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Instructors' Decisions That Integrate Inquiry Teaching Into Undergraduate Courses: How Do I Make This Fit?

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Keywords

Inquiry teaching, Undergraduate, Instructional decisions, Teacher education

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Abstract

In this qualitative study, we describe and characterize the pedagogical decisions that three college instructors made to mitigate challenges they faced as they taught by inquiry, as well as the rationale for their decisions and their perceptions of the efficacy of their decisions. We found that instructors made a range of decisions, including reorganizing course content and structure, adding more opportunities for and models of inquiry practice, adding more opportunities for feedback and assessment, and enhancing scaffolding of the inquiry. Notably, single instructional decisions had the capacity to mitigate multiple challenges. The instructors were satisfied with many of their decisions, yet they continued to question the efficacy of certain decisions and to generate ideas for further changes to address their students' and their own struggles with inquiry teaching. Although many of their decisions reflected the instructors' responses to external factors, such as their students' needs or the logistical constraints of their classes or institutions, other decisions reflected the instructors' own development as teaching professionals. Our findings serve as concrete examples of how instructors can alleviate the challenges of inquiry teaching at the college level. Our results also highlight the need for appropriate instructional preparation and support for all students during inquiry teaching, regardless of their backgrounds or undergraduate majors.

Key words: inquiry teaching, undergraduate, instructional decisions, teacher education

Introduction

Science educators, researchers, and policymakers alike advocate for more student-centered teaching in higher education and for broader involvement of both science majors and non-majors in the practice of inquiry (Brewer et al., 2011; Healey & Jenkins, 2009; National Research Council (NRC) 2002, 2003; Sunal et al., 2008). Teaching methods that actively engage students in learning, such as inquiry teaching, have been shown to promote student learning and performance (Handelsman et al., 2004; Handelsman, Miller, & Pfund, 2007; Minner, Levy, & Century 2010; Wood, 2009). Yet, inquiry teaching is still not prevalent in undergraduate education (Boyer, 2001; Park Rogers & Abell 2008). Most undergraduate instructors employ didactic approaches to teaching science, with a focus on knowledge transmission, even though a large body of research has shown that these methods prompt memorization rather than conceptual understanding (Novak, 2002). Instructors continue to lecture even when they are aware of and agree with the problems of lecture-based

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instruction (Dancy & Henderson, 2008; Norton, Richardson, Hartley, Newstead, & Mayes, 2005; Walczyk & Ramsey 2003; Yerushalmi, Henderson, Heller, Heller, & Kuo, 2007).

Instructors at all grade levels cite a number of barriers related to their students, contexts, and institutions as well as their own skills and preparation that discourage them from teaching by inquiry (Table 1). For example, K-12 teachers report that their students have limited experience with student-centered and collaborative learning (Anderson, 2002; Park Rogers & Abell, 2008) and negative attitudes toward learning by inquiry (Garvin, 2003; Powell, 2003; Smith & Anderson, 1999; Volkmann, Abell, & Zgagacz, 2005). Teachers are also concerned about their own inability to teach by inquiry, adopt the roles required by inquiry teaching, and guide and assess group work (Anderson, 2002, 2007). Teachers' beliefs about science teaching and nature of inquiry may also discourage them from employing inquiry teaching methods. For example, some teachers believe that inquiry methods are only appropriate for high achieving students, and thus are in conflict with their responsibility to provide "science for all" (Anderson, 2007).

Table 1. Teachers' reported barriers of inquiry teaching documented in literature

Barrier	Example
Students' characteristics	
1. Background and abilities	Limited science knowledge; varying cognitive abilities, inexperience with student-centered learning, inexperience with collaborative learning (Park Rogers and Abell 2008; Yerushalmi et al. 2007)
2. Attitudes, habits, and behavior	Varying levels of ownership and responsibility; varying attitudes toward learning by inquiry; poor study habits (Garvin 2003; Powell 2003; Smith and Anderson 1999; Volkmann et al. 2005; Yerushalmi et al. 2007)
Instructors' characteristics	
1. Background and abilities	Inexperience with student-centered teaching; lack of knowledge about the benefits of inquiry teaching (Crouch and Mazur 2001; DeHann 2005; Handelsman et al. 2004; Pukkila 2004)
2. Beliefs of science and inquiry teaching	Commitment to cover scientific content; inquiry is appropriate only for above average or upper-level science majors; science teachers should provide "science for all"; science teachers should prepare students for the next level of schooling; inquiry teaching is difficult to manage (Anderson 2002; Anderson 2007; Blumenfeld et al. 1994; Dancy and Henderson 2008; Hodson 1988; Welch et al. 1981)
3. Conceptions of science and nature of inquiry	Positivistic views of science; views that the scientific method is a universal stepwise procedure; teachers' conceptions of inquiry are inconsistent with those of the scientific community (Abd-El-Khalick and BouJaoude 1997; Crawford 1998; Flick 1995; Fradd and Lee 1999; Lederman 1992; Windschitl 2001)
Contextual barriers	
1. Logistics	Insufficient time; large class sizes; inappropriate classroom layouts; limited laboratory resources (Anderson 2002; Cech 2003; Dancy and Henderson 2008; DeHann 2005; Henderson and Dancy 2007; Shulman 1993)
2. Lack of institutional support and incentives	Promotion based on research rather than teaching achievements; lack of incentives for improving teaching effectiveness; lack of collegial support (Boyer 1998; Cech 2003; DeHann 2005; NRC 2003; Shulman 1993)

College instructors face professional and contextual barriers unique to undergraduate settings that likely influence their choice not to teaching by inquiry. For example, instructors at research-intensive institutions are concerned about the amount of time and effort necessary to learn new teaching methods and the lack of incentives for improving teaching, especially when compared to the incentives for research productivity (Boyer, 1998; DeHaan, 2005). Some instructors fear that being identified as good teachers will reduce their credibility as researchers and delay their promotion (Cech, 2003; DeHaan, 2005; NRC, 2003; Shulman, 1993). Many instructors are not aware of inquiry teaching methods and their impacts on students' learning (Crouch & Mazur, 2001; DeHaan, 2005; Handelsman et al., 2004; Pukkila, 2004). Furthermore, college instructors generally receive little formal training to teach and do not have clear guidelines for designing and implementing their courses. Instructors report that contextual factors such as the time consuming nature of inquiry teaching, large class sizes, inappropriate classroom layouts, and lack of support from peers or institutions undermine their efforts to teach by inquiry (Cech, 2003; Dancy & Henderson, 2008; DeHaan, 2005; Henderson & Dancy, 2007; Shulman, 1993). In summary, college instructors view didactic instruction as aligned with their previous experiences and departmental norms, and as expeditious for "covering content" in a way that they believe fits their students' needs and capabilities (Dancy & Henderson, 2008).

Since college instructors face unique barriers to inquiry teaching when compared with K-12 teachers, it is important to explore how they go about overcoming these barriers. Yet, research on inquiry teaching at the college level is limited (Brown, Abell, Demir, & Schmidt, 2006). In their review of 79 studies of undergraduate science education reform, Sunal and colleagues (2008) identified only eight studies that clearly described strategies of inquiry teaching such as cooperative learning, instructor modeling, connecting inquiry concepts to real world problems or applications, and using varied approaches to assessment. None of these studies examined how instructors made decisions to revise their curricula or teaching practices, or how their decisions made it possible to overcome the barriers to inquiry teaching. Here we describe and characterize the experiences of three college instructors as they taught by inquiry for the first time, made decisions to mitigate the challenges they faced, and then taught by inquiry a second time. Throughout the process, we sought to understand their rationales for making particular decisions and their views of the efficacy of their decisions. Specifically, we asked the following research questions: (1) What practical decisions did the instructors make to overcome challenges they faced as they taught by inquiry for the first time? (2) What were the instructors' rationales behind particular decisions they made to overcome these challenges? and (3) What were the instructors' perceptions of the effectiveness of their decisions in terms of students' learning and their own beliefs about teaching?

Conceptual Framework

Inquiry teaching has "multiple manifestations" (Anderson, 2007, p. 810) and is defined differently by different researchers (Anderson, 2002). Here we define inquiry teaching as involving students in scientific investigation or problem solving in ways similar to those used by scientists (Brown & Campione, 1990; Crawford, 1999, 2000; NRC, 2000). During inquiry teaching, instructors engage students in asking scientifically oriented questions, formulating, developing, and evaluating explanations based on evidence, and communicating and justifying their explanations (NRC, 2000). The majority of studies of inquiry teaching in college classrooms focus on beneficial outcomes for students (Ballone-Duran, Czerniak, & Haney, 2005; Burrowes & Nazario, 2008; Cianciolo, Flory, & Atwell,

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2006; Edgcomb, Britner & Wolffe, 2008; Hake, 1998; Kardash 2000; Krockover, Shepardson, Adams, Eichinger, & Nakhleh, 2002; Lord, Shelly, & Zimmerman, 2007; Russell & French 2002; Staples, 2004; Wallace, Tsoi, Calkin & Darley, 2003). Thus, in this study, we sought to identify the ways that instructors can integrate inquiry teaching successfully into their courses, rather than re-demonstrate the benefits of inquiry teaching for students (Handelsman et al., 2004, 2007; Minner, Levy, & Century, 2010; Wood, 2009).

A number of studies have documented that implementation of particular instructional strategies, including use of varied approaches to assessment and use of cooperative learning, leads to positive student outcomes at the college level (Ballone-Duran, Czerniak, & Haney, 2005; Krockover et al., 2002; Staples, 2004). How college instructors go about making decisions to integrate inquiry into their teaching as well as their rationales for making particular decisions and the outcomes of their decisions have not been explored.

Methods

Context and Participants

The context for this study is the Inquiry Teaching Project (ITP)[1], which was initiated in 2007 at a large public research university in the Mid-Atlantic region of the United States to engage undergraduates in research in the context of their science courses. The goals of ITP are to: 1) involve undergraduates and their instructors in scientific inquiry that has both learning and science research objectives; 2) promote student understanding of the relationships among genes, biochemicals, organisms, and ecosystems; and 3) examine the impacts of engaging undergraduates in classroom-based research.

Through ITP, students address the unanswered question of how disabling genes in *Arabidopsis* plants, which are widely studied in plant biology, influences the plants' interactions with root and leaf herbivores. With instructor guidance, students design and conduct their own investigations to determine differences in herbivory of wild-type plants, which include all functional genes, versus mutant plants, which include one altered gene. Students report their findings to scientists interested in the studied genes. Thus, through ITP, students have the opportunity to make discoveries that relate to their scientists partners' research and be a part of a broader scientific community, while learning concepts in plant biology, genetics, ecology, and the processes and nature of science (Dolan, Lally, Brooks & Tax, 2008; Dolan & Grady, 2010; Lally, Brooks, Tax & Dolan, 2007).

The three instructors involved in this study are Julia, Michael, and Samantha who teach at a two-year community college, four-year liberal arts college, and a large public research university, respectively, in the Mid-Atlantic region. All of them are European-American, and none of them had taught using inquiry prior to ITP or have any formal training in teaching and learning. None were familiar with the literature on inquiry instruction, although Samantha attended professional development on Process Oriented Guided Inquiry Learning (POGIL; www.pogil.org) during her second round of teaching ITP. All the instructors learned about ITP from the director of the program (second author) and believed that engaging their students in inquiry could improve their students' understanding of processes of science and enrich their own teaching. Thus, they agreed to incorporate ITP into their courses.

[1] The names of the project and the participants involved in this study are pseudonyms.

Since they represent diverse institutions, science courses, and students as well as different levels of teaching experience, we found them suitable to participate in our interpretive study. All the instructors agreed to take part in the study. ITP was implemented by these instructors in three undergraduate courses in three different Mid-Atlantic institutions during Fall 2008 and Spring 2009 semesters, as described here.

Julia, instructor of an introductory biology laboratory course at a two-year community college

Julia has eleven years of experience teaching biology in the same two-year college. She completed her bachelor's degree in biology, and her master's degree and Ph.D. in molecular biology. As a post-doctoral researcher, she studied lipid biosynthesis in plants, including *Arabidopsis*. Julia believes that inquiry teaching helps students' critical thinking skills and conceptual understanding, and help students to make "more connections to their life, whether it's a social worker or whether it is a housewife." In addition, Julia sees inquiry teaching as an opportunity to teach differently. She disagrees with the traditional way of teaching science as "memorization of facts" and believed that involving her students with "real" inquiry is "much more worthwhile than giving them a cookbook."

Julia integrated ITP into a course that enrolled 15 students per section in three sections each semester (45 students total). Students, who were in their first year of college or sophomores and had not yet declared a major, attended one three-hour class per week in a typical laboratory classroom, and were not required to enroll in a complementary theory or lecture course. ITP was the primary course curriculum. The course included other lessons and activities related to ITP, including anatomical, physiological, genetic, and ecological aspects of the plants and herbivores that were used in the experiments. Although the students varied in their academic achievement and science background knowledge, most were lower achieving and had not completed other undergraduate science coursework. Many were the first in their families to attend college or received scholarships to support their studies because of financial need.

Michael, instructor of an introductory biology lecture / laboratory course at a four-year liberal arts college

Michael has two years of experience teaching undergraduate biology and completed his bachelor's and master's degree in biology. His doctoral research focused on root dynamics of forest trees. In his post-doctoral research he investigated interactions between plants and root herbivores. Michael sees inquiry teaching as "a way to get more personally involved in the class and as a way to get the students more involved in the class." In addition, Michael believes that inquiry teaching prepares his non-major students for further research studies in their own disciplines. He emphasizes the importance of being familiar with the idea of research as a part of students' life as citizens, stating that ITP "would help them understand what their tax dollars pay for because they are ultimately the consumers of a lot of research."

Michael integrated ITP into a course that enrolled 16 sophomore, junior, and senior students each semester, 20% of whom were science majors and 80% of whom were non-science majors. Students met twice a week for three hours each time for a combination of lecture and laboratory learning. The course content comprised plant and animal biology, with ITP as the major focus of laboratory learning and the only lab experience that spanned multiple class sessions. The course included a few related and unrelated demonstration labs. These students varied in their academic achievement and science background knowledge.

Samantha, instructor of an upper level, plant biology course at a research university

Samantha has eleven years of experience teaching undergraduate and graduate plant physiology courses. She had completed her bachelor's degree in biology and poultry science, her master's degree in poultry science, and her Ph.D. in plant pathology and physiology. Although Samantha's primary appointment is in teaching, she continues to conduct small research projects related to her master's and doctoral work. Samantha believes that involving her science-major students in inquiry is necessary for developing their science research skills and to "allow them to see what research is really all about." She sees ITP as an opportunity to "give some [professional] direction" to students who are interested in further education or careers in science. Samantha also believes that inquiry teaching could enhance her creativity and innovation as a teacher.

Samantha integrated ITP into a course that enrolled 22 junior and senior science majors (*e.g.*, horticulture, biology, environmental sciences majors) and met twice a week for 75 minutes each time. The course curriculum included organism and ecosystem level concepts, as in the introductory courses, but also included molecular and cellular concepts such as the functions of enzymes and other biochemicals in plants. ITP was the only laboratory learning experience in this course, which was otherwise taught in a lecture format. In comparison with students in the other two colleges, these students were higher achieving and had completed more science coursework. Some had even completed science research internships.

Implementation of the Inquiry Teaching Project

ITP was embedded in each course for approximately ten weeks. In the first three weeks, the instructors taught concepts related to ITP, such as characteristics of *Arabidopsis* and the herbivores and the meaning of genes and mutations, using lectures and class discussions. In the next seven weeks, the students worked in groups of two to four to design and conduct their experiments, including: (1) planting their *Arabidopsis*, (2) brainstorming and selecting research questions and generating hypotheses, (3) developing experimental plans, including selecting variables to measure, planning ways to observe and collect their data, and drafting research proposals for feedback and revision, (4) infesting plants with herbivores according to their revised plans, (5) making observations, recording data, and taking care of their plants, (6) analyzing their data, interpreting their results, developing conclusions, and considering the implications of their results, and (7) presenting their final research in class and/or writing a final report or paper. All three instructors provided detailed instructions and written guidelines for each phase. They interacted with the small groups throughout ITP, providing feedback to students and directing their thinking. In addition, the instructors led whole class discussions, mainly regarding aspects of designing an experiment plan, collecting and analyzing data, and interpreting results.

Because the course formats differed, the introductory course instructors dedicated more in-class time for plant care-taking, making observations, and collecting data, while the upper-level students were expected to complete these activities outside of class. Michael and Julia dedicated about half of class sessions each week to ITP. Samantha dedicated a class session for planning experiments at the beginning of the inquiry, and three class sessions toward the end of the inquiry, one for groups to finish their analyses and prepare their final presentations and two for groups to present their work. Samantha also spent 15-20 minutes per week answering students' questions about collecting and analyzing data and checking students' progress in conducting ITP.

Data Collection and Analysis

Data were collected by the first author through semi-structured interviews (Merriam, 1998; Patton, 2002), which were audiotaped and transcribed verbatim for analysis. The instructors implemented ITP twice[2] and were interviewed three times, once at the beginning of their involvement, again after one round of ITP, and again after the second round (interview questions are included in the Appendix). The first interviews were used to identify each instructor's expectations about teaching by inquiry, including the challenges they expected to face in teaching by inquiry. The second and third interviews were used to identify each instructor's experience with teaching by inquiry. During the second interview, the instructors were asked about changes they would make when teaching by inquiry in the future. During the third interview, the instructors were asked about the changes they actually made and their rationales or explanations for each decision. All class activities related to ITP were videotaped and used to confirm the statements instructors made about their instructional decisions during the interviews.

A three-hour discussion among the instructors and program staff took place between the first and second rounds of ITP, which was also audio-recorded and transcribed verbatim. While the first author observed the meeting and took field notes (Angrosino, 2005), the second author led the discussion with the aims of encouraging idea sharing among the instructors and getting feedback to inform further development of ITP. The instructors discussed their expectations for their students, themselves, and the program, as well as the impacts of the program on their students. This discussion helped clarify the main challenges the instructors faced in teaching by inquiry and their recommendations for addressing these challenges. Triangulating these data sources helped to enhance the trustworthiness of the findings (Lincoln and Guba, 1985).

Content analysis of the interview transcripts was conducted to identify emergent categories and major themes. Validation of the themes occurred in three phases. The first author reviewed the transcripts for repeating ideas and created an initial set of codes for analysis. Then, two other researchers (second author and a postdoctoral researcher studying a similar inquiry program) used the initial set of codes to analyze the transcripts independently, generating new codes as necessary. The three coders then engaged in a consensus-reaching discussion about their codes, affirming the initial set of codes, agreeing on the establishment of new codes or the combination of existing codes, or removing codes not supported by the data. Only quotes for which the researchers reached full agreement about the coding are included here.

Results

Here we present the decisions that three college instructors made to mitigate challenges they faced as they first involved students in inquiry in their courses. We describe the rationales behind their decisions as well as their perceptions of the efficacy of their decisions, in terms of students' learning and their own beliefs about teaching, as they taught by inquiry a second time (Table 2). We elaborate on how the instructors' decisions relate to the unique opportunities and challenges afforded by inquiry teaching. We also present their ideas about their plans to teach by inquiry in the future, including decisions

[2] Julia implemented one semester of a pilot version of ITP in Spring 2008. Thus, she taught by inquiry for one more semester than Michael and Samantha.

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they expect to make as they do so. The instructors' decisions fit into four themes: (1) Reorganization of course content and structure, (2) Addition of more opportunities to practice and model inquiry, (3) Addition of more opportunities for feedback and assessment, and (4) Enhanced scaffolding of the inquiry.

Table 2. Instructors' decisions and perceptions of efficacy

Decision	**Julia**	**Michael**	**Samantha**
Reorganizing course content and structure			
1. Emphasizing connection between inquiry and the "real world" or daily life	● (gray)	○	○
2. Changing the order of topics	●	●	○
3. Cutting topics / "covering" less content	●	● (gray)	● (gray)
4. Adding topics	●	○	●
5. Starting inquiry earlier in the semester	● (gray)	●	○
6. Postponing due dates for assignments	●	○	●
Adding more opportunities and models for inquiry practice			
1. Including more opportunities to practice inquiry tasks	●	●	●
2. Providing examples of other students' work	●	○	○
3. Encouraging students to use their peers' work as a model	○	○	●
4. Making scientific reading materials available	● (gray)	○	● (gray)
Adding more opportunities for feedback and assessment			
1. Including more discussions	●	●	●
2. Clarifying guidelines and expectations for student work	● (gray)	●	○
3. Involving a teaching assistant	●	○	○
4. Using more formative assessments	● (gray)	○	●
5. Introducing peer assessments	●	○	● (gray)
6. Making inquiry worth more of the course grade	●	●	○
7. Assigning tasks for individuals AND groups	○	●	●
8. Establishing a "participation" grade	○	○	●
Enhancing scaffolding of the inquiry			
1. Improving classroom setting	○	●	○
2. Changing or fine-tuning protocols	●	●	● (gray)
3. Hiring a lab assistant to pilot test and refine protocols	●	○	○
4. Pointing out websites to demonstrate protocols	○	○	●
5. Decreasing number of independent variables from which students could choose	●	○	○
6. Encouraging students to collect data on fewer dependent variables	●	●	○
7. Stipulating that students must address a single research question as a class	●	●	○

○ - Instructor did not implement this decision

● (gray) - Decision was reported by the instructor as ineffective or partially effective

● - Decision was reported by the instructor as effective

Reorganization of Course Content and Structure

The instructors made a number of decisions to reorganize the content and structure of their courses to better align ITP with teaching of other topics, allow more time for students to complete inquiry tasks, and better motivate students to engage in the inquiry. Julia and Michael moved their teaching of topics related to ITP, such as mutations, *Arabidopsis* characteristics, and herbivore biology, to earlier in the semester so that their students had more background knowledge to conduct their inquiries successfully. Julia also added examples of how plant science research had medical applications so that her students could see how their inquiries had real world applications. Her belief was that "students often find plants very boring," and that illustrating how plant research had implications for human health would help students view plants as more interesting and relevant.

All three instructors recognized that inquiry teaching required much more time than lecturing and thus decided to reorganize their courses by cutting topics from their curricula. Michael and Julia decided to remove topics that they believed were too complex for introductory students or too disconnected from ITP, such as DNA replication, transcription, and translation. They recognized that teaching these subjects "did not touch any of the students" and interfered with doing the inquiry. Julia explained that the inquiry involved students in "collecting the data, analyzing the data, trying to organize the data, and all these processes need time." Julia and Samantha postponed due dates for inquiry-related assignments such that students had more time in and out of class to complete the work. All three instructors used the "newly found" class time for more student discussion which they believed improved the quality of the students' inquiries. For example, Julia dedicated more time for students to brainstorm and plan their inquiries, Michael added more discussions about data analysis, and Samantha dedicated more time for students to discuss preparation of their final presentations. The instructors reported that these discussions provided more opportunities for the students to better understand the rationale of their experiments or the meaning of their findings. It also motivated them to work, as Michael describes here:

> They enjoyed the analysis, trying to figure out what the data might mean. Then we also talked about what might be wrong… the students seem to grasp onto that idea very quickly, why this person's results might be different from that person's results.

Although the instructors cut topics in distinct ways to better align to the requirements of conducting inquiry, they expressed different degrees of satisfaction with "covering less content." Samantha explained that allowing more class time for students to think about the inquiry was more critical than adding lectures on new topics, although she struggled with this decision:

> When I saw how far along they were already, I gave them 15 or 20 minutes in class again to get together and talk… I lost a few lectures… They probably learned as much [as in the lectures]. It's okay, but it's just hard for me to back off.

Samantha's explanation reflects her struggle to change her pedagogical beliefs. She understood that her students need more time to discuss their investigations, but she was not entirely comfortable with relinquishing her role as a knowledge transmitter and controller of the class.

Michael tried to find a middle ground between covering content and allowing more time for inquiry. After one round of ITP, he planned to integrate ITP with teaching of ecology (*i.e.*, combining two previously distinct units in his curriculum) by asking students to think about their investigations in the broader context of plant-animal relationships in an ecosystem. Julia saw the decision to cut content as effective, but only after reflecting on how her course fit with other courses that students complete as part of their degrees:

> I am willing to accept that in one semester I do not think I can do all of it (*i.e.*, cover all of the content)… I am willing to just let certain things go and maybe just remind students that there is not a single semester, not a single course that will give the whole information to everything, that it is just one step in the whole process [of science learning].

Julia had an additional semester of experience with ITP. Thus, she may have been further along in her thinking about inquiry teaching, recognizing that effective inquiry teaching means covering less content and dedicating more time to support students' work.

Addition of More Opportunities and Models for Inquiry Practice

The instructors made several decisions to model inquiry practices for students and to give students more opportunities to practice inquiry skills. They made these decisions to improve students' preparedness for completing inquiry tasks, enhance students' understanding of how science works, better motivate students to engage in inquiry, and clarify their own expectations for students' work. Michael and Julia introduced additional activities during which students observed, collected, analyzed, and presented data. They reported that their students appreciated these activities because they felt better prepared to conduct their own inquiries, as Julia describes here:

> They were learning the importance of collecting data and being very diligent and very meticulous in recording the information, analyzing or organizing the information. For many, they really did not know how to put information in a table… they felt it was important to work on that prior to their experiments.

Julia decided to share previous students' notebooks and final papers to demonstrate her expectations for inquiry practice, including good data recording, proposal preparation, and final presentations. She reported that "it helped students, because once they saw examples of good and bad [inquiry practices], it was a little bit easier for them to try to do better than what they did." Because Samantha believed that ITP involved students in the ways that "real scientists work," she decided to use science research articles as models for inquiry practice, and encouraged her students to refer the existing body of scientific knowledge in their own work. She reported that discussing articles with students improved their ability to connect their own work to the rationales and methodologies in published articles. For example, she said, "they understood the idea about needing controls… one of the groups at the end said, 'If I had to do it over again, I would have this control [that was presented in the paper]'." However, Samantha reported that only few of her students used the articles she provided as references in their final presentations or looked for other literature to cite in their work. Julia generated summaries of science research articles, rather than expecting her introductory students to read primary literature, reporting that only the better students made reference to them in their final presentation and papers.

As students prepared their final presentations, Samantha also encouraged them to use their peers' work as models, hoping it would improve their ability to communicate scientific findings. She drew attention to the groups who were particularly skilled at communicating the purpose, methods, results, and interpretations of their investigations, hoping other students would learn from them. She reported that peer modeling, or "peer pressure" as she called it, was very effective:

> I said, "Oh, this group did a wonderful job of organizing their data and, if they don't mind, you could go talk to them and see what they did. Maybe you'd get an idea." You could see other groups that said, "Well, can I see what you did?" … [Scheduling class presentations over two class sessions] gave them a role model or yardstick to go by because the first three groups did an exceptionally good job. When the last group did their presentations, I was surprised because they had done a good job. I think part of that was because of peer pressure… I think me telling them, "You need to do this, this and this," probably didn't work as well as them seeing the other three groups… It motivated them to work… I saw a lot more camaraderie and working together the last two or three weeks than I saw the rest of the semester.

Once Samantha realized the impact of providing a "yard stick" of how to communicate about scientific investigations, she planned to use peer modeling when she taught using inquiry in the future.

Addition of More Opportunities for Feedback and Assessment

The instructors made number of decisions to provide more feedback to improve students' understanding of how science works, improve the quality of their work, better motivate students, and improve their own ability to evaluate students' work. All three instructors gave more formal and informal feedback, including small group, whole class, and out-of-class discussions. Instructors gave feedback primarily to direct students toward solutions for the problems they were facing as they planned their experiments and collected and analyzed data. Samantha added that interacting with students more frequently, especially outside of class when students were making observations and recording data, improved her ability to evaluate students' participation and grade accordingly:

> [This year] I knew who was here [in lab] and who wasn't. I knew how seriously they were spending an hour and a half counting aphids or did they just come in and do a quick little water… I know which ones put forth 100% effort and which ones didn't.

Julia and Michael made decisions that aimed to clarify their expectations for student work. For example, Julia simplified the instructions she gave to students for generating research questions. She did not find this effective, as some students still formulated research questions unrelated to the gene they were studying:

> Very few would really make the meaningful connection between the fact that you have an anthocyanin-deficient mutant and how that fits in their research. [They said], 'Let's see whether spider mites population will flourish better on wild type and anthocyanin-deficient mutant with more rain over less rain.' Basically, it's not really addressing the main focus of the project.

The purpose of ITP was to investigate the interaction between plants with altered genes and herbivores that consume them. Instead, the students Julia described here focused on studying the effects of environmental conditions on plants without considering the idea of genotypes. Julia saw students' selection of scientifically irrelevant questions as an indicator that they did not understand this element of the inquiry or see the purpose or value of studying organisms with altered genes.

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In contrast, Michael reported that simplifying instructions and communicating with groups to check their understanding and implementation of instructions improved his students' motivation and the quality of their work. Michael emphasized that his intention was to better guide students in inquiry, while maintaining its essential elements, including its student-driven nature and its embodiment of scientific practice:

> I need to be more prescriptive but I do not want to tilt the experiment too much in terms of me telling them what to do… They want to know exactly what to do and that sort of gets in the way of the process of what science is…"

Michael's reflective stance can be an example for instructors who must balance supporting students as they learn with reducing support as learners appropriate knowledge and skills.

Julia also provided more feedback to students by involving a teaching assistant (TA) who had previously participated in ITP. The TA answered students' questions, demonstrated protocols, and clarified scientific concepts. Julia reported that the TA's involvement not only improved students' scientific understanding and motivation, but also added an authentic dimension to the instruction "because the information doesn't come just from me but it comes from a student, somebody who is like the people who are taking the lab."

The instructors altered the formal feedback they gave to students in the forms of assignments and grading. For example, all three instructors gave feedback to students on their research proposals, and expected students to revise their proposals accordingly. As a result, the instructors felt more capable of evaluating students' progress throughout ITP rather than just at its completion. Julia also responded to her students' requests for more feedback by adding more written suggestions on their lab notebooks. She was disappointed, however, that few students used her comments to revise their assignments. She attributed this to their low motivation and willingness to put forth effort, which she planned to address in future years by grading the revisions. Another change Julia made in response to students' feedback and her two rounds of experience with ITP was to utilize research proposals and final presentations as the major summative assessments in her course, rather than the exams she had used in previous years. She felt that using exams as assessments was inconsistent with the nature of inquiry. Julia and Michael also attempted to more accurately reward students for completing ITP-related work, which required more time and effort than assignments students typically completed, by awarding more points for individual inquiry tasks. This decision also increased the weight of ITP in final course grades. They reported that this change improved students' willingness to invest more time doing the assignments.

After teaching ITP for three semesters, Julia questioned her choice to change the final ITP assignment from an oral presentation to a written research report:

> When students were writing their reports, it gives me a little bit greater insight into how much they really understood what they were working on... Presentations (force students) to organize their thoughts, to be very focused, and to try to clearly present the information in a relatively short time period. But, I cannot give a chance to every one of them to present. I don't know. To me, there is a different venue for each format… We cannot do all of it… I will have to choose one way.

Julia continued to question how best to assess her students. She believed students could demonstrate the depth of their understanding in a written report, and their ability to clearly and succinctly communicate their thinking in an oral presentation.

All three instructors struggled to balance assessment of individuals versus groups, and made decisions to reward students for successful work as individuals and in teams. Although they recognized the importance of teamwork for success with the inquiry, they decided to add more evaluation of individual work and participation. Samantha added more individual assignments so that she could reward individuals for investing more time and thought. Michael checked individual students' lab notebooks for data recording, observations, and analyses. He reported that this change considerably improved individuals' participation as well as the quality of data recording and analyses. Michael and Julia required individual students to submit final papers based on their group's work, providing a mechanism for summative assessment at the individual level. Julia further developed her peer assessment tool, asking students to assess the contribution of their teammates during each group activity. Although Julia reported that students felt uncomfortable assessing their peers and were inexperienced in doing so, she viewed this as an effective change because "more students became actively engaged, they realized that their peers could mark, instead of the highest value, the lower value if they don't do anything… [It] was like a catalyzer that profited all members to help out as much as they can."

Enhancing Scaffolding of the Inquiry

The instructors made several decisions to provide additional or improved scaffolding to students, either by simplifying the overall ITP design or by fine-tuning protocols so that they could be more consistently implemented. For example, in his second round of ITP, Michael stipulated that his students investigate a common research question. He explained that this strategy made it possible for his students to work around technical problems that would otherwise be insurmountable, such as death of the plants or failure to achieve infestation with herbivores. Specifically, students who had technical problems with some aspects of their investigations could combine their data with those of other groups, and thus finish ITP with an analyzable dataset. Michael indicated that this approach enabled students to consider their data as a group, better positioning them to draw conclusions based on statistical analyses of the entire dataset. Michael added that asking students to propose a common research question reduced their autonomy to some degree, but it enhanced his ability to simultaneously mentor multiple groups, which he thought was ultimately more fruitful for them. Julia made a similar decision but for different reasons. She preferred to give students more autonomy and found greater variety among experiments more interesting. Yet, she also asked students in a class to choose similar research questions because this structure made it possible for groups to be combined in response to attrition. The rate of attrition in Julia's institution is high: about 30-40% of her students in former semesters dropped her course, which caused problems with group work in previous semesters of implementing ITP. Again, she thought this decision enhanced the likelihood that students would collect sufficient data to be able to make interpretations and think about what their results mean.

Julia hired lab assistants to test and refine protocols to make them more novice-friendly. Thus, she avoided spending class time on improving methods and enhanced students' success with implementing technical procedures such as infesting with herbivores and maintaining controlled conditions. Samantha decided to change the particular herbivore her students used in the second round of ITP in order to ease students' management of their investigations. Unfortunately, working with this herbivore was equally challenging for students. After two rounds of ITP Samantha reported that, if she were more familiar with particular procedures, she could better mentor her students in implementing them. Since

Samantha was not familiar with the type of herbivores, and faced unpredictable issues with the procedure, she herself struggled with the experimental settings, as she described:

> The biggest problem with the whole experiment [second round of ITP] in terms of setting it up and getting the observations was with the aphids [the type of herbivore]… The aphids were so powerful and the plants were so weak to start with, that there wasn't a whole lot of stuff that they could look at in terms of collecting data…. The aphids also, because of the type of damage that they caused, I'm not sure the damage was as easy to see. I mean, how do you measure things like wilting? There may be a way, I just hadn't thought about it ... Some of the students wanted to look at eggs, which if this was in the real world and not in the lab setting, there might be some eggs, but there were no eggs… Because I wasn't that familiar with the herbivore myself, I'd done some reading on it and I realized that there probably are not going to be any eggs. So finally, I told the students to look at nymphs. Next year, once I'm more familiar with everything, it will be much easier...

Samantha's uncertainty about the inquiry procedures, coupled with her desire to maintain control in the classroom and continue in her role as knowledge transmitter, reduced her ability to help students navigate the challenges of managing their experiments. Her struggles also highlight the need for instructors, specifically those with extensive research experience, to be aware of the considerable differences between conducting investigations in research labs versus undergraduate courses. Samantha was more satisfied with her decision to show video demonstrations of ITP protocols in class, reporting that it helped students to complete procedures successfully.

All three instructors saw the complexity of ITP as intellectually demanding for their students, who had little if any experience with inquiry. Although the overarching design of ITP includes two independent variables (*i.e.*, herbivore and plant genotype), students have the freedom to choose between root and leaf herbivores and between multiple plant strains with different genotypes. Students also have the freedom to choose the nature of the dependent variables in their investigations (*e.g.*, plant mass, plant height, area of herbivore damage, number of infected leaves), as well as methodologies for recording and analyzing their data. Michael and Julia made decisions to better support their students in choosing among the myriad investigation options. Julia limited the plant genotypes that students could investigate, reporting that this change decreased students' confusion and simplified her classroom management. Michael and Julia did not stipulate which dependent variables students should investigate, but they did encourage students to collect data on fewer dependent variables. They reported that this decision was effective because students were able to think deeply about one or a few factors, rather than all possible observations or measurements, as they analyzed and explained their data.

Persistence of Inquiry Teaching

Despite the challenges the three instructors faced as they implemented ITP, all thought that inquiry teaching enhanced their students' learning. They reported that they intended to teach using inquiry in the future and that their experience with ITP influenced their understanding of inquiry teaching. Julia and Michael indicated that inquiry instruction improved their students' appreciation of science as a holistic and ongoing process. For example, Michael described the benefits of ITP:

> I really appreciate what the students get from a multi-week experience… they get to think about more over a period of time… When I didn't have ITP as a part of the

> course, we didn't have a lecture or activity on data analysis or data visualization or trying to collect and answer questions with data. It was mainly, "look at this organism …" It was more seeing rather than doing… One of the reasons that I was attracted to [ITP] was it allowed for incorporation of things like data analysis. And the project ran through several weeks, tied activities together over time so that they wouldn't be able to just have discreet units of learning that they could put down.

Michael added that, if he could not be part of ITP in the future, he would seek out other extended inquiry curricula. Julia explained that involving her student in inquiry was aligned with her belief that science learning should not be "memorization of facts." She also emphasized how ITP helped students develop holistic views of the process of science:

> I think, while (students) are working on a project like ITP, it helps them continue developing their critical thinking skills, looking at the results and the information with a little bit wider lens than usually they are used to. Very often, they focus very narrowly on just one particular detail, ignoring everything that surrounds it.

Samantha was less certain about continuing to teach by inquiry. She explained that her experience with ITP and in the POGIL workshop gave her ideas for future teaching. She still believed that involving science majors in inquiry was worthwhile, but could not fully embrace how her role as instructor would change:

> [In the POGIL workshop], I got a couple of ideas about things I can use in my class. Am I going to totally switch to [inquiry teaching]? No, because part of me is not 100% convinced that that kind of approach is perfect, not that any approach is. I still like to have a bit more control and lecture than this. Is it a good idea to incorporate? Yes! And I think I'm going to try to do that in regards to this project next year.

Samantha's ambivalence is consistent with previous reports that instructors continue to lecture even when they are aware of the value of inquiry teaching.

Discussion and Implications

We believe that instructors can use the decisions made by Julia, Michael, and Samantha as models for learning to teach by inquiry at the college level, across grades and majors. The fact that these instructors were able to make substantive changes in their teaching practice, thereby mitigating many of the challenges of inquiry teaching, should be encouraging to other instructors who are interested in teaching by inquiry but are hesitant to do so. Their decisions, as well as their rationales for each decision, indicated that these instructors faced challenges to teaching by inquiry that are widely reported in the literature (Table 1). In addition, some of their decisions were made as a result of considering students' requests for more feedback. The instructors made a number of similar decisions, even though their students, courses, and institutions differed widely. These similarities likely reflect the challenges instructors had in common, including their students' and their own inexperience with inquiry teaching. This finding is consistent with the large body of research on students' difficulties with active learning after many years of experience with more teacher-centered methods, regardless of their majors or achievement levels (Braxton, Milem, & Sullivan, 2000; Colbeck, Campbell, & Bjorklund, 2000; Michael & Modell 2003).

All three instructors reported they were satisfied with many of the instructional changes they made during the second round of ITP. This finding indicates that instructors believed that they successfully recognized, diagnosed, and addressed a number of obstacles to inquiry teaching. This finding is particularly encouraging: the instructors made significant improvements in their inquiry teaching practice in one class over two semesters. This demonstrates that instructors can make significant strides in their inquiry teaching abilities in a short time and without changing all of their courses. However, all three instructors noted additional ways to improve their inquiry teaching in subsequent semesters, indicating that they did not view the process of learning to teach by inquiry as completed.

The instructors in this study made diverse decisions that reflected their recognition that they had to make several substantive changes to teach by inquiry successfully. It was not necessary for the instructors to make multiple changes because each change had multiple outcomes. For example, all three instructors decided to add more group and class discussions, which they believed improved students' understanding of how science works, students' ability to work in teams, and their own ability to give feedback and evaluate students' work. Instructors should be encouraged that singular decisions can have broad effects on their own teaching and their students' learning. Indeed, instructors could prioritize one or two decisions, such as adding more formative assessments or offering peers' work as models, with the expectation of multiple positive outcomes.

The instructors expressed varying levels of satisfaction with decisions to cut topics, clarify guidelines and expectations, and change or fine-tune protocols. These differences could be a result of differences in their beliefs about science education. For example, differences in the instructors' satisfaction with cutting topics indicated that they differed in their beliefs about the purpose of science courses in college (developing understanding of core science ideas and processes versus covering content) or their roles as instructors (facilitators of students' learning versus knowledge controllers and transmitters). This finding highlights the relationship between instructors' beliefs about the purpose of science education and their experiences with inquiry teaching. Further research is needed to understand this relationship at the college level, especially how instructors' beliefs about science education change (or not) as they learn to teach by inquiry.

Differences in instructors' satisfaction with particular decisions also may result from misdiagnosis of the particular obstacles that they or their students were facing. For example, Michael and Julia both made decisions to clarify their expectations for student work. Michael was satisfied with this decision, indicating his students' work improved. Julia was less satisfied. Her rationale for clarifying instructions was her belief that her students misunderstood the point of generating research questions. However, the ineffectiveness of this change made her realize that the obstacle was not lack of clarity in her instructions but rather the gaps in students' knowledge about the idea and purpose of investigating plants with altered genes. This finding highlights the importance of careful diagnosis of students' struggles with inquiry. Dedicating more class time for students to reflect on and discuss their inquiry experiences would enable instructors to help students in "real time," as advocated in evidence-based teaching approaches (Handelsman et al., 2004, 2007).

Instructors' dissatisfaction with particular decisions may also derive from unrealistic expectations about undergraduates' abilities to conduct inquiry in a completely self-directed way (Brown et al., 2006). After one round of ITP, both Julia and Michael recognized that their students needed more assistance in navigating the process of inquiry for the first time. They made decisions to reduce the number of variables from which their students could choose, while maintaining critical aspects of the inquiry such as choosing variables to investigate, collecting, recording, and analyzing data, and making meaning of experimental results. After two rounds of ITP, Samantha remained frustrated that inquiry in the classroom did not proceed as smoothly as lab learning activities with predictable outcomes or as professional scientific research. Brown and colleagues (2006) recommend that instructors broaden their views of classroom inquiry to include varying levels of instructor guidance, ranging from teacher-directed to student-directed. Our findings support this recommendation and demonstrate how instructors can come to understand that offering guidance is necessary for students who have never experienced inquiry teaching and does not require sacrificing inquiry teaching in its entirety.

Based on our findings, we believe that on-going professional development programs that support college instructors in implementing inquiry teaching are needed. Most professional development for college instructors aims to improve instructors' knowledge and awareness of the positive outcomes of particular teaching approaches and provide brief, workshop-based modeling of these approaches (*e.g.*, Moog & Spencer 2008; Prince & Felder 2007). In contrast, programs that help college instructors make changes in response to their students' and their own struggles with inquiry in "real time" are limited. Ongoing support could provide instructors with responsive and timely teaching strategies. Professional development should provide opportunities for instructors to reflect on their experiences with inquiry teaching with more experienced instructors, share the challenges they face with colleagues, and get ideas about how to better diagnose and mitigate challenges. Professional development should also highlight commonalities and distinctions in the obstacles that instructors face as they involve different types of students in inquiry (*e.g.*, science majors and non-majors, introductory and upper-level students), and include discussion of ways to overcome particular challenges.

Steps are being taken to offer college instructors real-time support as they change their teaching practices. For example, the University of Wisconsin's Summer Science Institute requires participation by teams from each institution (Pfund et al., 2009). This model builds in collegial support through co-participation of colleagues, rather than relying on such support to grow serendipitously. Instructors are also utilizing the World Wide Web to consult with one another and with experts about pedagogical issues. Effective models involve mentoring by more experienced teachers (Dede, Ketelhut, Whitehouse, Breit & McCloskey, 2009). For example, the Inquiry Learning Forum at Indiana University supports Web-based communities of more and less experienced mathematics and science teachers through which they create, share, and improve their inquiry teaching practices (Barab, Schatz & Scheckler, 2004; Job-Sluder & Barab, 2004). Novice teachers in this program "visit" classrooms of more experienced teachers via videotaped lessons. These videos also include the experienced teachers' lesson plans and reflective commentary, as well as examples of student work and connections to state and national standards. A similar model could be utilized to make "real" examples of successful inquiry teaching practices available to college instructors.

Finally, substantive changes in college and university reward structures must be made to encourage instructors to adopt new teaching approaches and create student-centered classrooms (Brewer et al., 2011). McMaster University in Canada is a model of how structural and administrative changes can encourage instructors to adopt inquiry-based teaching (Justice, Rice, Dayle, Hudspith, & Jenkins, 2009). Specifically, the administration identified a group of instructors who taught by inquiry as examples for others to follow, engaged senior faculty members in curriculum development, and involved senior faculty members to influence others' teaching beliefs and practices. This example complements our results, both of which illustrate how barriers to teaching by inquiry can be overcome in higher education.

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Appendix

First interview: Instructors' expectations about inquiry teaching

1. Why did you decide to integrate inquiry teaching into your course in the first place?
2. What do you think could challenge or limit inquiry teaching in your course?
3. How are you going to deal with those challenges?
4. What do you expect your students to do in the inquiry?
5. How do you intend to structure your course to incorporate the inquiry?
6. What will you do to prepare your students to do the inquiry?
7. How much guidance are you going to provide to your students as they conduct their inquiries? Why?
8. How are you going to assess students' work during the inquiry?

Second Interview: Challenges faced, decisions made, and satisfaction with decisions

1. What were the challenges you experienced as you taught by inquiry?
2. What have you done to address those challenges? Why?
3. How did you structure your course to incorporate the inquiry?
4. Did you change your expectations of students and of yourself regarding integration of the inquiry into your courses?
5. What did you cut if anything? Why?
6. How much guidance did you provide to your students as they conducted their inquiries? Why? Would you change that?
7. How did you assess your students' work? Why? Would you change that?
8. What did you add besides the inquiry itself? Why?
9. How did you connect the inquiry to other course content, if at all?
10. What did you do specifically (*i.e.*, which activities) to prepare your students to do the inquiry? Why?
11. Would you have done these activities if you hadn't incorporated the inquiry into your course? Why or why not?

12. Which of these activities would you continue to do? Why?
13. What would you do differently next time you incorporate inquiry into your courses?
14. How would you change the structure of your course now that you have done it at least once?
15. Would you incorporate inquiry into your courses again? Why or why not?