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Undergraduate Research as Generative Metaphor: A Provocation

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Abstract

Students who engage in research as undergraduates appear to achieve many benefits compared to those who do not. But scaling up undergraduate research is challenging and faces inherent limits. Are there ways to achieve some of the benefits for students not directly involved in faculty research? Generative metaphors help us to view problems in a different frame, thus setting the problem differently and inviting different kinds of solutions. This article proposes using research as a generative metaphor for classroom learning and invites readers to rethink teaching and learning in light of what seems to work for undergraduate research.

Keywords: generative metaphor, undergraduate research, framing, re-framing

The Power of Undergraduate Research

Bruce Alberts (2000) was president of the National Academy of Sciences when he reflected on the beginnings of his own career:

> Essentially every scientist whom I know remembers being utterly bored by the cookbook laboratories common to college biology, chemistry, and physics courses. My own experience is typical. After two years as a premedical student, I could stand these required labs no longer. I therefore petitioned out of the laboratory attached to the physical chemistry course at Harvard, seizing on an opportunity to spend afternoons in my tutor's research laboratory. This experience was so completely different that it soon caused me to forget about applying to medical school. Within a year I had decided to go to graduate school in biophysics and biochemistry, in preparation for a career in science. (p. 6)

Looking at the process from the other end, Carl Wieman, a Nobel laureate in physics, reflects on his work with highly successful graduate students in his own research lab:

> Over the years I became aware of a consistent pattern. New graduate students would come to work in my laboratory after 17 years of extraordinary success in classes, but when they were given research projects to work on, they were clueless about how to proceed. Or worse—often it seemed that they didn't even really understand what physics was. But then an amazing thing happened. After just a few years of working in my research lab, interacting with me and the other

> student, they were transformed. I'd suddenly realize they were now expert physicists, genuine colleagues. If this had happened only once or twice it would have just seemed an oddity, but I realized it was a consistent pattern. (2007, p. 10)

Those who have tried to look objectively at the question have confirmed that these anecdotes are telling us something important. Indeed, scholars who have looked at undergraduates involved in faculty research have found that it changes them in significant ways. Elaine Seymour, Anne-Barrie Hunter, Sandra L. Laursen, and Tracee Deantoni (2004) from the University of Colorado, after surveying students participating in undergraduate research, found that 91% of students could identify specific benefits they had gained. The researchers concluded that "undergraduate research is an educational and personal growth experience with many transferrable benefits" (p. 530). Much of the evidence, as the observations noted above, seems even to point to a transformative effect. Undergraduate research seems to change students in ways that often involve their underlying frames of reference.

But there is a problem. Obviously, everybody cannot participate in undergraduate research. The problem of scale is acute: too many students and too few research slots. Setting aside the issues of selection and assessment of potential student researchers, the numbers seem bound to keep such programs limited to a small minority of undergraduates.

We might well ask whether there is any way of extending the benefits beyond the fortunate few. I'm not sure. But here's a thought.

Generative Metaphor

Donald Schön (1980) grappled for years with the problems posed by getting stuck in a particular way of thinking, the challenge of "how we come to see things in new ways" (p. 255). One approach he suggested was generative metaphor, which he defined as "a particular kind of SEEING-AS, the 'meta-pherein' or 'carrying over' of frames or perspectives from one domain of experience to another" (p. 254). Generative metaphor thus can lead to "frame restructuring."

He offered this example to illustrate the point. A group of researchers was seeking to develop a paintbrush that relied on synthetic bristles. But the synthetic bristles could not seem to produce the same even distribution of paint that natural bristles did. The paint tended to go on in a "gloppy" pattern rather than smoothly. They tried several approaches to modifying the bristles, but none seemed to help. Finally, one of the developers made the observation "*You know, a paintbrush is a kind of pump!*" (p. 257). This was a generative metaphor. And it works because, of course, a paint brush is not a pump. But there is, at a certain level of detail, enough similarity to make the metaphor work. When we dip a paintbrush in paint, the paint is captured between the bristles, in the spaces that, if you squint a little, seem like the "channels" through which the fluid passes in a pump. Then when we apply the brush to a surface, the bristles bend, and this bending pushes the paint out from between the bristles, like a pump pushes out water through a channel.

The metaphor let the researchers see the problem differently. Thinking now of the channels between the bristles as little pumps, they again compared the natural and synthetic bristles, and they noticed something they had missed before: when the natural bristles were pressed against a surface, they formed a gradual curve, which "pumped" the paint out smoothly, and at a pace that responded to the pressure on the brush. The synthetic bristles tended to bend at more of an angle, thus pumping the paint out in clumps rather than a smooth flow. They now knew what they were looking for: a synthetic bristle that would bend in a continuous, gentle curve. Once they knew what they were looking for, they were able to find it.

By reframing a problem or an issue, generative metaphor brings different features to light or emphasizes different aspects of the object under review. In the case of the paintbrush example, "One might say that the spaces which had been background become foreground elements, objects of attention in their own right, as in a pump the contained space called a 'channel' is a foreground element with a special name of its own" (p. 258).

For Schön the foundational challenge in policy making was not problem solving but problem setting. This is a radically different way of thinking about problematic situations than the one we tend to convey in much formal schooling, where the problems are given and the whole operations of the student's mind are bent toward solving those problems, often using learned rules and algorithms. Schön is not referring to education, but he might as well be, when he notes, "If problems are assumed to be given, this is in part because they are all taken to have the same form" (p. 261). But this is nearly always an illusion: "Problems are not given. They are constructed by human beings in their attempts to make sense of complex and troubling situations" (p. 261). Our approach to those problems is shaped by the processes of "*naming* and *framing,*" often carried out implicitly through the stories we tell: "Things are selected for attention and named in such a way as to fit the frame constructed for the situation" (p. 264).

Generative metaphor can allow us to break out of the frames we have been given, or believe we have been given, and by naming what was invisible, to see options we have not seen.

The Research Metaphor

The idea of generative metaphor can't solve the problems of education, but it might help us to reframe and rename them. In the present instance, we cannot put every student in a classroom into an undergraduate research slot, but we can attempt to reframe classroom learning using research as the generative metaphor. What if we thought of the classroom the same way as we do undergraduate research? Like the paintbrush designers, we are trying to build something that works—in this case for educating students—but we are stymied. We are in part stymied by the materials—the students, in this case—but also by the way we frame and name the problem. These students are unmotivated, unprepared, uninterested, uninspiring. What can we do to get them to succeed? More jokes in the lectures? Easier tests? The paintbrush designers reached for a generative metaphor: a paintbrush is a pump. It's worth a try, no? A student is a researcher.

The generative metaphor does not solve the problem, it sets the problem in a different way by naming and framing the materials of the problematic situation. I do not propose to spell out in any detail what pedagogy would emerge from the reframing, but to sketch in very general terms one way such a reframing might look.

If we adopt the metaphor, we think about students in class, who are certainly not researchers, through the metaphor, as if they were researchers. What difference would this make? There are many possible answers, and many of them are right answers because different researchers emphasize different things and different research methodologies lead different places. But one way to get a rough start on how research would name and frame the learning process is by looking at surveys of students who have engaged in research or faculty members who have supervised it. The survey done by Elaine Seymour and her colleagues mentioned above provides a long list of characteristics of undergraduate research as viewed by students. David Lopatto (2003) of Grinnell College in Iowa has done a survey of faculty at three different colleges asking parallel questions. My goal here is to provide some suggestions for how we might use research as a generative metaphor.

Scanning the faculty and student reflections on undergraduate research projects brings up many things about research that differentiate it from what usually happens in the classroom. So, there are several different ways of naming and framing research as opposed to class-taking. I present one way of doing this as an example, with no hope of being exhaustive. I'll mention just four categories of characteristics that seem to emerge from the studies: autonomy, teamwork, faculty mentorship, and using learning to cope with novel problems.

First, autonomy. In Lopatto's survey of faculty at three different colleges, faculty at all three reported that "Students should work independently (of faculty) . . ." They said, "Students should feel ownership of the project; there should be increased independence in the daily routine and problem solving" (p. 140).

Apparently, this happens. When Seymour and her colleagues asked students how the experience affected them, a frequently mentioned benefit was the increase in confidence in doing the work on their own. One female biology major reported, "At the beginning, I asked a lot of questions to get a good basis and a good idea when I didn't really know what I was doing. By the end of the summer, I didn't speak to my advisor so much, because I would just do it" (p. 508). A male biochemistry major said, "I now feel confident that I can walk into any room with any instrument and figure out how to make that instrument work" (p. 508). A male biology major said, "When you're faced with kind of a novel problem when there's no right answer yet, and you have to find the right answer, I think research does a good job of teaching those skills. Because you don't have anything to go back and rely on . . .you're having to do it yourself" (p. 512).

Many students contrasted the research experience with the classroom experience, often in the context of doing it yourself. For instance, a female chemistry student noted, "I think it comes with hands-on work, because as a student you're handed this as fact . . . and you don't question that. But what you find out in research is that a lot of things that people have found out need to be questioned" (p. 514). Research experience leads to students questioning, testing, and relying on their own abilities in a way that seems, to them, to contrast with their experience in the classroom.

But, second, if research leads to increased autonomy, it also seems to contribute to more teamwork. That might seem anomalous. But here is how the teachers in Lopatto's study finished the sentence about student independence: "Students should work independently (of faculty) and have an opportunity to work on a team (of peers)" (p. 140). The two are related. The student who feels empowered to shape her own thoughts is also more confident sharing them, and testing them, with others. Seymour, et al., reported that working integrally with other students/researchers "was, to most students, a new experience that . . . involved reappraisal of their accustomed ways of relating to classmates. It included the pleasurable sense of 'belonging to a community' of like-minded individuals who are working toward similar goals and discovering their intellectual strengths" (p. 510). There seems to be a dynamic with research teams that brings people together, perhaps around their perceived weaknesses or needs, but then keeps them together through their discovered strengths. A male physics major, reflecting on the reliance he developed with his lab partner, said, "I think if we were alone, we just couldn't have mustered the strength to go on with it because it's so open-ended and so overwhelming—to not have someone else to talk to would have made it very difficult" (p. 511). The support of peers makes it possible to safely question your own approach. A female chemistry major, reflecting on the weekly lunch meetings with the whole team, noted, "that provides time for insight . . . maybe they're thinking about this problem a different way from you" (p. 511).

Third, both of these factors, autonomy and teamwork, affect students' thinking about their relationship to faculty members. Faculty supervising students in research apparently want them to think and act independently, as indicated above. The one other faculty-related outcome that the teachers in Lopatto's study mentioned was "establish a mentoring partnership between student and faculty" (p. 140). What is the difference between a mentor and a teacher? That may be a productive question to pursue in several contexts, but in the case of undergraduate research, it was summed up by a male biology major in Seymour's study: "I've gotten to know all the faculty. . .. I actually see them more as peers. As a researcher, they are your peers; you're working with them. And you ask them questions, and they are just as excited to know what I'm doing as I am to know what they're doing, or what they could help me with. . .It gives a totally different aspect than being a student. . .And you don't have to be intimidated by them anymore" (p. 510). Whew! What a relief that must be!

One of the gains students reported in Seymour, et al.'s survey was "increased confidence in 'feeling like a scientist,'" and most frequently reported reason for that increase was "because of being taken seriously by others" (p. 507). One male psychology student reported, referring to a faculty mentor, "He said he's learning as much from us as we are learning from him. . .During our semester meetings, he'll start taking out his notebook and start writing down things we are saying. . .It feels just great when someone takes me seriously, or takes my work seriously" (p. 510). A mentor is someone who takes you seriously, who respects you, at some level, as a contributor or potential contributor to the work.

Fourth, research appears to bring out the ability to apply learning to novel problems. Faculty in Lopatto's survey said that students learned to "construct meaningful problems" and "apply knowledge to a real situation" (p. 141). In a way, research involves students in what Schön calls problem setting, rather than just problem solving. Constructing a hypothesis and a research design requires that we define the nature of the problem. Indeed, much research in many fields is quite self-consciously about framing the problematic situation as a necessary step toward describing the conditions of a solution. This is because research problems are novel problems in the sense of not being pre-formatted and pre-described. In undergraduate research, both students and faculty, of course, report that students learn the subject matter that is the object of the research. But that seems to be in the context of constructing and troubleshooting a new problem using prior knowledge. One female chemistry student in Seymour, et al.'s survey said, "I think there's only so much you can get from classroom learning . . .You get into the lab and you say, 'Okay. This should work.' No, it doesn't work! Because there are so many other considerations you have to make. And that's the kind of thing you can get only from research" (p. 513).

Students frequently mentioned learning to correct their own mistakes: "It really does help to learn to detect your own dumb mistakes" (p. 513). And they often discussed this in the context of planning and designing the research. Students saw both self-correction and planning as things that they could apply beyond the research domain, but that seemed to be clarified in a powerful way through the research process. One female biology major commented, "Just learning how to plan, learning how to be careful, how to take care of mistakes, and recover from mistakes. I think that's something you can apply to any field" (p. 513). Another said, "Just thinking about things completely, and trying to think of all the possibilities before you plunge into things. So that if you're designing an experiment you want to know ahead of time, 'What are all the possible things that could happen?' and, 'How would you explain each result?' And I think that's something I can use in other areas, too" (p. 513).

So, research for some students, more than a few, has the effect of re-framing science itself, and perhaps thinking itself. One female chemistry student put it this way: “Well, intellectually I think that it’s helped me to understand chemistry better. Not just the chemistry that I happen to be doing in the lab, but also chemistry as a whole. . .And learning how to look through the primary literature and to really synthesize and understand the information about the project has helped me to better understand other areas of chemistry and pick things up more quickly” (p. 515). Several students reported that research helped them to take a larger view, to see the details in a fuller context.

The Provocation

If we take the generative metaphor of research seriously, how would it change the way we teach? How would it change our relationship to students, and students’ relationships to each other? If we think of the student as a researcher, how would we do things differently, even if the student was not in a research lab? Some of the answers to these questions are obvious and are widely discussed in the SoTL literature. But if we take the questions seriously, I suspect that they will provoke quite different ideas from different teachers, just as the experience provokes different learning in different students. Among the obvious things we will not do if we think of students as researchers is simply tell them what we want them to know. But if not that, what? What should they do? With whom? Where? What would treating students as researchers mean for our assignments, our tests, our way of communicating with students? I leave this as a provocation rather than a proposal because different teachers will probably have different answers—and should. I am confident, though, that if we take undergraduate research seriously as a generative metaphor, we would end up doing many things differently than we do. Try it. Sit down with a few colleagues and try to reframe the problem: “How would we teach if we thought of students as researchers?” If we want students to reframe and rename their work, we need to lead the way.

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Transformative Pre-research Mentorship Design: Jump-Starting Undergraduate Research Experience in Molecular Biology

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Abstract

Performing research greatly enhances undergraduate educational experiences and science-based career trajectories, yet there are many obstacles in implementing research training both for students and faculty. In particular, undergraduates must gain theoretical knowledge and practical skills prior to attempting molecular and cellular biology laboratory research. Individual research training is extremely time consuming for both students and faculty, and by the time students gain enough knowledge and experience through their majors' curriculum, it is often too late for them to pursue more rigorous research opportunities and put their skills to use. In this article, I describe a streamlined design of a semester-long research mentorship that focuses on training first year undergraduate students in a small group setting. As an experienced molecular research mentor, I narrowed down essential skill sets and theoretical knowledge to jump-start their research that transformed their undergraduate research experiences. The pre-research mentorship gears toward transforming students' pre-conception of what authentic research experience entails, enlightening them with existing opportunities for original research early in their academic career. The close and focused mentoring from weekly mentorship meetings helps students to align their academic interests and future career paths with specific research areas. The success of the mentorship was reflected by the fact that a majority of the students who completed the mentorship were able to engage in rigorous laboratory research opportunities and either pursued or planned to pursue graduate and professional education in science and medicine. Although the model of mentorship was developed for molecular research, the key features of the mentorship can be applied to other disciplines to enhance the undergraduate research experience.

Keywords: pre-research mentorship, molecular biology, transformative

Background: Undergraduate Research and Biology Education

Since the publication of BIO 2010 (2003): Transforming undergraduate education for future research biologists by the National Research Council, there has been numerous discussions as to how educators might transform the undergraduate biology education experience (O'Connor et al., 2011; National Academies of Science, Engineering, and Medicine, 2015). In particular, undergraduate research (UR) is considered a "best practice" in transforming students' overall educational experience by providing students with real problem-solving skills and prepares them better for their future scientific and professional careers in STEM fields (Lopatto, 2007; Thiry, Laursen, & Hunter, 2011). The value of UR is strongly reinforced by the large number of published studies discussing the positive impact of UR in enhancing education experiences as well as graduate and professional education trajectories (Eagan et al., 2013; Elrod, Husic, & Kinzie, 2010; Hathaway, Nagda, & Gregeman, 2002; Hunter, Laursen, & Seymour, 2006; Kremer & Bringle, 1990; Lopatto, 2003; Lopatto, 2004; Seymour, Hunter, Laursen, & DeAntonni, 2004).

While transformation of undergraduate education with UR in the U.S. is vitally important, and incorporation of research into curriculum is well documented, designing and implementing an effective UR program presents obstacles for both faculty and students at primarily undergraduate teaching institutions (Carson, 2007). First, teaching intensive institutions where most UR is carried out, the burden of student research training usually falls on faculty, who have heavy teaching loads and cannot rely on support from graduate students, postdoctoral researchers, or in-lab research scientists. Secondly, resources to fund student projects and procure instruments are often limited. For undergraduates, a major challenge is that they must gain an abundance of theoretical knowledge and practical experience that are quite new and complex to them prior to successfully conducting laboratory-based research in biology—even more so in molecular biology. Based upon conversations with new research students and my own UR experience many years ago, first and second-year students are quite intimidated by the basic instruments and technical terminology commonly used in the laboratory.

The Development of Pre-Research Mentorship

Over several years of working with undergraduates in my own laboratory and trying different methods to prepare them for research, I felt an urgent need to develop a special training strategy to move students from their “Taken for granted frames of reference,” particularly as they pertain to “the paradigms of science and mathematics” (Mezirow 2003). I identified the timing of basic training as a pivotal factor for undergraduates to gain meaningful research experience. On prior occasions, thinking it would save training time, I would wait to recruit suitable research students who had gained sufficient foundational knowledge and basic laboratory training through their major’s program of study as juniors. However, the actual result was that by the time the focused training was complete, it was too late for students to use their skills effectively to perform original research as seniors. On the assumption that the recruiting has to occur much earlier, I selected a small group of freshmen students to invite them to participate in a “pre-research mentorship” I created. The selection of students for invitation was primarily based on their laboratory skills, talents I observed, and the level of enthusiasm towards research training and opportunities, not necessarily based on final course grades. Given the extensive scope of molecular research, I carefully narrowed down a set of basic molecular laboratory skills and essential laboratory techniques. The goal of the pre-research mentorship was to 1. provide students with a basic understanding of research process, 2. to reduce the intimidation of the laboratory setting (e.g. equipment and reagents), and, most importantly, 3. to expose undergraduate students to a variety of available research opportunities early in their academic career. A small group setting allowed me to train more than one student at a time; also, the small groups allowed for individual attention to each student’s learning style. The trial mentorship was taught outside my regular teaching load, and enrolled students received one credit hour for participating.

The Core Pre-Research Mentorship Design for UR training

In the mentorship class, students began by learning how to properly calculate and prepare common chemical reagents since much of the lab time is typically spent in the preparation of the reagents. Although all biology majors are required to take one year of general chemistry, they rarely get hands-on experience in preparing the actual chemical reagents for their labs as everything is prepared and set up by a laboratory coordinator who oversees the student laboratory courses. They also learn necessary formulae and equations for reagent preparation. Yet, they rarely have a chance to apply the formulae and appreciate the true value of what they learned in chemistry. For molecular biology techniques, we followed the basic principles and protocols underpinning fundamental molecular lab techniques utilized by almost all molecular laboratories such as nucleic acid and protein handling (Baker, 2005). As the selected students for mentorship completed the first semester of introductory biology lecture and laboratory, the connection to knowledge gained from the introductory courses was brought out and expanded further to connect to the techniques that are used in a customary real laboratory setting, such as DNA purification, DNA gel electrophoresis, and protein quantification techniques. A detailed list of weekly activity and topics is listed in Table 1.

Table 1

Weekly topics and activity/contents covered in mentorship

Week	Topics	Activities and contents
1	Mentorship Introduction	• Group discussion—expectation of being in a molecular research laboratory and conducting research
2	Laboratory notebook keeping	• Group discussion —the essential elements for a proper laboratory notebook • Examination of sample notebooks and comparisons
3-4	Basic molecular reagent preparation, storage, and disposal*	• Introduction of chemicals (e.g. buffering agents, acids, bases) • Basic formulae for preparing reagents and calculation practice • Introduction to basic instruments used in molecular biology
5	Techniques on cultivating and handling cells	• Introduction of cell lines • Discussions on attributes of different cell types-caveats of cell culture

Week	Topics	Activities and contents
		• Basic techniques in handling cells; Growth curve
6-9	Principles of basic molecular techniques*	• Micropipetting practice • Principles of - Isolation of nucleic acids; nucleic acid concentration measurement - Gel electrophoresis - Polymerase Chain Reaction - Restriction digest and cloning - Epitope tagging; Cell lysis - Biochemical protein purification - Protein sample preparation - SDS-PAGE - Basic light and fluorescence Microscopy • Data based problem-solving assignments and review
10	Introduction to scientific literature	• Elements of scientific literature and basic approaches to article reading • How to conduct science literature research
11	Elements of scientific presentation	• Best practices • Sample oral presentations • Formatting of effective oral presentations
12-14	Presentation practice	• 10 minute student presentations
15	Discussion on research misconduct and ethics	• Reading and discussion of articles that bring up data fraud/statistical pitfall • Discussion of unethical conduct cases
16	How to seek research opportunities	• Discussion on finding and assessing research opportunities on campus and beyond (e.g. NSF sponsored Research Experience for Undergraduate program introduction; other opportunities)

Note. The topics with * indicate that basic information and principles of protocols discussed were adopted from “At the Bench: A Laboratory Navigator,” updated ed. by K. Baker (2005).

We also spent some time discussing the elements of good laboratory records via critiquing good vs. bad laboratory notebooks. To track progress at the end of the semester, students were expected to apply learned techniques by completing a set of problems that included selected data from research publications which they did perform quite well.

Thus far, two cohorts of students have completed the pre-research mentorship; the first cohort consisting of five students, and the second with ten students. The transformative impact of training is clearly evident from the students' likelihood of pursuing research opportunities. For example, mentored students in the first cohort (n=5; 40% under-represented minorities (URM)) had 100% pursue research experiences in faculty laboratories over a minimum of two semesters. The second cohort (n=10; 20% URM) resulted in 80% of students, who are currently juniors as of fall 2018, being engaged in active research on campus for over two semesters and continuing to do so. Two sophomore students from the combined cohorts were selected for the NSF sponsored summer Research Experience for Undergraduate (REU) programs. All students who engaged in active research on campus had opportunities to present their original research during the Georgia College Campus Research Symposium as well as at regional and national research conferences. 100% of the first cohort students either began graduate programs in biomedical fields or are in the process of applying for medically oriented professional schools.

Linking Transformative Learning with Pre-Research Mentorship

According to Mezirow (2003), transformative learning is defined as "learning that transforms sets of fixed assumptions and expectations." In addition, Mezirow notes that reflective judgment about students' own perspective is an essential condition for transformative learning. The exit survey at the end of the mentorship and follow-up interviews provided an excellent opportunity to observe critical reflection of student assumptions which, in turn, reflected student engagement in the transformative learning process. For example, one student expressed her initial surprise of "how tedious" technical procedures really were on her exit survey, but, on the follow-up interview, she said that understanding scientific principles behind procedures really helped her adjust to learning the procedure properly and performing experiments in her research project successfully. Overall, all mentorship students engaged in research after completing the mentorship reported the exposure to basic laboratory settings and to molecular research greatly enhanced their learning the requisite technical skills and developed more realistic expectations in pursuing original research as compared to their original assumptions.

Although transformative learning appears to lead to a more mature, autonomous, "developed" level of thinking, Merriam (2004), in her forum article, argues that a certain level of cognitive development would be a prerequisite for engaging in the meaningful transformative learning process. Drawing from her critical reflection of transforming theory, I believe that the pre-research mentorship significantly contributes to cognitive development of undergraduate researchers and serves as critical prerequisite to meaningful undergraduate research experience. In particular, it is extremely important to correct students' prior misconceptions about research. Namely, the misconception that experiments often do not produce incontrovertible results, and instead show that they are much more time-consuming processes requiring frequent trouble shooting and trying out many new strategies to probe answers that are experimentally possible. Indeed, there is very little in their early biology experiences in high school or freshmen level classes that prepares them for real bench work as students typically follow proscriptive lab manual procedures with all reagents prepared and laid out for them, thus obtaining expected results almost every time they conduct experiments.

Another noteworthy transformative effect of the pre-research mentorship is the close and direct mentoring it engenders. A recent review by Linn, Palmer, Baranger, Gerad, and Stone (2015) identifies such mentoring as an essential component for successful support of undergraduates considering careers in science. The review further points out that "successful mentoring balances the dual goals of helping undergraduates deepen their understanding of science and guiding them to develop a scientific identity via articulating their knowledge, reasoning, or problem-solving skills." The mentorship design supports all aspects of building individual scientific identity by exposing students to reading a variety of research literature and seeking out research opportunities that would fit their research interest best along with frequent opportunities to share their scientific interests. Finally, pre-research mentoring provides opportunities for students to communicate and ask insightful questions. In the small group setting of the mentorship, everyone is geared to actively participate in weekly meetings discussing their distinct interests, personal backgrounds, strengths, and weaknesses. Following up on their interests in research opportunities greatly enhanced the high success rate of the post-mentorship research engagement described above. Representative of sentiments echoed by many students in the class was their being significantly less intimidated by the laboratory setting after learning the terminology of common chemical reagents and instruments. Likewise, the students valued the connection to what they learned to other laboratory-based classes such as organic chemistry.

Conclusion

In summary, the implementation of a pre-research mentorship is effective in transforming undergraduate research. From the students' perspective, it promotes students' confidence in viewing themselves as potential researchers because it 1. demystified the laboratory and 2. bridged the gap between the prior perception they held of the requirements for research and the actual knowledge and technical skills required to produce meaningful research data. In particular, the early timing in their undergraduate career encourages students to actively pursue and engage in research opportunities early. This early research boost in turn allows for much needed time to generate meaningful, experimental data presentable at professional venues. Indeed, the benefit students gain from research is known to be significantly enhanced in multi-year research experiences (Thiry, Weston, Laursen, & Hunter, 2012). Finally, the research experience confers a host of personal, intellectual, and professional benefits to students along with an increased capability of improving their future careers and professional identity development. From the faculty side, the pre-research training reduces the time burden to the potential UR mentors. Students who completed the mentorship can now operate some of the basic instruments, calculate and prepare basic chemical reagents, and keep good laboratory records as they carry out specific experiments, all of which would otherwise take months to learn. The UR mentors can, therefore, focus on aligning research students to their specific research interests and on helping develop their bench work skills tailored to specific experiments. While the model I developed for a pre-research mentorship was based on my own interest in molecular biology laboratory research, the key features of the mentorship—early selection of mentees and a highly streamlined list of essential training elements needed for a specific type of research—can be expanded and applied to other areas of interest in undergraduate research.

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Innovation in Preservice Teacher Preparation: Undergraduate Research in Special Education

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Abstract

Teacher preparation programs emphasize the connection between student outcomes in achievement and behavior, but the framework of teachers as researchers is rarely presented as a foundational basis of good instruction. Teachers are aware of the need to consider scores and trends and alter their instruction based on the response of the students to their teaching, but the techniques involved are not explicitly taught as research methods in most preparation programs. The initial purpose of including a research course in the undergraduate program of study was to provide preservice teachers with research skills to enhance their instruction. The long-term goal is to provide the preservice teachers with the tools and techniques whereby they are encouraged to critically reflect on their own assumptions about the role of teachers. Through the implementation of the current research course, which is included in their program of study, students examine ways teachers use single-subject design in the classroom as part of their daily routine in teaching and managing their classroom. Encouraging preservice teachers to learn more research methods not only prepares them for their classrooms, but also serves as an introduction to graduate-level expectations. This essay explores preservice teachers' views on the value of learning research methods as a transformative event in their understanding of what teachers do in the classroom.

Keywords: preservice teachers, undergraduate research, research methods

Innovation in Preservice Teacher Preparation: Undergraduate Research in Special Education

It is the intent of university programs to prepare preservice teachers for meaningful careers in education. Teacher preparation in most undergraduate programs has a high concentration of both content literacy and pedagogical instruction (Darling-Hammond, 2016). While knowledge of content is a predictor of successful teaching, and good teaching practice is linked to student outcomes, these two components of what it means to be a teacher will not predict that the teachers will remain in the classroom. The attrition rate of special education teachers is often linked to the teachers' perception of being overwhelmed by the amount of paperwork that is required by law in assessing and monitoring student progress (Vittek, 2015). Thus, attention to teaching preservice teachers' research methods that can be incorporated into their daily teaching routines, which can then assist in managing this required paperwork and research methods, may be viewed as worthwhile professional competency, instead of viewing data collection as a heinous legal necessity with little connection to their practice. The collection and analysis of student learning and behavioral data are research skills that are often overlooked in teacher preparation, and when these skills are addressed, it is considered part of the documentation piece of reporting and incorporated into a larger skill set directed at the collection of data as a daily occurrence and one that informs one's practice. Data collection and analysis can then be closely linked to selection of curricula, shaping and scaffolding instruction and differentiation of teaching and assessment methods which are all techniques that teachers recognize as necessary competencies. If special education teachers were prepared in such a way as to understand that data collection is an integral part of what it means to be a teacher, then it could have some impact on how teachers view their responsibilities as teachers, and the requirement to collect and analyze data may be less daunting. Transformative learning occurs when the students shift from viewing their role simply as recorders of events into analyzers of data; the transformation of learning is extended when they critically assess their assumptions, reflect upon that data, and exact change in their teaching methods and classroom facilitation. As a result, the authors critique current practice by exploring ways to include activities involving formal research skills preservice teachers can practice within their future classrooms. We believe infusing research methods will increase the likelihood of transformative learning for our preservice teachers and, if used within their future schools, could support developing classrooms that closely monitor student success. Whether or not this transformative content may have any influence on retention rates of induction level teachers, the ability of preservice teachers to recognize the value of learning research skills is perhaps an integral component of supporting teachers as they begin their careers. The transition of preservice teachers' perception of their ability to use research methods to become a better classroom, teachers represent a true transformation in their learning and in their understanding of the teaching field.

Transformative Learning Theory

All individuals have their own view of the world and their place in that world. This view has been developed from a variety of sources—their upbringing and influences by parents and others in the formative years, life experiences, cultural beliefs, and educational experiences. In the case of teachers, they have also been consistently exposed to teachers as models throughout their entire life, which influences their perception of the teacher's role within the classroom. However, there are limited opportunities for any student to see or understand the planning and preparation that is required in order to provide instruction and support both in and out of the classroom. For preservice teachers, many have been exposed to the art of teaching prior to beginning a teacher preparation program, but exposure to the reality of instructional responsibility may challenge their initial thoughts of what educators actually do within the classroom. It is during these early preparation experiences that candidates are exposed to the hard work behind becoming an effective educator. Preparation course work should increase their knowledge and deepen their understanding on the groundwork it takes to know the students, communicate goals and execute plans to achieve outcomes.

Taylor (2000) reviewed literature on transformative learning and discovered six themes related to the essential characteristics of transformative learning and how to promote it. They include: (a) promoting ownership by the group along with individual agency, (b) providing shared experiences, (c) developing an understanding of personal and social influences, (d) delivering values-rich content within coursework, (e) recognizing the relationship between critical reflection and affective learning, and (f) understanding that time is needed to change one's way of thinking. Similarly, Kasworm and Bowles (2012) noted that higher education settings provide ample opportunities for challenging students' frames of reference. They indicated that innovative higher education programs that engage in transformative learning "challenge student perspectives, promote critical thinking and creativity, integrate knowledge across disciplines, create community-university collaboration, develop inclusive communities of diverse learners, and enhance connections among student and faculty" (p. 396).

Colleges and schools of education may be particularly well-positioned to transform preservice teachers' frames of reference, or worldview. Initially, the preservice teachers' frame of reference may be made up of their own educational journey, and as such, they may have limited exposure to diverse students or challenging settings. In some cases, this worldview can become "set," and an individual can have difficulty changing because their worldview becomes habits of mind—broad, habitual ways of thinking and acting. However, teachers enter classrooms that are increasingly diverse, and as a result, they cannot afford to have set ways of thinking or assumptions about students. In fact, "developing more reliable beliefs about the world, exploring and validating their dependability, and making decisions based on an informed basis is central to the adult learning process" (Taylor, 2000). The process of becoming a teacher, both outwardly and inwardly, means that many students' beliefs of what it takes to be a teacher and what it takes to become a teacher (their "worldview") may be radically different from the reality of the process.

Developing these beliefs in an informed way is supported by transformative learning theory. This theory "explains how adult learners make sense or meaning of their experiences, how social and other structures influence the way they construe that experience, and how the dynamics involved in modifying meanings undergo changes when learners find them to be dysfunctional" (Mezirow, 1991, p. xii). According to Mezirow (2000), there are distinct steps that make up transformative learning: (a) a disorienting dilemma, (b) self-examination, (c) critical assessment of assumptions, (d) recognizing that one's discontent and the process of transformation is shared, (e) exploration of options for new roles, relationships, and actions, (f) planning a course of action, (g) acquiring knowledge and skills for implementing one's plans, (h) provisional trying of new roles, and (i) reintegration into one's life on the basis of conditions dictated by the new perspective. The first step in transformative learning, the "disorienting dilemma," is often experienced by induction teachers when they are faced with the expectations to teach all the students in their classroom, many with vastly different learning needs than those that the induction teacher may have experienced. In the best cases, this will lead to the next step, "self-examination," when they consider the strengths and weaknesses of their own abilities to address the knowledge, skills and dispositions of the educational field. It is the intention of our teacher preparation program to provide this transformative learning prior to the student being a teacher of record, so that the process of facing a disorienting dilemma and choosing to self-examine will be a practice that the teacher already engages in with some measure of competence.

Mezirow's next distinct step in transformative learning involves, in large part, using critical reflection as a way to change existing worldviews, frames of reference, and habits of mind (Mezirow, 1991). Reflection has been a significant part of teacher education for decades, supported by educators such as Dewey, Kolb, and Schon. However, reflection in teacher education often occurs in a vacuum; preservice teachers have little real practical experience on which to base their reflection. Embedding a research course in the undergraduate special education teacher preparation program seeks to provide this critical reflection as students experience life as a teacher. This introduction to data collection, and the companion reflection as the analysis of the data is completed, can be viewed as a necessary "teacher skill" which may promote transformative learning as students experience the connections within making data-informed decisions to enhance their practice.

Transformation learning occurs in the program described in this study in which undergraduate students are asked to conduct research in field placements. In this program, the faculty engaged in "an approach to teaching based on promoting change, where educators challenge learners to critically question and assess the integrity of their deeply-held assumptions about how they relate to the world around them" (Mezirow & Taylor, 2010, p. xi). Teachers in the field undertake research skills in their daily practice through both formative and summative assessment. Certainly, many preservice teachers come into their preparation program having some idea of the necessity of assessment as well as the need to understand the outcomes of assessments, but few recognize that what teachers do nearly every day is, in all regards, significant data collection and analysis. As such, it is our intent to help them understand their role as a researcher.

Benefits of Undergraduate Research in Teacher Education for Transformative Learning

Our program examined the empirical basis for including a research experience within the program of study in order to ensure that the skills that the preservice teachers would gain would aid in supporting them in their own classrooms. The opportunity to conduct research while in a teacher preparation program is beneficial to special educators because it promotes the refinement of both their teaching and service skills and can serve to broaden their knowledge of their related disciplines, which is essential to special educators who oftentimes work with a variety of general educators with content specialties across disciplines (Lassonde, 2008; Levy, Thomas, Drago & Rex, 2013). Undergraduate research encourages leadership and collaboration, promotes logical analysis, and enhances students' written and oral communication skills (Ishiyama, 2002). These skills are an integral part of what it means to be a teacher. An undergraduate research experience provides an ideal context for prospective educators to demonstrate required practices of innovative and inquiry-based teaching and learning, familiarity and competence in evidence-based interventions, and reflective teaching (DeVore & Munk, 2015). Considering these benefits, undergraduate research provides prospective educators and educational specialists with the skills necessary to transform schools into centers of innovative teaching, learning and scholarly activity and creative activity. They become thoughtful, purposeful professional educators who become leaders in their educational institutions, units, schools and communities. Conducting research as an undergraduate for many students is, by nature, a transformative learning experience. Our goal in providing research methods is to prepare the preservice teachers in their undergraduate program the opportunity to learn research methods in preparation for a research experience that is embedded later in their program.

As faculty, we were committed to include undergraduate research in our teacher preparation, and to that end, the College of Education created avenues to establish an innovative outlet to connect research methods within the initial certification special education program. Through a collaborative effort between the research and special education professors, we created a new course to serve as an introduction in research methods. In addition to the teaching and research faculty, administrative support was also present, in the person of the associate dean for research. This support by the associate dean was in line with current research that indicates that once the administrators in education units (deans, department chairs, program coordinators), are informed about the benefits of undergraduate research, they are more likely to negotiate with their academic departments for innovative ways in which to sponsor interdisciplinary undergraduate research **(**Brakke, Crowe, & Karukstis, 2009; Murray, Naimoli, Kagan, & Snider, 2004).

Teacher as Researcher

In the very nature of their role as a classroom leader, teachers become informal researchers. Many days teachers enter their classroom with a new activity to try and a new strategy to engage students. Consistently testing attempts and seeking differences in student achievement and or behavior, teachers' classrooms become an incubator for learning experiments. For new teachers, their daily routine is persistently creating new ideas, techniques and skills to further sharpen their skill as a teacher and give better instruction to their students. However, much of the literature overlooks teachers discussing their development in researching their experiences. Teacher preparation courses share little on research methods that undergird teacher practice in documenting ways to monitor student progress through a formal approach of gathering research data.

Current research on beginning teachers developing formal research skills has been documented as self-study research (Bullock, 2009; Loughlin, Hamilton, Laboskey, & Russell, 2004; Marin, 2014), and also teacher as researcher in an international context (Brantley & Crocco, 2010; Kosnik, 2005). An important result of this work is the increase of teacher practices that involve critical self-examination and reflection to examine change within their classrooms. Teacher as researcher is part of the action research paradigm that calls for the practitioner to actively study their own practice to measure change within their students and growth within their teaching skills and/or knowledge (Hollingsworth, 1995). When teachers include formal research methods to their practice, they increase their professional role to include a systematic, self-reflective, intentional inquiry into aspects of classroom practice. Towards that end, teachers carefully review their teaching duties, they engage in constructing critical questions based on perceived local problems, collect and interpret data, and write up their findings in a report with the interest of improving their practice (Kane, 2007). The teachers are key players within the research process and it can take up to a few weeks or several years to complete pending on the problem under investigation.

By infusing action research methods within the preservice teacher course work, these college students are exposed to ways they can increase their professional judgement by using evidence. Top-down policies and past schooling experiences help to shape the prior knowledge of preservice teachers and what they envision are the possibilities of classroom teaching (Beuhl & Beck, 2014). However, we propose that using action research methods sheds light on how teachers make evidence-based decisions to lead their classrooms. Involving students within the research process earlier and more often can support their development in asking critical questions and adapting to evidence as they encounter it (Hatch, Eiler-White, & Faigenbaum, 2005).

This process is situated within transformative learning by suggesting that preservice teachers now have the concepts to investigate what works relative to their current classrooms instead of relying on previous experience in that grade or what the previous teacher of that content has shared with them. They can explore other activities or methods and test the results on which techniques works best for their students. Additionally, they have the skills to write up the differences observed within the classroom and disseminate to others in reports or presentations.

Description of Research Course

This course is an undergraduate introductory course in educational research. Students enrolled in the course are special education majors and approximately 20 students enroll in the course as a cohort. Research designs, methods, and applications of research specific to investigations in special education practice are explored. The course includes essentials in evaluating a literature review and key issues in data collection using qualitative and quantitative approaches. Students investigate the development of instruments for measuring student progress and applying intervention, understanding variable relationships, and descriptive studies. They develop the capacity to frame research questions, determine appropriate research designs, collect necessary data, interpret results, and develop awareness of the range of alternative instructional and behavior approaches.

The course contains several learning activities that center on data collection and data-driven decision making. Towards that end, students learn that data collection and analysis of the data is a more sophisticated way of understanding problems and concerns in the classroom versus just simple documentation of occurrences. A survey of student interest was used in this project to gather data; however, the researchers explored several sources to understand how transformative learning occurred within the instructional content of the course. The purpose of the survey was to provide an interest inventory of how the students in three sequential cohorts viewed particular instructional devices used within the course of the class (i.e., quizzes, lectures, projects) as well as their relative interest in the content of the class itself. It was intended to provide the instructor (second author) with information regarding the clarity and transferability of instruction more so than the end-of-course evaluations that were administered by the university.

Methods and Results

Students completed a 10-item pre/post survey on their interest in research methods and course activities. Item analysis results were determined for each cohort individually (2016, 2017, and 2018), to measure differences within each group. When comparing the mean item scores, cohorts' scores revealed an overall increased familiarity with the research process between the pre-course surveys and post-course surveys. Additionally, students who presented research at various conferences were contacted about their experience as a presenter and how helpful it was to their practice as a teacher.

In general, the survey was useful to the instructor to gauge student interest in course activities. Many of the items were developed to gather additional data on the course format and to gain a deeper understanding of students' attitudes on course projects. Items on the survey requested a self-report on their attitudes of importance in studying research methods, understanding the process of scientific research, and their abilities to identify procedures commonly used in qualitative or quantitative research methods. By moving beyond the students' attitudes of the projects, the researchers wanted to investigate if the survey would also be useful in sharing insights on transformative learning of the course material.

Several observations were made in comparing the pre/post data in each group. However, very little could truly provide sufficient evidence of transformative learning as the survey was not designed specifically for that purpose. However, we did observe differences in students' interest and attitude mean scores to an item specifically on teacher skills, indicating their personal level of importance of the course to foster a better understanding of using data to improve teaching practices. Specifically, in the 2018 cohort of 21 students, reported mean scores were as follows: (4.38 pretest and 5.42 posttest, with a STD of 1.25). The increased difference on this item we propose there exist some transformative learning experiences that will impact their skills as a teacher and developing researcher.

While transformative learning was not directly associated with the survey, several other observations were made of students' progress throughout the course and during presentations that were related to transformative learning and provide some evidence of change in students' habit of the mind. In connection to the tenets by Kasworm and Bowles (2012), we offer activities within the course and its connection to the survey where we can assume transformative learning was achieved.

Transformative learning was demonstrated through many of the course activities, as evidenced through Kasworm and Bowles' six tenets. In regard to the first tenet, "Challenging student perspectives and assumptions," we reference Mezirow's (2000) description of a "disorienting dilemma," in which students attempt to solve problems using abstract reasoning. In one specific course task, students were asked to consider which research approach is more precise—qualitative or quantitative? After reading and in-class debate, we discussed the differences in Likert-scale measure anchor items and how people view these differently. Consider common terms to indicate frequency such as Never, Rarely, Sometimes, Often and Always. We examined the varied meanings for each term for each person within the classroom, how exact then can we assume in gathering the attitudes of a population when people vary on the meaning of terms even for the term NEVER. Over the course of teaching this class, there were several students that indicated the possibility of NEVER happening 3 times; however, they would still respond by using NEVER on a survey. Visualizing the differences among their classmates gives the students another frame of reference to consider as they continue to read other research articles and review different surveys. While the survey did not test transformative learning, we use the evidence to suggest there was change in student thinking related to the nature of research as suggested in Table 1.

Regarding the second tenet, "Promoting critical thinking and creativity," our students spent time analyzing hypothetical qualitative and quantitative data sets as well as creating display charts and graphs for these data sets. While the class serves as an introduction to research approaches, we spend a third of the course on analysis techniques that K-12 teachers find useful for disseminating data to their team, grade level, and principal. Also, we explore analysis techniques to track student progress on alternative assessments beyond K-12 test scores. Creating data charts for individual K-12 students, grade levels, and schools can be tedious and rigorous, yet, requires undergraduate students to organize material and think critically of the best approaches to display the data. The connection to the survey is one particular item that directly explores level of importance; the analysis projects are as a learning activity.

Table 1 *Student Interest in Learning More About the Nature of Research Pre and Post-Survey*

Year	N	Mean Scores	Standard Deviation	df	p-value
2016					.461
Pre-Survey	19	4.95	1.35	18	
Post-Survey	19	5.26	1.97	18	
2017					.025
Pre-Survey	21	5.50	1.34	20	
Post-Survey	14	4.21	1.05	13	
2018					.231
Pre-Survey	23	5.52	1.44	22	
Post-Survey	21	4.81	1.66	20	

Note. The p-value reflects individual t-tests drawing from each individual year.

For the next two tenets, “Integrating knowledge across the disciplines” and “Engaging in community-university partnerships and collaboration,” we provide several examples that weave these items seamlessly together. One of the more obvious activities is students’ involvement with action research studies from our recent graduate students. Students are required to offer a reflection on action research studies from our previous Education Specialist (EdS) students who completed action research studies as a requirement for their degree. The studies range in topic on issues related to reading, math, science, and social studies at different levels. The undergraduate student gains practical knowledge from current teachers’ attempts to conduct classroom research. It also reaches into the community and university partnerships through the school context that are also described and considered a major part included in their reflective writing. For the last two tenets, “Developing supportive and inclusive community of diverse learners,” and “Enhancing connections between and among students and teachers” (Kasworm & Bowles, 2012), we provide the example of students’ weekly goals, discussion posts, and in-class group activities to build our learning community. Each week, the students set a goal for submitting assignments under a pseudonym they create at the beginning of the semester. The professor is not aware of the identity of the students but gives feedback on the shared Google form for each student who completes his or her weekly goal. This goal sheet is a motivator for students to state when they start and finish weekly assignments. Discussion posts and in-class activities also offer students opportunities to share opinions and collaborate on assignments. These activities reflect transformative learning by encouraging students to process information and make connections with others. The students must personalize, process, and connect or consolidate their ideas to create projects for in-class assignments, such as creating a survey activity. Students randomly draw a topic from a hat and must work together to create a survey for the other class members to complete. There are several limitations to completing the assignment, such as time, effective survey design rules and number of survey items. This is an intense activity, but one we have come to appreciate in building our classroom learning community. Changes in students' attitude on the importance of common procedures used in quantitative and qualitative research methods provide us some evidence of transformative learning. Cohort 2018 students self-reported a greater importance placed upon their ability to identify procedures commonly used in qualitative and quantitative research methods at the conclusion of the course. Table 2 illustrates a significant difference ($p<.005$) in students' opinions.

Table 2 *2018 Cohort Importance on the Ability to Identify Procedures Used in Research*

	N	Mean	Standard Deviation	Df	p-value
Pre-Survey	23	1.58	0.69	22	.002
Post-Survey	21	3.16	0.76	20	

While there were several limitations to the survey that prevent us from making any generalizations from these initial results (i.e. small size, reliability of instrument, etc.), we did find it useful to question students about their experience and restructure the materials in the course to address specific needs. As we increased our engagement with previous research on transformative learning the authors attempted to examine if undergraduates were transforming in their learning within the research methods course. While the data collected here does not overwhelmingly support transformative learning, we did observe student change and development within the activities. Our next steps are to include more qualitative data in our sample after students complete the course and prepare for conference. For example, we include here one student's statement shared after her presentation at a state level research conference.

Chelsea, a senior education major stated, "*I would not have done any presentations without the research course. I think that without this course I would not have even thought about doing research or about research being possible in education. I also do not think that I would have known how to go about creating an abstract or presentation had I not have completed the research course or had professors that knew more about research to lean on and ask for help*."

To capture the depth of student transformational change we may need to add more qualitative approaches to gather the details illustrating the connection of the course to student change.

Conclusion

A powerful result of transformative learning experiences is that once someone's understanding has been transformed, it is impossible for them to revert to their old perspective. Teachers cannot come into the classroom each time thinking, "This is how I teach." Every time they are given something new, they need to critically assess their assumptions and approach—that is where the transformative learning occurs.

"Transformative learning causes an individual to "come to a new understanding of something that causes a fundamental reordering of the paradigmatic assumptions she holds and leads her to live in a fundamentally different way…Transformative learning and education entail a fundamental reordering of social relations and practices" (Brookfield, 2003, p. 142).

While our intention was to provide preservice teachers with more tools to support them in the classroom, what we found was that embedding the research course within their teacher preparation had the additional benefit of changing how they viewed their role as teacher. By expanding this perspective of the preservice teachers and enhancing their critical thinking, they were able to explore the classroom through the lens of a researcher. Using action research methods may be a serious consideration to transform learning the art of teaching our preservice teachers.

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Barriers to Transformative Learning in Undergraduate Research: Helping Student Researchers to Embrace the Hurdles

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Abstract

Data shows that undergraduate research is a high impact practice utilized as an essential part of many college campuses (Sternquist et al., 2018). Within the last decade, much of this influence on student success is beginning to be attributed to transformative learning. Transformative learning involves the student in more than just learning about problems. It causes the individual to undergo significant phases of reassessment and growth that challenges old assumptions and takes the student towards higher-level thinking processes and new directions (Mezirow, 1978). However, this is not an automatic transformation that occurs when a student first engages in an innovative research project. Many students falter when first exposed to the need to move up Bloom's taxonomy from simply memorizing facts or concepts to applying them in the research setting. Therefore, undergraduate research mentors are challenged to not only teach the skills of the discipline, but also help students increase metacognition to aid in the transformative process. With this dual responsibility, several pitfalls in the process can be found including: 1) Time constraints on faculty and student engagement in the research process, 2) Ill-prepared students lacking foundational knowledge as well as fundamental skills, and 3) An increase in students' participating in research only to fulfill an admission requirement for graduate programs. These three aspects are discussed in terms of why they exist for the student population and how mentors can help the students embrace these hurdles in an effort to gain greater understanding of why the research is beneficial to their development as an undergraduate student and a lifelong learner. This includes recognizing and identifying learning bottlenecks (Middendorf & Shopkow, 2018), overcoming student resistance, and developing a welcoming research culture that recognizes students come from a variety of frames of reference (Taylor, 2008). Mentors must help students to acknowledge how the frame of reference is unique for everyone on a team, even in disciplines which are traditionally believed as completely objective. Practical guidance for mentors to overcome the three major barriers mentioned above is provided to increase transformative learning growth of student researchers.

Keywords: transformative learning, culture, undergraduate research, bottleneck, threshold concept, mentor

Introduction

The high impact practice of undergraduate research is a high-impact strategy used by many institutions of higher learning (Sternquist et al., 2018). Additionally, more and more focus on transformative learning and its impact on student achievement that has occurred over the last decade. Transformative learning changes from the traditional focus of the student simply encountering and solving a problem. Transformative learning shifts the focus towards higher-level thinking via significant phases of reassessment where the student continually reassesses old assumptions and must apply new ideas or techniques to the curriculum (Mezirow, 1978). Undergraduate research has been shown to increase satisfaction of learners and retention of specific research skills (Lopatto, 2004), but can it also improve transformative learning? Since the retention of STEM undergraduate majors throughout U.S. colleges and universities is quite poor compared with other majors, Wilson et al. (2012) developed a model that incorporates undergraduate research to increase retention. This model involved three tiers: traditional strategies involving support via academic advising and early intervention is the first tier in the model, an integrated undergraduate research experience, and faculty mentoring. Mentoring and research opportunities combined to help students become metacognitively aware and allowed students to outperform colleagues not participating in the program (Wilson, 2012). Possibly more noteworthy is that participants in the program developed constructive strategies for enhancing their higher-order thinking skills which helped with scientific understanding and improved performance in coursework (Wilson et al., 2012). Both the development of self-examination skills and increased mastery of discipline-specific competencies can be considered transformative learning. Therefore, this study strongly confirms that transformative learning can be achieved via undergraduate research.

However, it is not an automatic transformation that occurs when a student first engages in an innovative research project. Many students find comfort in memorizing simple facts or concepts and being quizzed or tested on this information. It is when they are challenged to think critically or apply this basic material in new scenarios, such as undergraduate research, that many formerly-successful students falter. A hesitation to advance upward on Bloom’s taxonomy is a common attribute of the beginning research student. Therefore, undergraduate research mentors are tasked to not only teach the discipline-based techniques and modes of inquiry, but also help students increase metacognition to aid in the transformative learning process. With this dual responsibility, several pitfalls in the process can be found including: 1) Limited time available for faculty and student engagement in the research process, 2) Ill-prepared students lacking in foundational knowledge who struggle to complete basic tasks, let alone move to cognitive expertise of the subject matter and the process occurring, and 3) An increase in students’ desire to participate in research solely as a pre-requisite for graduate programs or as part of a capstone course. Fortunately, each of these three areas can be remedied to allow for transformative learning to occur and greatly impact the success of each student. Below is a discussion of these obstacles along with why each exists and how mentors can help embrace these hurdles in an effort to gain greater understanding of why the research is beneficial to their development as an undergraduate student and a lifelong learner.

Area 1: Time Constraints on Faculty and Students

The expectation of faculty to excel in the classroom, perform unique scholarship, and find time for service has become an even more daunting task in the last several decades (Jacobs & Winslow, 2004; Townsend & Rosser, 2007). Therefore, the balance of giving their time to students and completing an ever-lengthening list of tasks becomes difficult to achieve. While involving undergraduates in research projects is extremely beneficial to the students, the investment in time, and often financial resources, is much more risky for the faculty member. As the investigator, a tremendous amount of time is committed to the student in training discipline-specific techniques, helping develop critical thinking skills, and simply checking the work for accuracy. The return on investment for the instructor's specific scholarship project is quite minimal. So, the push and pull of obligation in other areas with the desire to help the student succeed is not to be negated or ignored. How can a professor successfully fulfill the needs of his or her own scholarship and give a beneficial experience to the student?

The first area of focus for faculty mentors that is often ignored, even by very effective researchers, is to invest time outside of the project to personally know the student researcher. Whether the institution's student population is highly-diverse or rather uniform, each student possesses a variety of specific strengths, weaknesses, and cultural complexities. Each of these characteristics may help or hinder the student's ability to perform specific tasks. Understanding these characteristics takes time over the first few weeks of the project, but the emotional investment will show the student that each person is a member of the research group and an intricate part of the team.

The work of Erez & Gati (2004) can help the mentor better understand the need of students to be seen as individuals within the team. They developed a multi-level model of cultural characteristics which is dynamic and therefore always changing. This model includes levels of cultural importance including global, national, organizational, group, and individual (Erez & Gati, 2004). Conducting research with a student or multiple students would be considered group culture. In this model, each level will impact another, so clear expectations and expressing team-level values such as shared learning orientation, interpersonal trust, and support are crucial to developing a positive research culture (Erez & Gati, 2004). There are various ways that research mentors can build community. This starts with communication by clearly stating expectations of the student and reciprocating by listening to the student as well. Students have been shown to be experiencing more stress than the generations before them and this is exhibited in widespread increases in university counselling service referrals (Macaskill, 2012). The mentor should build community by listening to concerns of the student outside of the research project that occur both in and out of the classroom. The instructor must also provide specific training for the jobs the student will be expected to perform and give praise and admiration for small student successes along the way. These small investments in time will help develop and cultivate a strong group culture for success.

A second area of focus for a research mentor under time constraints is to specifically focus on particular areas of Douglas' Research wheel (Douglas, 2013). This wheel is a tool that categorizes research into four broad categories (Creative, Community, Applied, and Scholarship) with 18 subcategories including diverse activities such as data collection, service enterprise, invention, or service. In graduate school, students acquire the skills necessary to accomplish many areas of the wheel at one time. For example, a graduate student may conduct a literature review, data collection, communication of the lab results to community groups, create new equipment, and conduct a simulation. However, graduate students are further along in their careers and often fully-immersed in their projects. That will not be the case at the undergraduate level, so it is inappropriate to assume the student is capable of accomplishing such a tremendous workload at the same time as juggling classes, extracurricular activities, and often another job. Therefore, a research mentor should focus an undergraduate towards not only one of the four major categories on Douglas's research wheel but towards one of the individual activities. A thorough literature review is a great activity to undertake, but difficult for an undergraduate to accomplish by simply being sent to the library to conduct. Instead of sending the beginner off in search of what literature is available, start by giving the student a landmark paper in the field or a recent manuscript of importance. Additionally, the mentor must make sure to teach that student how to read a discipline-specific document. Each discipline approaches knowledge and research in somewhat unique ways (Middendorf & Shopkow, 2018). Often research experts are unaware of discipline-specific nuances because they have used them for decades. Mentors must take the time to reflect on their own practices to be able to successfully teach these skills to the undergraduate scholar.

After the student has been exposed to an example of successful research, the mentor should focus that student's project in only one of Douglas's 18 activity areas (Douglas, 2013). If a student is conducting experimentation, keep the project narrow and focused at the beginning. Having an experiment that has too many options for the student may lead the student astray and waste time. The research mentor is the expert and can ensure that the research conducted is new and innovative as the mentor has knowledge of current literature. Then, the mentor can continue to provide additional relevant research papers as the research progresses. After some results have been accomplished and the student has a comfortable understanding of the project, this is the time to have the student go back and dive deeper into the literature themselves.

Area 2: Ill-Prepared Students Lacking in Foundational Knowledge

Threshold concepts is a theory that certain particularly-difficult concepts are critical to understanding a discipline (Middendorf & Shopkow, 2018). If a student researcher failed to grasp specific concepts taught in the coursework, this will impede his or her progress in that course and further hamper transformational learning via undergraduate research. Additionally, learning bottlenecks are parts of the curriculum in which students fail to grasp material even if they are diligently trying, prepared for class, and aided by instructors that have thoroughly presented the discipline-specific content (Middendorf & Shopkow, 2018). These bottlenecks, which occur across virtually every course regardless of discipline, will also appear in undergraduate research. Again, if a student lacks basic foundational knowledge, application of that knowledge is impossible. Therefore, through clear communication with the student, the mentor must find the learning bottlenecks that have occurred with each individual research student. Only after identified can these learning bottlenecks be remedied and transformative learning be afforded the opportunity to occur.

After identifying threshold concepts necessary for the student project and the potential bottlenecks of these knowledge areas, the mentor should focus the student on very specific tasks and ensure that the necessary threshold concepts are taught to the student once again. As addressed in area 1, student weaknesses and strengths can be identified when an environment of open and positive discourse is developed. The skill set of the student researcher is built by allowing him or her to complete small tasks with success. The researcher must dedicate time away from the student-mentor interaction to prioritize what tasks can be taught that will allow the student to gain independence and also be most valuable for the mentor to further the research project.

Once small skills are taught and repeated, larger tasks can be performed. As this continues, having the student keep a diary of the research process (and not just a log of data collection) can be extremely useful (Wallin, 2017). Begin by using specific prompts such as, "What was the most important thing you realized this week?" or "What was the greatest challenge this week?" (Wallin et al., 2016). These small diary entries allow for communication to deepen and will provide insight to the thought-processes of the student, helping to identify if a threshold concept is understood or if a bottleneck has appeared. These diaries will also augment the transformative learning process bringing the student back to personal understanding of key concepts, having the individual think about the process and why tasks were performed, and how the results will impact the next steps in the project.

Area 3: Students Participating in Research Solely as a Pre-Requisite for Graduate Programs or Capstone Courses

Again, the mentor must remember that all students come with individual worldviews that have developed over their lifetime. Returning to the work of Erez & Gati (2004), every individual has a dynamic cultural frame of reference including many levels. Before a mentor can develop the teamwork aspect of the group culture level, the attributes of each individual must be considered. Why wouldn't an undergraduate appreciate a faculty member gifting time to work with a student on a project? Three aspects may play into the cultural perspective of the student: 1. This requirement appears to be of the same value as any other pre-requisite such as number of credit hours obtained or a minimum GPA. 2. This is yet another hurdle placed in the way of the student that prevents a degree, and therefore, career and paycheck, from being achieved. 3. Research has nothing to do with the future career itself.

These three ideas seem fairly naïve to an academic but may be deeply entrenched within the student's worldview and culture. What individual involved in any sort of education hasn't heard that "those who can do, those who can't teach?" This maddening phrase, adapted from the George Bernard Shaw play, *Man and Superman*, has become commonplace amongst frustrated students. And, while completely absurd, misconceptions are extremely hard to remove from the brain. Unlearning what is already believed is often more difficult than learning new information (Angelo, 1993). So, a student may perceive conducting research with a professor, not as an opportunity, but an obligation to work with someone not actually doing work of any real significance. Hands-on undergraduate research is a great way to remedy this fallacy. Showing the student why the work has been important to other research, how scientists actually communicate with one another via peer-reviewed manuscripts and presentations, and how the student will be actively engaged in the process will help alleviate this initial delusional state.

This particular student is really the best opportunity for the mentor to develop transformative learning. Fostering transformative learning must be deliberate and conscious (Taylor, 2008), so the mentor must work with the student to explain why participating in research is a necessity. Many undergraduate research students are in their third or fourth year of college and have entered the cognitive level to understand that their learning is strengthened by moving up Bloom's taxonomy. As well as setting specific expectations, the mentor should teach the student about the learning process. A mentor may even take the time to explain the importance of Bloom's taxonomy to learning or why graduate programs need students to use critical thinking. If a student can understand that being required to undertake research is not meant as a barrier to success, but instead, meant to grow one's ability to learn, the student may put forth more effort and achieve greater comprehension.

Conclusion

Practical guidance based in research from a variety of fields has been provided pertaining to three common pitfalls found by mentors when undertaking undergraduate research. Tremendous time constraints impact the capacity of the mentor and student to interact. Researchers must ensure that the project given to the student is well-defined and attainable to the undergraduate. The mentor must also construct a work environment that recognizes personal individuality and constraints in student preparedness. Lastly, the initial interactions between mentor and student need to address the significance of the research to the student as a mechanism for the growth of the student. Habits and misconceptions can be a barrier to learning (Angelo, 1993) and should be acknowledge and addressed so they can be overcome by the student researcher.

This metacognitive contemplation will set the stage for the beginning of the transformative process via undergraduate research. Being aware of these hurdles and understanding how to overcome each will increase transformative learning growth of the student researcher. This will allow for deeper understanding and increased retention via the research experience, strengthening the process and outcome of the research itself, and therefore benefiting both mentor and student. When a student is motivated, provided the resources, and given the knowledge to explore classroom concepts at a deeper level, he or she can become a lifelong learner in a rapidly changing world (Christie et al., 2015). Undergraduate research provides this experience and allows for an excellent opportunity for a transformative educational experience.

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Transformative Learning in Client Based Research Projects

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Abstract

Using client-based research projects can be a difficult but transformative learning experience in introductory courses. This essay incorporates three voices: a research client, a student, and the course instructor and explores the transformative learning of each. Each person shares the disorienting dilemmas he or she faced in a course that encouraged productive failure. Productive failure on a client-based research project as a feature of transformative learning is the innovative and key element of the introductory course. The shared dialogue among the client, student, and faculty member illustrates how transformative learning leads to better course design and enhanced student learning.

Keywords: project-based learning, productive failure, transformative learning courses

Transformative Learning in Client-Based Research Projects

Project-based learning (PBL) allows students to see the connection between concepts presented in class and their application in the real world. Today, faculty frequently adopt a pedagogy that includes PBL rather than straight lecture reporting increased student engagement, motivation, and academic gains (Perrenet, Bouhuijs, & Smits, 2000). Many faculty members scaffold their PBL so that students can achieve success. Instead, this paper examines the role of failure in project-based learning and its relationship to transformative learning theory. The sequence of steps in transformative learning theory: experiencing a disorienting dilemma, critically reflecting on the dilemma, engaging in dialogue with others, and developing an action plan (Mezirow, 1997) provide tools by which students can transform failure into success. We suggest that adopting transformative learning techniques and allowing students to experience productive failure leads to greater student confidence and the acquisition of important project management skills.

Typically, introductory courses use carefully scripted projects to teach students ideas and skills while methodically working through new materials. Such projects are unlikely to mirror real-world experiences. This essay explores an alternative approach, the incorporation of undergraduate research projects into an introductory course. When students encounter non-scripted, client-designed projects in an introductory course, it can be disorienting, but also lead to a transformative learning experience. College students who tackle real-world projects for the first time often are surprised by the clients' expectations regarding required levels of communication, academic skills, and knowledge. Students accustomed to success in traditional classroom settings become rattled when their skills and knowledge are not sufficient for the task the clients want them to complete. They may begin to perceive the project as a failure.

Similarly, outside clients who agree to have work done by these students may overestimate the students' abilities or skill level. Clients may think they are receiving free help from a well-prepared student team with current skills and knowledge. When the student team fails to communicate, does not grasp the work, or are simply missing the necessary skills, the client becomes frustrated. When the client's expectations are unmet, students also may perceive the project as a failure. Both the experience of perceived failure and the ability to work through this experience are at the core of transformative learning.

The careful design of an undergraduate course that includes a research project, along with the management of student and client expectations, can facilitate transformative learning. Undergoing this transformation enables students to move forward confidently and clients to feel good about participating in an important learning process. By incorporating three voices: a research client, a student, and the course instructor, we explore how expectations, definitions, and experiences of failure enhance PBL and become the building blocks of a transformative learning experience.

Literature Review

To understand the motivations and context of the course, we first examine how it fits within the curriculum. The course discussed in this study is "Introduction to Data Science," the first disciplinary course that data science majors take, although it occurs during their 2nd (or later) semester at the university. Thus, students have not (necessarily) spent time understanding what the field of data science encompasses. Typically, they have some vague ideas, based on pop-culture, other courses, or secondary education in mathematics, statistics, and computer science.

Whether or not students understand what data science is, they all enter the course lacking "data acumen," a skill widely accepted as a necessary component of data science education. Data acumen refers to the ability of students to "make good judgments, use tools responsibly and effectively, and ultimately make good decisions using data" (Committee on Envisioning the Data Science Discipline: The Undergraduate Perspective et al., 2018). The 2018 report from the National Academy of Science, Engineering, and Medicine (NASEM), and other literature hypothesizes that the best way for students to develop this skill is through projects working with real data. Typically this occurs in upper-level, capstone style, or graduate courses (Saltz & Heckman, 2016). However, in designing the course, the professor felt that through a *transformative project-based learning experience*, students' acquisition of data acumen could begin earlier.

Regular use of project-based learning in upper-class or capstone projects is due to several features (Balzotti & Rawlins, 2016; Cooke & Williams, 2004; Kramer-Simpson, Newmark, &

Ford, 2015; Rice & Shannon, 2016). Project-based courses engage students because they contextualize new learning (Corbett & Hill, 2015; Hill, Corbett, & St. Rose, 2010) and present realistic problem cases. Project-based courses motivate students to enhance their knowledge and acquire twenty-first-century skills (Savery, 2006). Twenty-first-century skills as identified by the Partnership for 21st-century learning (P21) include creativity and innovation, critical thinking and problem solving, flexibility and adaptability, initiative and self-direction among others (Partnership for 21st Century Skills, 2009). By completing projects, students construct a personal portfolio of examples to draw on in future endeavors (Helle, Tynjälä, & Olkinuora, 2006). All of these aspects make PBL fit extremely well with its typical placement in advanced or capstone courses.

Despite the benefits of PBL, there are many challenges to using it in introductory classes. Butler and Christofili (2014) talk about the lessons they learned when introducing first-term college students to PBL. They describe a situation in which the final project was incomplete. Course integration was therefore limited, and students resented others for not doing their fair share. Based on their initial failures when using PBL, Butler and Christofili suggest projects need to be well defined, laid out systematically, and interesting to students, for PBL to succeed. By the third time they taught the class, they provided students with more preparation at a lower level, included more systematic and detailed instructions, and more slowly decreased their hands-on support. Scaffolded problem-solving activities with a gradual reduction in supports as students gain expertise is paradigmatic of PBL (Puntambekar & Hubscher, 2005). Butler and Christofili's (2014) experience show the progression from students experiencing minimal learning, either immediately or long term, to a design that helped students master the short term content and retain it for future use.

Performance on a project is not always a good indicator of how much one has learned. Kapur (2014, 2016) argues the disparity between learning and performance may have at least four outcomes: productive success, productive failure, unproductive success, and unproductive failure. In the context of PBL, "failure simply means that students will not be able to generate or discover the correct solution(s) by themselves" (Kapur, 2016:289). Meanwhile, many scholars have touted the educational benefits of productive failure (Ferrandino, 2016; Kapur, 2014, 2016; Lai, Portolese, & Jacobson, 2017; Leong, 2013). Both productive failure and productive success maximize learning in the long run. Productive success also maximizes performance in the short run while productive failure does not. Essentially, Butler and Christofili's (2014) experience describes the movement from unproductive failure to productive success. While they ultimately achieved productive success through PBL, we propose that designing a course to take advantage of productive failure may be better for introductory course design within a major.

Introductory or foundational courses typically prepare students to do more extensive work within a discipline. Productive failure by design forces students to work together to use what they know in new ways. It may result in less than ideal deliverables, yet the process is often helpful in preparing students to work on future projects (Kapur, 2014; Kapur & Bielaczyc, 2012; Schwartz & Martin, 2004). Thus, productive failure is especially helpful in foundational courses where one student learning objective is: preparation for learning from subsequent instruction (Kapur, 2016). Additionally, productive failure may better mimic future work environments and give students the opportunity to develop important work management strategies. One way to incorporate productive failure into projects is to use transformative learning theory in the course design.

Transformative learning emphasizes a paradigm shift (Mezirow, 1997) which helps students perceive success and failure differently. A transformational learning experience includes four key steps. The first two steps are a “disorienting dilemma” and “critical reflection” (Mezirow, 1997). Transformative learning requires critical reflection to make sense of the dilemma or perceived failure. To conclude the transformative learning experience, the third and fourth steps: dialogue and action are required. Through dialogue, the learners process their reflections and begin to reframe the failure experience. Typical actions that follow the dialogue include planning changes, acquiring new knowledge and skills for implementing the plan and building new competencies.

Transformative learning is a progression by which individuals move from discomfort and perceived failure to successful and productive future action. And while most of the literature focuses on students, transformative learning may be applied to clients and teachers (Swanson, 2010). Disorienting dilemmas are those that are unfamiliar to the individual. For students, and potentially for project clients, dilemmas include perceived project failure, unresolved communication issues, and behavior that does not conform to typical client-provider models.

Perceived failure is uncomfortable yet necessary. The discomfort lets the individual know that their traditional ways of operating are not working. If there were little to no discomfort, an individual would continue as he or she always had. Perceived failures motivate students, faculty, and clients to question their knowledge and think about new ways of problem-solving and working. The process of questioning and thinking about new ways is described by Brookfield (2015, 1995) as a model of critical reflection, which is similar to the dialogue step in the transformative learning model.

The critically reflective dialogue step asks individuals to examine their assumptions and actions from as many different perspectives as possible (Mezirow, 1997). When one shares one’s thinking with others, it helps the individual make sense of experiences, particularly those that are disorienting. In the following section, we illustrate this process of making sense of our dilemmas. Each author experienced some disorienting dilemmas as part of our work in this class. Each author has also critically reflected on his or her actions. Through the letters that follow, we replicate the dialogue process. The final section summarizes this case and the transformative learning that occurred.

Shared Dialogue and Critical Reflection Letter from a Client

Dear Professor and Student(s),

Thank you for welcoming me and my project into your class. Through this letter, I will share my initial thoughts, critical reflections, and new thinking. Trying to recreate dialogue is hard but I think that if I share what I learned and how talking with you helped me see things differently, it might help others in the future. First, let me say that I was excited to learn that students were interested in my project. I anticipated that the students in this class would have statistics and database management skills much greater than my own. I also assumed they would be eager to learn more about student cheating and working on a real research project.

As I reflect, the project started well. I worked with three students who appeared eager to learn. We met initially in my office, and I gave them an overview of the project, explained what I hoped they would be able to do, and provided them with my data and some other resources. Getting more advanced statistical analysis of my data and having students think through questions about why high school students cheat were the outcomes I hoped to receive. After an initial meeting where I shared my goals for the project and some background materials, we agreed to meet every Friday.

Meetings quickly became the first dilemma I experienced. After the initial meeting, I'm not sure all students were ever present at a meeting. Sometimes two would show up, at other times, only one. I did not receive much communication from them regarding meetings or their progress. At most meetings, the student(s) did not have anything to show me. To me, that meant no progress. I was eager to see their analysis and talk about the meaning of the analysis, issues they may have uncovered, etc. Instead, progress was slow, and I did not receive any analysis that was particularly meaningful to me. In retrospect, Fridays proved to be a bad day to meet. I had to miss two or three due to conferences. Students sometimes needed to go home for the weekend and left on Friday. Eventually, there were large gaps in time between meetings.

Finally, I asked the one or two students who showed up for a meeting that occurred about 6 or 7 weeks into the project to tell me more about their work on the project. The students explained that there was little time in the class devoted to project work. With the other demands from this course, as well as their other classes, they were finding it difficult to get work done.

The second disorienting dilemma for me centered on student output. Because I did not see evidence of their work, I eventually gave up hope that I would receive any useful analysis from these students. I knew they were under stress and guessed that they felt bad about not providing me with more results. Upon reflection, I wish I was more direct with them. I was a client hoping to receive free statistical help on my project. I did not view the students as novices but rather as individuals who possessed advanced statistics and database skills. I failed to consider how little they might know about working with a client.

Through conversation with the professor after the class ended, I realized my mistake. If the University had a sign out front reading "Data Scientists in Training," I would have entered into this project differently. I would have realized that getting free help from people in training means I may not be totally satisfied with the output. I approached the students as if they were professionals with advanced data science and project management skills. As a client, I took a risk asking for free help from novices. I now see these students as learners in need of experience from which they can learn about data science AND about how projects using data may be constructed and developed 'in the real world.'

The role I wish I had played would be less 'client seeking solution' and more 'client paying it forward.' I hope that the relative failure of the project in terms of providing me with expert data analysis still taught them valuable lessons. I realize that students need to develop project skills such as clarifying client expectations, arranging manageable deadlines, and communicating regularly about their progress.

The dilemmas of losing valuable work time to unproductive or canceled meetings, not getting what I thought I'd receive, and realizing that my unrealistic expectations played a significant role in the project's failure will help me approach future contracts with students differently. I will ask more questions and clarify my role. I hope to create an environment in which I can share the context of the project while they share their knowledge of statistics and database management systems. It is likely I will assume more of a managerial role and require meetings as well as proof of their work each week. I will seek to determine the level of knowledge of the student(s) and then assign tasks accordingly. I will also ask the student(s) how I can help them, and we will negotiate the workflow together.

Professor Letter

Dear Colleague,

As you consider running a client or project-driven course, I hope you will take a few minutes to consider some advice based on my experience. My course, *Introduction to Data Science*, was designed for beginning students, typically freshman and sophomores. It also typically enrolls several upperclassmen from various disciplines. All enrolled students are new to the field of data science. It can be challenging to design content for such a mix of students.

I included client projects, to expose students to the full data-science cycle, including addressing questions posed by a client. By experiencing the full cycle, students realize that what matters more often to the client is the summary and explanation of results. The actual mechanism for producing the results is often less relevant. Most students have previously seen data as something to be used in computations. They see math and statistics as operations to be applied to problems. A full-cycle project emphasizes the need to understand "why" the data answers the question, "why" results have meaning, and more. Shifting one's perspective from the mechanism (or "how") to a focus on the result (or "why") presents students with a mental dilemma. This dilemma can lead to a transformative learning experience that prepares them for future courses and professional environments.

The successful implementation of this design turned out to be far more challenging than I anticipated and involved much more than simply including projects. After two semesters of teaching the course, I have experienced as much transformative learning as my students. Originally, I believed that after I solicited projects and assigned teams, everything would run smoothly. I could provide students with a clear set of deliverables, a grading rubric, and due dates. Then the students would be able to take what they learned in class and apply it. Traditionally, in successful projects, students deliver a product or report that addresses the client's (actual) needs and questions. Here's my dilemma: using this model, only about 1/3 of the conducted projects were "successful." When so few of the projects were "successful," I realized there was a definite problem in my course design and delivery.

Another dilemma I experienced was that while the students achieved the learning goals I had for the project component, the students and clients often felt the projects were a failure. Even productive failures felt frustrating for students and clients. Clients were disappointed that they invested time and energy, yet, received minimal or no actionable/usable work. Students often felt they had failed, were concerned that their grades would be poor, and generally were unsatisfied. This frustration and disappointment was a major dilemma for me since, as designed, the projects in my course did not satisfy two of the major stakeholders. Let me provide an example.

One project was for a non-profit interested in knowing how long after a flooding event a house foreclosure happened. I had extensive conversations with the client and felt the question was reasonably specific and manageably scoped. It turns out that unique flooding events are difficult to identify. Moreover, when looking at foreclosure data, the housing market crash of 2008 and the annual cyclic behavior of seasonal foreclosures far outweighed any evidence of foreclosures from flooding. In this case, the clients did not receive an answer to their question. The students worked very hard, yet, failed at answering a seemingly simple question.

Did something go wrong with this project? That is a matter of perspective. The students did succeed in "answering" the client's question. The answer was simply negative about being able to predict foreclosures from flooding data. To view the project as a success required me to manage both student and client expectations. Could a different outcome have been achieved? Possibly, and for that, I want to pass on some more explicit advice.

Originally, I included client projects as a mechanism for increasing engagement and providing a target to apply the knowledge and skills students were learning. I thought the far more "important" part of the course was the traditional content that covered data science algorithms, data types, etc. After one semester, it was clear this was not entirely true. Therefore, I included a full lab day each week for project related work. After two semesters, I have come to realize I need to shift how I teach the course. I need to transform the design from being focused on data science knowledge to focus on the data science *project* life-cycle. I will be implementing several changes to both the content (more on project management, group dynamics, etc.), and how I run the class itself (include upperclassmen or graduate students as 'project managers'). If you would like more details, I would be happy to share them.

Student Letter

Dear Future Student,

In this letter, I will address the primary disorienting dilemmas of Project Based Learning as well as the transformative benefits I experienced. Entering college, I had a predisposed idea of what an "introductory" class should entail. These classes should include background details on the subject, surface-level descriptions, and controlled learning environments. However, I have come to realize that the unique PBL design of this course was beneficial in several ways.

Having very limited knowledge of data science, I was nowhere near ready to handle a project with an outside client. Reporting to professors and meeting academic standards have never been issues for me. However, dealing with real-life clients is much different. Outside clients do not have the same investment in your success as the university staff. I learned this very quickly. What my professor expected was primarily structured around meeting project deadlines. From the perspective of a student/teacher relationship, these guidelines seemed reasonable and achieving academic success was possible. Working with outside clients was not as simple.

Upon reflection, there is one key takeaway from the first dilemma I faced in the Introduction to Data Science course. This takeaway is that you absolutely need to understand your client and they need to understand you. This understanding includes their role in the company, their availability, and how valuable your project is to their future success. Client expectations differ, so setting realistic expectations are crucial. The client needs to understand that, although their project is important to you and you are shooting for successful outcomes, it is not your job. They need to be cognizant of your academic workload, as well as the fact that you can only dedicate a set amount of time to their project. Part of this responsibility falls on the professor in project establishment, but part of it falls on the student to be transparent with the client. It is essential that the client and student are on the same page at all times throughout the semester.

During my project, I failed in understanding our team's client. Specifically, I failed in understanding our client contact. Our client assigned a contact person with limited knowledge about the topic to work with us. Thus, a majority of the key decisions about project direction became subjective interpretations on our part. For students, not knowing the answers and feeling completely alone in figuring them out can be incredibly frustrating. Looking back, I have come to realize how different the project outcome may have been had our team known more about our client. While the client lacked knowledge about data, they may have been able to provide insight into other aspects of the company or created a bridge between our group and an employee contact better suited for our task.

My second dilemma, a lack of clear communication and power dynamics, flows from the first dilemma. When communicating with professors, addressing issues and sharing your feelings about course workloads is simple. However, with outside clients, these simple conversations seem incredibly daunting. A majority of this is due to the inherent power dynamics of a client-student relationship. These power dynamics were one of the main causes of communication failures. Students tend not to challenge the clients' wishes, making it increasingly difficult to communicate honestly. Clients expect you to achieve a level of success similar to that of a paid employee unless you tell them otherwise. Be reasonable about your availability and be honest about your expected commitment to the project. Had our group had more transparent communication and an equal relationship with the client, our work would have felt far more valuable.

The final dilemma I experienced had to do with the value of our work. We perceived that our project had little real value for our client. It is crucial that students feel that their work is meaningful. For my team, our project seemed incredibly trivial in the scope of our client's company. The client made no effort to schedule meetings, did not have any interest in hearing about our progress, and never seemed to care about the work we were doing. The lack of attention only reaffirmed my feelings of inadequacy. I struggled to find ways to be useful in the scope of a seemingly useless project. I looked to our client for instruction and was incredibly disappointed. I firmly believe this led directly to my failures in this project. At the end of the day, as "consultants," our job is to problem solve independently of the client. Had I understood that independence should be embraced rather than passively accepted, the project would have been much more beneficial for me. Instead of making excuses for lack of progress due to poor client leadership, I should have taken what I was given and run with it to create my own success.

After reevaluating the causes of my dilemmas, I have come to realize how much the course taught me. Despite my frustrations over the dilemmas I faced, I learned that the real world is messy. Clients can be unreliable, expectations can be unfair, and equal-opportunity communication is rare. To me, these lessons were key to my success in the year after this class. PowerPoint presentations and a clean, controlled project could not have taught me how to respond to real-life scenarios. Combining academics with the outside world is crucial to truly learning how to succeed in the workforce.

During an academic year, it can be difficult to see personal growth. Often, it takes another experience for an individual to realize how much they benefited from past experience. For me, that was precisely the case. At the time of the course, I felt only frustration with my progress. However, after reflecting on my dilemmas and discussing the learning with my professor, I am more ready to enter a summer internship.

Knowing I have experience in dealing with clients, I feel ready to enter the business setting. Critically reflecting on my past communication failures will allow me to interact with my future boss as well as other business professionals both maturely and confidently. For me, that confidence is where I felt the most transformative growth. The class allowed me to become confident in the course material as well as in my interpersonal communication skills. I have overcome the dilemmas of understanding a client, communicating clearly and fairly with someone of equal or greater professional status, and perceiving true value in my work. I feel confident in facing future professional settings without fear of failure.

Conclusion

Within this project, the student transformative process is U-shaped. Students often enter the class buoyed by their previous academic successes and excited by research projects which put them in the roles of employees with a needed skill set. Their confidence is high. However, as McEachern (2001) states, client projects challenge students in ways that “not even the best-written case study or end-of-the-textbook-chapter-exercise can duplicate” (p. 211). Students wrestle with research questions that are ill-defined, have failed directions of investigation, and require initiative or unique thought. Client projects can cause students’ confidence to plummet as they realize they are missing skills needed for work in the ‘real world.’ By setting the research project amid a full course, students can receive support and guidance in rebounding from an initial realization that they do not yet possess real-world level skills.

Moreover, we observed that by exposing them to this drop in their perceived abilities, then helping them reflect on the experience, students gain important maturity, insight, and skills. These gains enable them to successfully implement deeper projects in their junior and senior years. Thus, they transform from overconfident novices to realistic, skilled students.

For the instructor, transformative learning occurs when careful attention to student and client perspectives is used to design the entire process. The instructor has to work with both students and clients to reframe failure and learning. Reframing is vital to supporting a successful transformation experience in which everyone retains enough confidence to engage in future projects. Successful transformation is accomplished for the student, in part, through an academic grading method that weighs skill development and gains in knowledge along the way more heavily than the final deliverable given to the client. For clients, the instructor must help them see their role as part of the students’ learning process, as well as help them formulate realistic expectations about student work.

Clients enter the course with a variety of expectations. Some hope to receive ‘free’ help with thorny database or project issues while others simply want to work with students who may have the knowledge they do not possess. Given the client’s reflection above, the reader might wonder if it is worth the personal capital to recruit clients, or if clients return for future projects. While many clients did not receive a “successful” project, the majority did receive a positive return on their investment of time. In some cases, this was through the clarification process required to relay their questions to the students. In others, there was a partial success as students completed early steps in the solution generation process. And, as stated above, approximately

35% of the projects did achieve success. Based on personal communications between the instructor and clients, most clients left satisfied, and open to working on another project.

For transformative learning to take place, educators have to establish an environment in which several key conditions exist. To begin with, they must make sure those participating have complete information. They must understand power dynamics; it is important that all who participate in the dialogue are free from coercion and have an equal opportunity to advance, challenge, defend, and explain beliefs, assess evidence, and judge arguments. Individuals should be encouraged to examine their assumptions critically, as well as be open to other perspectives. Finally, those who participate should pledge to listen and work toward a synthesis of different views or find common ground. When these conditions exist, the work of examining failure and finding new ways of thinking and doing becomes easier (Mezirow, 1997). Thus, the three authors believe we were able to experience transformative learning precisely because we took time to talk about the power dynamics, especially those between the student and the adults (project manager and professor). Ultimately, the learning occurred because all stakeholders shared their thoughts, listened to others' perspectives, and together, crafted plans.

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The Role of Course-Based Undergraduate Research Experiences in Extending Transformative Learning to All Students

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Abstract

Meaningful undergraduate research experiences have traditionally been limited to elite students. Barriers on the student side, and incentive structures that reward faculty for mentoring high performing students, have served to maintain the status quo. As research confirms the multifaceted benefits derived from undergraduate research experiences, it is essential that they are extended broadly, so that a more diverse group of students can profit. This paper argues that shared elements of well-designed course-based undergraduate research experiences, including instructor scaffolding and collaborative dialogue, serve to both make undergraduate research more widely accessible, and foster the achievement of a transformative learning experience. This claim is supported by case studies of three different types of course-based undergraduate research opportunities that delivered transformative learning experiences to average students.

Keywords: Undergraduate research, transformative learning, experiential learning, high-impact teaching practices, economics, environmental and resource valuation, mathematical modeling, statistics

Introduction

Undergraduate research experiences have been championed as high-impact practices which foster the attainment of higher-order learning outcomes. Growth in the Council on Undergraduate Research (CUR), from its origins in the 1970's as a small group of private liberal arts chemistry professors, to an influential organization supporting and fostering undergraduate research in every discipline and type of academic institution, serves as a testament to the efficacy of undergraduate research. It remains an open question, however, whether these experiences also deliver transformative learning outcomes. We argue that well-designed undergraduate research experiences have the potential to deliver transformative learning outcomes, particularly when scaffolded within a course-based context.

Meaningful undergraduate research experiences have largely been limited to high performers (Siegfried et al. 1991; Bangera, Gita, and Brownell 2014; Seifert et al. 2014). Yet providing average students with the opportunity to create new knowledge can result in a transformative experience, and foster the attainment of higher-order proficiencies (Henderson 2016). Indeed, Seifert and colleagues found that the greatest benefit from these experiences may accrue to those in the bottom third of the critical-thinking distribution (Seifert et al. 2014).

Many factors contribute to the exclusion of students from undergraduate research opportunities, including barriers on the student side, as well as incentives that encourage faculty to limit research mentorship to high performing students. Some of these barriers disproportionately impact women, students of color, and first generation students (Bangera, Gita, and Brownell 2014). The exclusion of these groups will only serve to exacerbate existing achievement gaps. Given the transformational impacts associated with meaningful research experiences, it is imperative that the benefits of undergraduate research be extended to all students, not just a privileged subset. We argue that doing so effectively requires offering consequential research opportunities within a classroom setting.

This paper calls for the development of more course-based undergraduate research experiences, in order to extend the multifaceted benefits of undergraduate research to all students, not just high achievers. Doing so will also increase the likelihood of achieving transformative learning outcomes through undergraduate research, as engagement and dialogue with others have been shown to be key contributors to transformative learning (Feinstein 2004; Taylor 1998, 2007). We argue that it is imperative that the positive benefits of transformative learning be extended to all disciplines and all students, regardless of race, gender, or prior achievement.

In recent decades the dominant model of transformative learning has been that advanced by Mezirow (1991, 1996, 2009), but other conceptions—including the more subjective, even spiritual, focus articulated by Dirkx—have been influential as well (Dirkx 1997; Dirkx, Mezirow, & Cranton 2006; Friere 1971; Boyd & Meyers 1988; Pugh 2002, 2011). As research in the field increasingly moves towards investigating how best to foster a transformative learning experience, it is only natural that researchers explore proven high-impact teaching practices (Kuh 2008), such as service-learning and undergraduate research experiences (Kilgo, Ezell Sheets, & Pascarella 2015), to determine if such practices can also be potent tools for delivering transformative learning experiences.

Our approach to transformative learning is grounded in the work of Mezirow (1991, 1996, 2009), while also being influenced by the earlier work of Dewey (1938), which emphasizes the critical relationship between experience and learning. Building on this work, we argue that a key indication of transformative learning in quantitative fields is an essential shifting of the locus of motivation from external to internal. Furthermore, students who have experienced transformational learning within the context of undergraduate research demonstrate increased self-efficacy.

The present paper contributes to the nascent literature on the intersection of transformative learning and course-based undergraduate research by presenting results from course-based undergraduate research experiences in economics and mathematics. Each course involved authentic research experiences leading to the production of new knowledge. Critically, these courses were open to all majors, extending the benefits of consequential research broadly.

The course-based undergraduate research experiences reported on here confirm earlier findings that direct and active learning experiences foster transformative learning outcomes (Taylor 2007). We follow Henderson (2018) in defining undergraduate research experiences as those where: 1. the research question (and associated finding) is of interest to an audience beyond the classroom; 2. the scientific method, as practiced in the relevant discipline, is employed; 3. the outcome is not known in advance to either the student or the professor; and 4. findings are disseminated to a broader audience (Henderson 2018)

Course-Based Undergraduate Research in Economics and Mathematics

We present three case studies of course-based undergraduate research in mathematics and economics: environmental and natural resource valuation, mathematical modeling, and experiential statistics classes. All three are upper-level courses meant to develop students' higher-order proficiencies, including problem solving, oral and written communication, and the production of new knowledge. These classes were open to all majors, thus extending the benefits of consequential research broadly. In Dirkx, Mezirow, and Cranton (2006), Mezirow discusses contexts for transformative learning. All three cases we present have the social action, community, organizations, conflict resolution, citizenship, and mentoring contexts, which contribute greatly to the increased self-efficacy and deep-learning experienced by the students. The conflict resolution component is a central element of group work, as is the supportive dialogue within and across groups as students work collaboratively to see differently. These essential elements in supporting a transformative experience are natural components of a well-designed course-based undergraduate research experience, but are generally lacking in more traditional undergraduate research conceptualizations.

Direct and active learning experiences have been shown to be catalysts for transformative learning, particularly when those experiences involve personal engagement with an external community (Diduck et al. 2012). The experiential nature of these courses generates clear benefits for the students and is a key reason why they effectively enhance self-efficacy for students at all levels. Many of those drawn to quantitative fields like economics and math are "assimilators," people who are comfortable with abstract conceptualization and can consolidate learning through subsequent "observation and reflection" (Bartlett 1996, 148). Yet, research shows the majority of students learn best when provided the opportunity to grapple with concrete information from which they can construct meaning (Ziegert 2000). The learning theory literature also indicates that this inclination may be more pronounced within some groups, such as women and people of color, who are reported to learn better through concrete experiences and active experimentation than through abstract conceptualization (Bartlett 1996).

In each course-based undergraduate research experience detailed below, students transitioned from being externally motivated by the instructor or grades, to being internally motivated due to personal investment and interest in the research. In turn, the instructors experienced a significant improvement in their teaching. The interdisciplinary nature of the research projects allowed the instructors to utilize the resources they and students developed in other classes. For example, in mathematics, the instructor presents the undergraduate research produced by students in mathematical modeling and experiential statistics courses in subsequent Calculus classes. This has had a positive impact in recruiting and retaining students—particularly women and students of color—as seeing how mathematics is used to solve problems meaningful to students increases its relevance and motivates students to persist.

Too few students are afforded the opportunity to participate in transformative learning experiences. Below we provide models of three different types of course-based undergraduate research experiences which led to transformative learning outcomes. While developing meaningful course-based undergraduate research experiences does require a significant investment on the part of the instructor, sharing details of successful course models can reduce start-up costs and facilitate more wide-spread adoption.

Capstone Course with Community Engagement: Environmental and Resource Valuation

A course-based undergraduate research experience combining community engagement, structured teamwork, and concrete economic analysis made meaningful research accessible to average students, thereby, transitioning them from "learning economics" to "doing economics." In the process, students changed both their frame of analysis and sense of self. Three key elements of course design that proved instrumental to fostering transformative learning have been identified: 1. student-led design and execution of a concrete economic analysis; 2. community interaction; and 3. structured group work including reflective dialogue.

As a capstone experience, the course was targeted to senior-level students, but was open to anyone who had completed the foundational work in economics, which includes the 200-level economic statistics course. None of the enrolled students had previously taken an advanced statistics course. The class consisted of twelve students, five female and seven males, a typical ratio in economics at liberal arts colleges. A strength of a concrete, experiential course such as this one, is the impact it can have on an average student. None of the enrolled students were among the elite—the top 10% of economics majors. In fact, key metrics show that the sample of students enrolled in the course fell just below average relative to the population of senior economics students: average SAT score, mean GPA within economics and overall mean GPA were all lower than the population average (Henderson 2016). Thus, the course was truly serving the typical economics student, not the high achievers in the discipline.

The concrete form of analysis employed was contingent valuation methodology (CVM). CVM is a survey-based stated preference methodology commonly used to inform policy-making decisions. None of our students had done extensive work with CVM, thus the opportunity existed to learn a new methodology through investigation of the literature, modeling a life-long learning process. Additionally, CVM is a concrete form of economic analysis which produces data. The expectation is that having generated the data themselves, students will be eager to see what the data reveal, and thus will be intrinsically motivated to further develop their statistical capabilities. Further, their ownership of the data will make them more open to reexamining their previously held beliefs and perspectives, as well as revising those beliefs in light of newly acquired data. Finally, there is a natural fit between contingent valuation analysis and local policy, creating a ready constituency for the outside presentation of findings. Other concrete methodologies with which students are unfamiliar prior to the course, and which are well documented in the literature, would also work well, and could be chosen based on the professor's area of expertise. In this instance, though the instructor was familiar with the CVM literature, she had not personally conducted survey-based research, thus was learning along with the students, modelling life-long learning.

The scope of the course is ambitious for a single semester. The timeline had to be carefully developed to include the following essential elements: 1. Student engagement with the academic literature to identify best practices; 2. Student identification of the policy issue; 3. Student ownership of the contingent valuation survey process, including instrument design, survey deployment, and processing of returns; 4. Review and execution of statistical methods including database construction, data handling, programming, descriptive statistics, and linear regression; and 5. Presentation of findings in both written and oral form, including sharing those findings with community stakeholders.

Topic Selection

Making the transition from learning economics to doing economics, and in the process transforming both one's way of seeing the world, and sense of self-efficacy in the world, requires that motivation transition from an external locus to an internal locus. Having students collaboratively select the research topic fostered investment in the project and augmented internal motivation. Students started the process of topic investigation in small teams of three. An iterative pitch process was employed to achieve buy-in from all 12 students on a single policy issue. The class collectively evaluated proposals through constructive dialogue. Students discussed whether the issue was meaningful to the local community, suitable for valuation via CVM, and whether sufficient information could be obtained in a timely fashion to craft a survey instrument consistent with best practices. Students ultimately identified the issue of deer vehicle collisions (DVC) as a local community problem and developed a policy proposal to reduce DVCs.

Following topic selection, the class worked as a cohesive unit on this single policy issue. Some tasks were still assigned to small groups, but everyone was collaborating on the same research project. Overall, the process worked well, not only for the stated purpose of issue selection, but, also for consolidating mastery over material encountered in the literature (for greater detail on the selection process, see Henderson 2016).

Survey Instrument Development

The development of the survey instrument involved small-group work, individual or pair-based work, in-class collaborative work, and out-of-class collaborative work. Careful scaffolding of group work during early stages was essential for productive and thoughtful engagement, necessary conditions for transformative learning. Having access to a variety of successfully deployed survey instruments was critical during this stage, as were the models provided by the Champ et al. (2002), Whitehead (2006) and Whitehead et al. (2009) articles, along with the associated survey instruments provided by the authors. Instructors employing alternative concrete methods should take care to curate source materials which provide adequate scaffolding.

After the survey instrument and focus-group consent forms were submitted to the Institutional Review Board (IRB), our class hosted a guest speaker with expertise in conducting focus groups. Students took full ownership over focus-group script development, as well as the arrangements to recruit focus-group participants and secure appropriate meeting space. Moving in the world as community-organizing agents increased self-efficacy and internal motivation.

The experience of conducting focus groups ignited a passion for the project. In every focus group, teams encountered local citizens who cared deeply about the DVC issue. Focus group participants took the process seriously and expressed strong opinions on both the issue and the survey instrument. Students thus had the opportunity to engage in productive and challenging dialogue with community members, members of their small group, and the broader class. The impact of this experiential component, which entailed direct engagement with the community, was consistent with previous findings from the literature—it increased engagement and intrinsic motivation for all students and created a personal connection with complex academic material.

Survey Deployment and Analysis

Engagement in dialogue with focus group participants convinced students that their project was truly relevant to the local community and motivated them to assiduously follow best-practices in deploying the survey. Survey deployment is a hands-on process that requires organization, attention to detail, and problem solving. Drawing on these skills provided students who struggled with earlier assignments their own opportunity to shine. Additionally, the assembly-line approach, and the satisfaction of seeing the completed packages go out in the mail, helped to forge a team identity for the class as a whole.

There was a tremendous amount of excitement when responses began to arrive. Students arrived at the next class early, eager to see the returns for themselves. A profound curiosity about what they could learn from the data they had worked so hard to collect drove some students to do far more programming than was formally required; a clear indication that the locus of motivation had shifted from external to internal.

Presentation of Findings

Students presented the results of their findings to local policy makers including the County Administrator, President of the County Commissioners, and the Director of Public Works and Transportation. In addition to preparing presentation slides, students developed folders of materials for the officials, including a white-paper, graphs, and charts. Though not everyone served as a formal presenter, all students participated in answering officials' questions after the presentation.

The event had a powerful impact on the students. Upon entering the County Commissioners' meeting room, a hush fell over the students. They were initially intimidated, as the grandeur of the room drove home the point that this was to be a serious, professional, presentation. The change in the students over the next hour was visible, as their carriage and demeanor changed. They engaged professionally with the public officials, whose genuine interest—demonstrated by their detailed questioning regarding the research findings—confirmed the relevance of the students' work to the broader community, and established that they had, indeed, created new knowledge.

Mathematical Modeling

The senior-level mathematical modeling course described below provides a course-based undergraduate research experience open to all majors. Essential elements of course design that contribute to transformative learning outcomes include collaborative dialogue, critical engagement with the relevant academic literature, and student determination of the research project. Additionally, well-designed scaffolding of the research process opens this consequential research experience to a broad range of students.

Mathematical modeling is about the representation of physical, biological, and other real-life phenomena by mathematical "models" to better understand and make predictions about these meaningful phenomena. It can be argued that modeling is the quintessential aspect of applied mathematics, and therefore, as students begin to master model, they become practitioners of applied mathematics.

Mathematical modeling is a senior-level elective course offered by the Mathematics Department every two years. Linear algebra and differential equations are pre-requisites for the course which is usually taken by students at the junior or senior level. The class size ranges anywhere between 6 and 20 students. Modules covering models addressing issues related to epidemiology, climate change, social networks, social justice, environment, mathematical oncology, and classic literature have all been employed. In each module, the basic principles, field specific background information, and required mathematical methods are introduced.

The modeling process in its entirety is a transformative learning experience. Modeling begins with an awareness of, and curiosity about, a real-world phenomenon. It is essential to understand the relationships and laws that govern a phenomenon in order to define the relevant set of assumptions and critically assess them. The recognition that there can be new ways to approach a problem, potentially leading to the discovery of new knowledge, motivates the act of modeling. It requires questioning existing models and their assumptions. Once a mathematical model is created, it must be checked against existing data for validation. Finally, a validated model may be used to make change in the world. Since a large part of modeling is applying principles of earlier models to new issues—such as imagining traffic as a water wave, thus revealing the possibility of utilizing water flow or fluid dynamics methods to solve a rush hour traffic problem—it encourages the modelers to be open to new ways of seeing.

The traditional learning outcomes of the class include: being able to model physical processes with discrete and continuous methods by making necessary assumptions and then translating them to mathematics, solving said systems to make predictions about the future of the process at hand, improving the existing models by calibrating them, and finally, communicating mathematical findings in written and oral form. The assessment for student work is based on homework assignments, a midterm project and a final project with oral presentation and written paper components. The first half of the class involves critically reading 15 mathematical papers and analyzing them, reproducing various findings in some. In each of the four offerings of this course, a reference librarian was invited to provide instruction on information literacy, finding reliable sources, and creating an annotated bibliography.

Prior to the final projects, students work on mini-projects that the instructor provides. Those are inevitably shaped by the instructor’s interests, while also introducing students to a variety of different approaches to modeling. This scaffolding has been effective, since most students have not had prior research experience that required them to both select a research topic and develop a mathematical model relevant to the problem.

Although students have full freedom to choose both their midterm and final projects, the instructor has found providing a list of potential topics helps students to connect the modeling process to their own interests and lived experiences. When the students are free to choose their own research problems, it forces them to think about the issues they care about, examine their existing beliefs and assumptions around those issues, approach issues from new perspectives, and finally look at the phenomena from a mathematical perspective. As the work progresses, they need to determine what kind of simplifying assumptions they can make without compromising the essential features of the problem, what kind of mathematics they will need to use, and maybe more importantly, will they be able to answer the question they initially set out to answer? Each of these fundamental steps of mathematical modeling gives them an opportunity to understand the issue at a deeper level, develop a more open frame of reference, and take ownership of their projects.

Going into the final projects, students have eight weeks to define their problem, develop the model, draw conclusions and prepare a written and oral presentation. The final projects are done in groups of two since the projects require careful study of existing models, creative imagining and adaptation to suit their chosen problem, rigorous computation, and significant writing. During the problem identification stage, as well as while researching context, assumptions, and mathematical approaches, dialogue among the group members is essential. Weekly progress reports provide an opportunity for groups to present their progress, as well as struggles, to the class and receive feedback. This allows collaborative dialogue that facilitates an opening of perspective for all class members. Additionally, the class community becomes invested in each group's work, which reinforces larger-group cohesion, supporting transformative learning. The final reports are the first production of scientific writing for most students in the class. The structure of the course scaffolds this experience by incorporating a peer-review process, which further enhances the investment in one another's work.

Some examples of former final research projects are: "Oysters in Chesapeake: Are We Going to Have Any?", "Differential and Stochastic Models for the Ebola Outbreak,", "Analyzing the Gateway Hypothesis in Drug Use", "Anchoring the Geographic Profiles of Serial Murderers," and "Determining Crime Hotspots." One of the students who worked on the "Oysters in Chesapeake" project described the research experience as solidifying her identity as a mathematician. She later became a high school math teacher and reported that her experience in modeling an open-ended problem encouraged her to design similar experiences for her own students to help strengthen their creative problem-solving skills. Another project, "Mathematical model of the effect of poaching on Loxodonta cyclotis (forest elephant) populations," was developed by one student who aimed to show that poaching was not sustainable for elephant populations. The mathematical model did reveal that the elephant population under analysis was going to go extinct in less than a century, but contrary to the student's expectations the effects of poaching did not change based on the targeted sex of the elephants. This unexpected outcome highlighted the importance of using mathematical modeling to reveal the underlying structures which may not be obvious or intuitive, and thus the importance of being open to changing previously held beliefs.

The feedback for this course is overwhelmingly positive. In addition to students requesting to pursue their research in the form of an independent study the following semester, there has also been an increase in students applying for REUs in applied mathematics. The vast majority of students report increased confidence in their ability to use mathematical tools in meaningful ways.

Experiential Statistics: Service-Learning Courses in Economics and Mathematics

The authors collaboratively developed a service-learning based undergraduate research course centered on statistical methods. Well-designed service-learning courses have been shown to deliver a range of positive learning outcomes, including enhanced civic engagement, increased openness to alternative experiences and perceptions, greater awareness of context, increased ability to examine previously held assumptions and revise as appropriate, and deep learning which persists, and can be applied in different contexts (Markus, Howard, & King 1993; Eyler, Giles, & Braxton 1997; Sax & Astin 1997; Mabry 1998; Novak, Markey, & Allen 2007; Warren

2012; Celio, Durlak, & Dymnicki 2011). One section of the course was housed within economics, while the other was housed within mathematics. Most elements of course design were consistent across sections.

The course was designed to serve (pre-screened) local non-profit organizations by providing statistical consulting services. The instructors recruited partner organizations over the preceding summer and used a multi-stage screening process to identify organizations likely to benefit from a consulting partnership. Those that passed this initial screening were then required to submit a formal research proposal and description of available data. Ultimately six partner organizations were selected—three for each section of the course.

The pre-requisite for the economics section of the course was a lower-level statistics course; there was no similar pre-requisite in the mathematics section as statistics is not a required course in the mathematics major. There was no application process for students—the course was open to all students who met the (low) pre-requisite. Because students entered the course with varying levels of statistical competency, the first eight weeks of the course devoted a considerable amount of time to statistical instruction and syntax programming. Individual homework assignments and exams, worth a combined total of 25% of the economics course grade and 40% of the mathematics course grade, ensured that all students developed the required statistical competencies.

Early in the semester, students reviewed organization proposals to familiarize themselves with the mission of each organization, the research question(s) the organization sought to address, and the type(s) of data initially available. Students submitted essays at the end of the second week providing a detailed justification for their preferred client organization. Honoring research interests as much as possible, while also considering student strengths and weaknesses, instructors formed balanced consulting teams (three students per team in economics, five per team in mathematics).

Once consulting teams were formed, each group was provided access to the data that had been developed by the client organization. Teams re-examined the client proposals in light of the available data and began preparing for their initial client meeting by conducting outside research. Engaging with client data and proposals motivated students to master the statistical techniques necessary to complete a quality analysis. Motivation increased further following students' initial meetings with their client organizations.

Consulting teams were required to submit weekly project management reports which provided organizational structure and accountability, as well as creating opportunities for self-assessment and reflection. Details regarding the program management reports can be found in Henderson (2018). Each team met multiple times with their organization partner, with at least one meeting held on site at the non-profit.

Every team successfully created new knowledge that was useful to their partner organization. Teams produced white papers and methodology reports for clients and publicly presented their findings in a forum attended by community stakeholders and client organizations. Two different clients requested that their student consultants travel to present their findings at the organization's annual board meeting, experiences that further enhanced students' sense of self efficacy.

Conclusions

Well-designed course-based undergraduate research experiences incorporate elements such as instructor scaffolding and constructive dialogue that support students in working collaboratively to examine existing assumptions, consider alternative framings, validate alternative approaches empirically, and ultimately see differently. These components of course design are key to delivering transformative learning outcomes to students of all backgrounds. This paper has provided examples of three different types of course-based undergraduate research opportunities that incorporate these components of course design, empowering average students to enjoy transformative learning experiences. Course-based undergraduate research experiences should be offered more broadly, so that the profound benefits associated with undergraduate research generally, and transformative learning experiences specifically, can be extended to all students, and no longer reserved for a select few.

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