Scheme 1: Proposed student reactions of neurolenin D.

The first half of the course was demanding, and students sometimes spent more than the scheduled three hours per week in lab to complete tasks like filtration and solvent removal. Students spent many hours outside of lab searching the chemical literature and writing proposals. Students uniformly agreed that the pilot lab required more time than what was required of their peers in the traditional lab sections, though students in the traditional labs spent considerably more time on lab report writing.

The next six weeks focused on implementing the proposed reactions. This was an exciting time in the course; the students were running different reactions in hopes of making a molecule that had not been previously reported. The instructor treated this section of the course like a typical research lab and acted as the students' lab consultant. Instructors provided students with guidance on new techniques, regularly asked questions about project progress, and gave helpful suggestions when obstacles were encountered. Some of the neurolenin reactions looked encouraging by TLC, showing new spots with similar polarity. Other reactions did not work as planned, showing no reaction or decomposition of the starting material. Students with less promising reactions continued to experiment with different conditions; these students could run up to two additional reactions. Students were restricted to exploring only the proposed reaction, and with variations in reagents or reaction conditions, this provided ample opportunity for optimization. In the end, several reactions in each lab section appeared to generate new products. A major challenge at this point in the project was the inexperience of second-semester Organic Chemistry students in a research lab environment. They lacked experience running small scale flash chromatography and had limited exposure to analysis of complicated NMR spectra. To unambiguously determine the success of their reaction, the students needed more experience with these topics, especially 2D NMR which is introduced in the curriculum as part of upper-level elective courses.

For the example reactions shown in Scheme 1, the esterification, dehydration, and Michael addition reactions all provided promising TLC and/or NMR data and looked worthy of further investigation. Several of the students' reactions did not turn out as predicted. The unexpected outcomes highlighted the struggles and challenges inherent in independent research. Despite initial frustration, students with failed reactions soon accepted this as part of the authentic research process.

The conclusion of the course featured a full lab report using the *Organic Letters* template and a public poster session. Creating the poster and writing the paper yielded excellent academic products that helped students reflect on their semester of work on this research project and gave them practice in scientific communication. The quality of the posters and papers did not depend on the success of the proposed reactions. Students had much to communicate regardless of the research outcomes, including background literature, reaction mechanism, TLC and NMR data, and future directions.

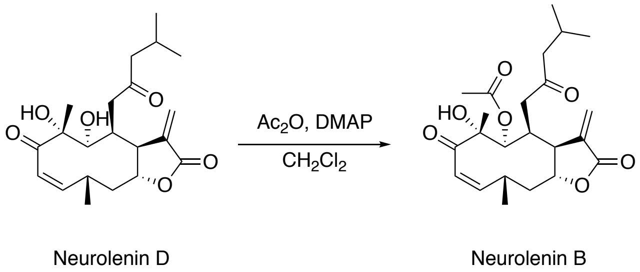
Teaching this class was a challenging and rewarding experience. Student enthusiasm and engagement were much higher than all other introductory or intermediate labs previously taught in the department. Some drawbacks were the occasional need to spend more than the allotted three hours of lab time and coordinating with the instructors who used the same lab space for a different course. Instructors of the pilot lab agreed that the time required to prep, teach and grade the pilot course vs the traditional course was comparable.

One key aspect of the course was the support of a student teaching assistant and a student prep assistant. The prep student was critical for setting up the lab with equipment and reagents prior to each lab section. The prep assistant worked closely with the instructor to order, organize, and prepare chemicals for each student research group. Selection of a talented teaching assistant who had independent research experience and required minimal instruction was vital to the success of the lab.

One concern about research-based labs is the potential higher costs versus traditional labs. The average cost in 2016 and 2017 for the traditional lab course was \$125/student. For the pilot course, there were significant up-front costs, but the running costs were less than the traditional lab. The largest expense was the purchase of 16 Soxhlet extractor set-ups (glassware and paper thimbles) along with the requisite heating mantles that cost a total of approximately \$4,000. For one section of the course with 16 students, consumables for the extraction and purification of neurolenins like dried *Neurolaena lobata*, solvents, charcoal, and silica gel cost around \$400 while reagents and supplies for the research portion were around \$800. Thus, the course cost about \$75 per student for each pilot section.

RESEARCH LAB BUILDS ON RESULTS FROM EXPERIMENTAL LAB

The experimental lab generated enough questions and ideas to spawn several undergraduate honors research projects related to discoveries in the pilot lab section. In the first year of the pilot lab, one group discovered that an acetylation reaction converts neurolenin D into bioactive neurolenin B (Scheme 2). This is especially useful since a reproducible method to obtain pure neurolenin D from *Neurolaena lobata* has been developed. Prior to the discovery of the acetylation, only trace amounts of neurolenin B were obtained directly from the natural source. Additionally, hydrogenation and other reduction reactions on neurolenins B and D were investigated first in the pilot lab section and then in the research lab. Some of the investigations in the research lab were conducted by students who began their work in the pilot lab and other projects were completed by students who did not run the initial reactions. All new neurolenin derivatives were subsequently evaluated for bioactivity against the lymphatic filariasis assay, and results from this interdisciplinary investigation will be reported in the future.



Scheme 2: Conversion of neurolenin D to neurolenin B.

RESULTS

Various methods were used to assess the outcomes of the pilot lab course and to address the stated research questions. Statistical analysis of students' overall grades in the course was used as a quantitative measure of overall impact. Lecture exams and final course grades of students in the pilot vs traditional labs were analyzed. There were no significant differences in the lecture grade outcomes (p-values>0.05). The results from comparison of lecture grades suggest that there was no significant impact on students' performance in the lecture class that correlates to the pilot lab. Additionally, students' involvements in research post-course were tracked to observe potential differences between students who were enrolled in the pilot lab vs. the traditional lab. With a strong culture of students conducting independent research already in place, significant gains were not expected. Post-course research was defined as participation in an independent course (typically consists of an independent or lab group project with a faculty member) or an honors thesis. Like the results shown with the lecture grade analysis, no statistically significant impact was associated with students' likelihood to pursue independent research opportunities after completing the pilot course versus the traditional lab (80% versus 73%, p-value>0.05). The significant impacts of the pilot lab section became apparent when analyzing the various surveys and evaluations that the student completed.

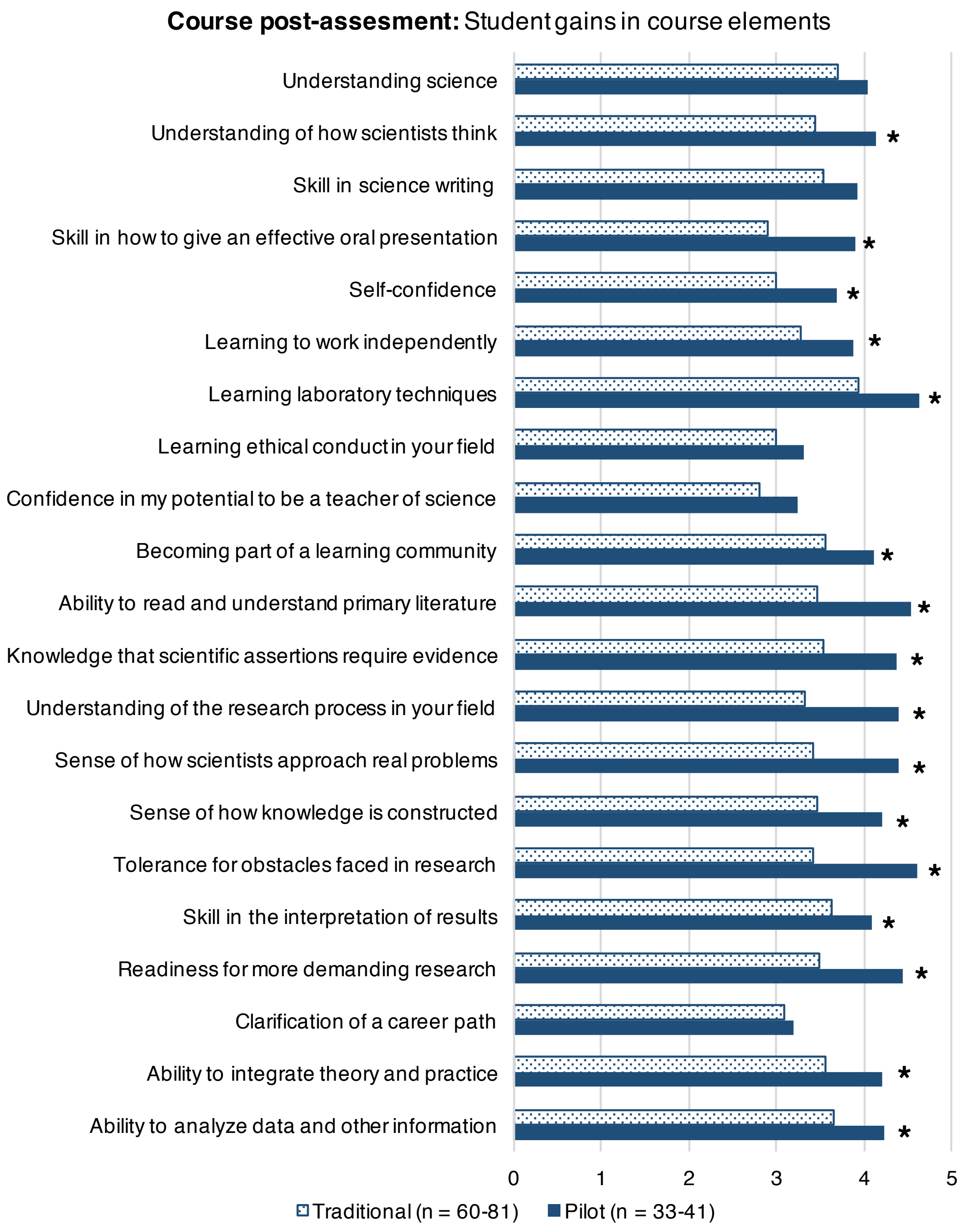
CURE Survey

CURE (Course-based Undergraduate Research Experiences) surveys were used to compare course student outcomes in the pilot lab vs the traditional lab. Over the three semesters, a total of 247 students were surveyed. Responses were collected electronically through individualized survey links embedded in an invitation and two reminder emails. The survey was open during the last week of classes until the end of the semester. Pilot students had a response rate of 65% compared to 50% of traditional lab students. Statistical analysis of the difference of mean scores for each survey item was conducted. An alpha level of 0.05 was used for all statistical tests.

The surveys were used as a method to address the concerns that students in the pilot lab may not get the same exposure to the lecture course material as those in the traditional course. The traditional lab provides a more direct means for students to reiterate and apply learned material from lecture. In contrast, the pilot lab involves more independent work and focuses on the project goals established by the students. The survey focused on student self-reported gains on knowledge of subject matter, course benefits, and perceptions.

Questions were developed focusing on several different outcomes: overall attitudes and confidence, general course topics, specific course content, and broader learning objectives.[27] Statistically significant increases for students in the pilot lab were observed for questions related directly to research, such as exposure to novel ideas and learning about scientific research (Figure **S6**). Pilot lab students reported higher ability to visualize organic molecules, identify reaction roles, and use mechanisms to describe selectivity (Figure **S7**). Students in the traditional lab reported higher ability to determine molecular structure from spectroscopic data, consistent with the larger emphasis on this topic in the traditional lab curriculum. Students in the pilot lab reported being more comfortable with reaction mechanisms, reactivity of alcohols, and reactivity of carbonyls (Figure **S8**). Both student cohorts were equally comfortable with the reactivity of aromatic compounds even though the traditional lab contained a two-week experiment on this topic.

Student responses to questions related to broader learning goals that are typical for a CURE survey are outlined in Figure 2.[1c] The results provide strong evidence toward the benefits of the pilot labs vs the traditional labs. Significant increased gains were shown for several of the broader learning goals. Students in the pilot lab reported greater gains in ability to analyze and interpret data, and in learning laboratory techniques. More specifically, questions related to research reported significant gains. Students also reported having a stronger sense of a learning community in the pilot lab. It is important to note the significance in self-confidence gain and presentation skills. In the pilot lab, students were required to give group presentations on their topics in a symposium and a poster session. There was no significant difference in science writing skills or understanding science.



375 Figure 2. Comparison of post-class benefits and learning gains for students in the pilot lab versus the traditional lab, part 1 (1 – “no gain” to 5 – “very large gain). *Statistically significant difference was found ($p<0.05$).

Lastly, the CURE survey results were analyzed to compare student responses with respect to their lab instructor. In the three semesters taught, there were three different faculty at varied levels of experience (full professor, associate professor and a post-doctoral fellow) who taught the course. There was no significant difference in students' responses based on the instructor (Figure **S9**). These results support that this type of course can be taught by instructors with varied experience and not affect the overall outcomes of the course.

College-Administered Course Evaluations

Completion of the college administered course evaluations yielded interesting qualitative and quantitative results. Using a 4-point scale, in response to the statement, "This course contributed significantly to my education," the average score for the pilot section with 51 student responses was 3.73 ± 0.55. The average score for the traditional lab sections with 168 student responses was 3.57 ± 0.55. This addressed a major concern expressed by many faculty thinking about teaching a course-based research class, "How will it impact my teaching evaluations?".[28] Overall, the student evaluations were overwhelmingly positive.

For the qualitative questions, responding to the prompt, "How would you describe your own efforts to learn in this course?", students talked about how much effort they put into this lab section. "Wow, I think I did too much work for this, but it all paid off!" Another open-ended prompt, "What features of this course made the most valuable contributions to your learning?", elicited comments about their ownership of the project. For example, "One of the greatest features of this course was that it was an independent lab project. Students had the opportunity to conduct their own projects." Finally, several students mentioned their desire for more structure in response to the prompt, "In what ways could specific features of this course be improved?" "More structure, more help for students, it's really hard to do research for the first time with no experience and therefore students should be supported more throughout the process."

Instructor-Administered Course Evaluations

In addition to the college-administered course evaluations mentioned above, the instructor-administered evaluations were distributed on the final day of class. Most of the students' responses provided useful and candid feedback. An overwhelming majority of them responded "yes" when asked, "Looking back, would you choose to be in this lab section if you were starting this course over again?" When asked about the "pros" of taking the course, students responded with:

- *Having the opportunity to do actual experimental research and learn chemistry in the context of real life applications*
- *It was really exciting to be doing reactions that weren't fully spelled out for us in a lab manual. We were able to explore reactions that were interesting to us, and I felt really invested in my group's project.*

The "cons" of the course included:

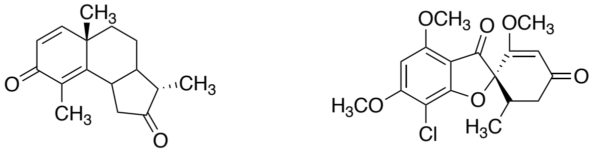
- *Being almost completely oblivious to the work done in the regular lab sections, and this may have helped understand concepts in lecture*
- *This lab definitely took more time than a normal class lab.*
- *Less practice writing lab reports*

It was very reassuring to have the students echo our thoughts on both the pro and con sides of offering the course. We believed the pros greatly outweighed the cons and from all the student feedback we received, they agreed with this opinion.

Two other open-ended questions were asked. Student responses to “Comment on the impact of investigating a novel problem versus your traditional lab experience in Organic I.” and “What will you take from this experience as you move forward at Smith?” were very inspiring. Students wrote about exactly the sorts of things we imagined they might when designing the course: embracing failure, learning perseverance, developing practical skills, and working with others. It was clear from their narrative responses that this pilot course had a positive impact on these students.

FUTURE DIRECTIONS

The overall results of the pilot project were positive, though implementing this semester-long research project in all the second-semester Organic Chemistry lab sections will be logistically impossible. As mentioned previously, during the extraction and purification process, students regularly needed to perform lab work outside of regular class hours. Trying to accommodate these needs across all sections in only two lab rooms (one that is used by the organic course every afternoon of the week) would be overwhelming. Also, beginning with impure neurolenin D made a difficult experiment too challenging for many groups. The positive student outcomes explained above are motivation to modify this idea to provide all students with a research-based laboratory experience. Therefore, current discussions have centered around how to develop a version of this course that can be expanded to all the lab sections. The new version of the course will include a five-week, research-based module focused on synthesizing analogs of the natural products santonin[29] and griseofulvin[30] (Figure 3). These molecules are commercially available for less than $10/g and contain a variety of reactive functional groups. Students will be guaranteed to start with pure material and known spectral data. All second-semester Organic Chemistry students, not just those in the pilot sections, will propose and carry out reactions of their own design and will hopefully gain the benefits described for the neurolenin lab.



Santonin

Griseofulvin

Figure 3: Molecules for future research-based second-semester Organic lab experiments

CONCLUSIONS

The efficacy of a course-based research experience in a traditional second-semester Organic Chemistry lab was demonstrated. Based on direct comparison of student performance and survey results between traditional lab sections and the pilot research section, students in the pilot sections reported greater perceived understanding of course topics and learning goals, and larger gains on most topics related to broader course and research-type goals. Student narrative responses also highlighted the positive learning gains associated with the course. Furthermore, the students made real progress on the scientific goal of conducting reactions on neurolenin D in hopes of generating molecules to treat lymphatic filariasis, and they have followed up on these results in faculty research labs. We hope that instructors at other institutions are inspired to implement similar pilot research projects in their organic teaching labs.

ASSOCIATED CONTENT

Supporting Information

Class handouts; Experimental details for the isolation and purification of neurolenin D and synthesis of neurolenin B; Reactions attempted by students; Sample student proposal; Sample student papers and supporting information; Figures for survey results (PDF)

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26. We subsequently learned to purify the neurolenin D fraction by recrystallization to yield pure, colorless crystals. Starting with 34 g of dried plant material, we obtain 72 mg of pure neurolenin D. In the future, we will perform recrystallization during week 5 in the experimental lab section.
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