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Effects of Inquiry-based Learning on Students' Science Literacy Skills and Confidence

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Keywords

Undergraduate, Laboratories, Inquiry-based learning, Science literacy, Self-efficacy

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Abstract

Calls for reform in university education have prompted a movement from teacher- to student-centered course design, and included developments such as peer-teaching, problem and inquiry-based learning. In the sciences, inquiry-based learning has been widely promoted to increase literacy and skill development, but there has been little comparison to more traditional curricula. In this study, we demonstrated greater improvements in students' science literacy and research skills using inquiry lab instruction. We also found that inquiry students gained self-confidence in scientific abilities, but traditional students' gain was greater –likely indicating that the traditional curriculum promoted over-confidence. Inquiry lab students valued more authentic science exposure but acknowledged that experiencing the complexity and frustrations faced by practicing scientists was challenging, and may explain the widespread reported student resistance to inquiry curricula.

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Introduction

Current science curricular reform efforts throughout the world have re-focused on the necessity of teaching students to make informed and balanced decisions about how science impacts their lives and to use scientific knowledge to solve problems (American Association for the Advancement of Science, 1993; Australia, 1998; Council of Ministers of Education, 1997; Millar, Osborne, & Nott, 1998). This type of learning is best accomplished using more student-centered active-learning strategies (e.g. peer instruction/discussion; problem- and case-based learning; peer teaching; team-based learning, and inquiry-based learning) (P.A. Burrowes, 2003; Crouch & Mazur, 2001; Knight & Wood, 2005; Smith, et al., 2009; Tien, Roth, & Kampmeier, 2002); (D. Ebert-May, C. Brewer, & S. Allred, 1997). Surveys of instructional practices suggest that inquiry-based scientific investigations have been widely embraced in college biology laboratory curricula over the past decade, reportedly ballooning from less than 10% to almost 80% of laboratory classrooms at universities in the U.S. (Sundberg & Armstrong, 1992; Sundberg, Armstrong, & Wischusen, 2005). While this change clearly demonstrates that efforts to promote reform in laboratory education have been successful, several questions remain unanswered. First, aside from surveys, there are little data indicating if this reported change corresponds to actual changes in instructional practices. Second, there is a paucity of published research assessing the impact of inquiry instruction as compared to more traditional instruction on college students' general level of achievement in science, science literacy, and confidence with respect to their scientific abilities. In particular, there are a lack of studies which assess changes to entire course curricula, instead, they focus on changes to individual lab activities (Rissing & Cogan, 2009). This study attempts to add to that knowledge by (1) clearly defining the types of inquiry-based activities developed for a non-science majors introductory biology laboratory course, (2) measuring changes in science literacy, science process skills, and self-confidence in doing and writing about science exhibited by the students engaged in the course, and (3) comparing skill acquisition and self-confidence of students taught using the inquiry laboratories and those taught with a more traditional approach.

Since its inception, the term "inquiry" has been burdened with an identity crisis (Barrow, 2006). Originally, the term was used to invoke the idea of teaching science in the way it is actually practiced by scientists—problem solving through formulating and testing hypothesis (Dewey, 1910; Schwab, 1960). But after decades of policy statements geared toward clarifying the definition of inquiry (National Academy of Sciences - National Research Council Washington DC. Center for Science Mathematics and Engineering Education., 2000), educators continue to debate exactly how to measure it in practice (Abrams, Southerland, & Silva, 2008; Chinn & Malhotra, 2002). Sundberg and Moncada (1994) describe several alternatives to traditional, didactic, "cookbook" type laboratories where students are told what to do and learn. One of these is the "inquiry" lab, which they credit to Uno and Bybee (1994) and define as a laboratory activity in which the instructor leads students to discover a specific concept after being prompted by a basic question or problem. More recently, Chinn and Malhotra (2002) developed an "authentic scientific inquiry scale," which characterizes the degree to which an inquiry lab requires complex reasoning processes as exhibited by practicing scientists. Using this scale to analyze published laboratory manuals, Chinn and Malhotra (2002) discovered that current high school inquiry tasks bore little resemblance to authentic scientific reasoning and were better described as simple inquiry tasks (including simple observations, simple illustrations, or even simple experiments). They argue that simple tasks where students are provided with a research question, protocol, and told what data to collect and how to analyze it vary dramatically from authentic inquiry where students choose the research question, variables, procedures, and must explain their results in light of other studies and theories. Clearly, research attempting to assess the benefit of inquiry instruction must first define exactly where the curriculum falls on this large continuum of inquiry activities in order to assess the impact of instructional practice as well as to compare results between studies.

Our labs contain many, but not all, of the attributes of Chinn and Malhotra's authentic inquiry but are best described as "guided inquiry." In guided inquiry labs, the instructor poses an initial problem such as in the "simple experiment" labs of Chinn and Malhotra but then guides the students in selecting variables, planning procedures, controlling variables, planning measures, and finding flaws through questioning that will help students arrive at a solution (Buck, Bretz, & Towns, 2008; Magnusson, 1999). This method avoids one of the serious problems found with adopting the "simple experiments" categorized by Chinn and Malhotra: laboratory exercises that reinforce the simplistic view that science involves completion of simple tasks to confirm or reject hypotheses rather than reasoning about complex methodological flaws (Chinn & Malhotra, 2002; Germann, 1996). Our "guided inquiry" approach also provides more direction to students who may be poorly prepared to tackle inquiry problems without prompts and instruction because of lack of experience, knowledge, or because they have not reached the level of cognitive development required for abstract thought (Lawson, 1980; Purser & Renner, 1983). The guidance provided by the instructor's questioning should provide that instruction and therefore lower student frustration levels while still maintaining a high level of intellectual challenge (Igelsrud & Leonard, 1988).

In addition to differences in how inquiry-based instruction is implemented, researchers have also differed in how they attempt to measure the effectiveness of this instruction. Decades of research from meta-analyses (almost all from pre-college instruction) suggest that inquiry instruction results in improved student learning (Lott, 1983; Schneider, Krajcik, Marx, & Soloway, 2002; Shymansky, 1990; Von Secker & Lissitz, 1999; Weinstein, 1982; Weinstein & et al., 1982). But, at the college level the data are mixed as to whether increasing inquiry instruction can significantly change student learning or attitude toward science (Berg, Bergendahl, Lundberg, & Tibell, 2003; Hake, 1998; Igelsrud & Leonard, 1988; Lawson & Snitgen, 1982; Leonard, 1989; Luckie, Maleszewski, Loznak, & Krha, 2004; Udovic, Morris, Dickman, Postlethwait, & Wetherwax, 2002). Most studies on the effectiveness of inquiry investigations have measured student achievement through acquisition of content knowledge, conceptual understanding, and overcoming misconceptions. Using these variables, studies have demonstrated increases in student achievement in inquiry lab classrooms (Basaga, Geban, & Tekkaya, 1994; Hall & McCurdy, 1990; Luckie, et al., 2004; Sundberg & Moncada, 1994). However, other researchers have found either little or no statistically significant differences in student achievement in inquiry labs (Jackman, 1987; Pavelich & Abraham, 1979), or have found increased abilities for reflection and ability to describe concepts, but not in general knowledge or comprehension (Berg, et al., 2003). Comparing these studies is somewhat difficult due to the fact that each differs in the type, scope, degree, and definition of the inquiry activities as well as the student populations and instruments used to assess the learning gains.

The underlying question behind all these studies is whether an inquiry teaching method attains the over-arching goal of science education—preparation of scientifically literate citizens. It has been argued that inquiry-based teaching methods are the best path to achieving scientific literacy because they provide students with the opportunity to discuss and debate scientific ideas (American Association for the Advancement of Science, 1993). Hogan and Maglienti point to this as the primary way practicing scientists evaluate scientific ideas and conclusions (Hogan & Maglienti, 2001). Most studies of the effect of inquiry instruction, however, have focused on measuring only one type of scientific literacy—gains in scientific knowledge. Norris, Phillips, and Corpan (2003) define this type of science literacy as "fundamental," and note that it includes simple recall of scientific principles. Norris *et al.* (2003) argue that there is also a second type of science literacy that they refer to as "derived," which includes the ability to transfer conceptual understanding and accurately interpret and evaluate texts dealing with scientific concepts (Norris, Phillips, & Korpan, 2003). This "derived" science literacy is the same set of skills a citizen would need when reading a newspaper article, interpreting published tables and figures, and making personal and societal decisions (Demastes & Wandersee, 1992). No study to date has measured the effect of exposure to inquiry laboratory activities on the scientific thinking skills that a college student would employ and find useful in their daily lives.

Our major goal for this study involved determining if the inquiry laboratories we developed could increase the "derived" science literacy skills described above. Our student population involved non-science majors participating in activities designed to focus on developing an understanding of how scientific knowledge is acquired and the critical habits of mind that must be used to evaluate popular reports of science that they would encounter in everyday life. More specifically, we examined: (1) whether students actually acquired skills for understanding and planning investigations; (2) whether they could transfer this ability to real-world activities and reports from their own lives, and (3) whether they expressed higher levels of self-confidence in these abilities.

Methods

Context of Study

The materials described in this study were developed for a non-science majors introductory biology laboratory class taken by university undergraduates to fulfill the life sciences general education requirement. The course met two consecutive hours per week in small sections of 20 students. Data were collected over two consecutive semesters (Fall of 2006 & Spring of 2007) from 72 lab sections with a total of 1300 students. Over both semesters, half the lab sections were taught in one room using traditional course content that had been taught successfully for over 10 years, the other half were taught in an adjoining room using a "guided inquiry" curriculum developed by the authors. Students registered for the laboratory course without prior knowledge about the type of instruction that they would receive. Demographic information including gender, year in school, and ethnicity were collected to demonstrate that there were no significant differences between students in the two lab treatments. Additionally, initial pre-test scores were collected for the instruments used in the study during the first week of labs for both lab treatments.

During both semesters, 6 teaching assistants (TAs) each taught 3 inquiry sections and 6 different TAs each taught 3 traditional sections. Four of the 6 original inquiry TAs from the fall semester returned to teach inquiry sections again the following spring semester, and one TA switched from teaching traditional to teaching inquiry labs. Training was provided to both groups in 2-hour weekly preparatory meetings. Inquiry-lab TAs were given an additional 4-hour, pre-semester orientation to inquiry methods which included: participation in an inquiry-based physics exercise, observation of videotapes of inquiry and traditional classroom exercises, and discussion of questioning techniques utilized in inquiry-based teaching. Inquiry TAs were also observed twice during the semester by their supervisors to determine the success of implementation of inquiry-teaching methods using a modification of the Reform Teaching Observation protocol (Sawada, et al., 2002).

Comparison of the Inquiry and Traditional Laboratory Curriculum

In the traditional labs, students worked in groups of three or four, following a detailed experimental design to carry out experiments with confirmational results. Each lab sequence typically lasted for one to two consecutive weeks. Students completed pre-lab assignments prior to class designed to prepare them for the lab activity and were quizzed on the previous week's concepts at the start of the class (Table 1). Short-answer quiz questions and two short essays comprise the extent of the writing required of students participating in the traditional labs.

To better focus on process of science skills advocated by the NRC standards, the "guided inquiry" labs (hereby referred to as inquiry labs) involved less step-by-step instruction. Instead, students were challenged to solve a particular problem though open-ended observation followed by opportunities for making and testing their predictions through a self-planned experiment. These problems usually revolved around a real-life scenario, such as measuring the overall health of a stream, or determining the optimum conditions for a brewing enzyme (similar to project-based science curricula of Schneider *et al.* (2002)). Each lab topic began with an introductory text from a popular science media report such as a newspaper account of a mother on trial for the euthanasia of her adult sons suffering from Huntington's disease or a "Consumer Reports" article on contamination of chicken with antibiotic resistant bacteria. Students were asked to apply what they had learned from the pre-lab homework assignment to design their own experiments.

In the inquiry labs, students worked in groups of three or four to plan, set up, and carry out their own investigations for each lab sequence, which typically lasted for two or three consecutive weeks. Students documented their thought processes in writing throughout the experimental phase and completed written final reports using a modification of the Science Writing Heuristic template (Keys, Hand, Prain, & Collins, 1999) that has been previously demonstrated to improve students' understanding of chemistry concepts as well as their ability to design and carry out experiments (Rudd, Greenbowe, Hand, & Legg, 2001). The benefit of these "writing to learn" methods stems from their ability to help students organize and analyze their thought processes in a way that encourages transfer of knowledge (McCrindle & Christensen, 1995). Because the inquiry lab course required so much writing, it was designated as a special "writing intensive" course and received additional support for the training of the TA instructors from a university-sponsored Writing Intensive Program. Students registering for the laboratory course, however, had no prior knowledge about this designation.

Science Literacy Assessment

A science literacy assessment, focusing on interpreting pragmatic meaning from popular reports, was administered for 30 minutes during the first and last sessions of the lab, and students received several points for completing the assignment. The science literacy assessment was a 30 question multiple-choice instrument that was previously developed (Norris, et al., 2003; Wheeler-Toppen, Wallace, Armstrong, & Jackson, 2005), and that we have continued to modify in order to increase test reliability (measured via a Cronbach Alpha analysis) (Hallar & Armstrong, in preparation). Internal consistency among a set of items suggests that they share common variance or that they are indicators of the same underlying construct (Spector, 1992). Thus, for the science literacy assessment we wanted to first establish a high enough reliability to ensure that this assessment could be used from semester to semester to accurately measure the constructs of science literacy. According to DeVellis (DeVellis, 2003), in order to use an assessment during an extended period of time, the reliability needs to be between 0.70 and 0.90 on a 1.0 scale. For our science literacy assessment the test reliability, using a Cronbach Alpha analysis, was $\alpha = 0.73$ for Spring 2007 but was only $\alpha = 0.63$ for Fall 2007. Thus, we only performed further analysis on the data we received from the Spring 2007 assessment. After analyzing inquiry and traditional lab students' pre test scores for differences, an analysis of covariance (ANCOVA), using the pre-test as the covariate, was used to determine whether the post-test scores on the science literacy assessment differed by lab type in the Spring 2007 student test responses.

Science Process Skills Assessment

The science process skills assessment was administered simultaneously with the science literacy assessment. The 30-minute assessment comprised 26 questions, 22 of which were multiple choice items modified from a previously developed instrument (Diane Ebert-May, Carol Brewer, & Sylvester Allred, 1997): see (Burns, Okey, & Wise, 1985; Germann, 1989; Tamir & Amir, 1987), for basis of test), measuring the ability to identify experimental variables, the ability to interpret data, and the ability to choose a graph that best represents the data provided. We modified the assessment to include: 2 multiple-choice questions that required students to perform quantitative skills necessary for conducting an experiment; 1 essay question that measured students' ability to design an experiment; and 1 question where students had to construct a graph when given data. These questions were specifically developed to assess whether students acquired these skills by participating in the labs. The original Science Process Skills Assessment examined different subsets of skills independently (Ebert May, *et al.*, 1997). Because we observed similar results for each skill subset, we report results only for the entire modified assessment. Test reliability was determined via a Cronbach Alpha analysis for the questions from the original instrument, our newly added questions, and the instrument overall. The composite post-test reliability including both the original questions used from Ebert-May *et al.* (1997) as well as the newly added questions had Cronbach's alpha coefficients of $a = 0.61_{(F06)}$; $a = 0.65_{(S07)}$. As discussed above, a Cronbach coefficient alpha value of 0.70 is considered acceptable when developing instruments (Nunnally, 1978). However, Ware *et al.* (1998) suggested that scales with reliabilities of 0.50 to 0.70 are considered sufficiently reliable for use in group comparisons (Ware, et al., 1998). After determining whether there were differences between lab types in pre-test scores, ANCOVA, with the pre-test as the covariate, was used to determine whether process skills post-test scores differed significantly by lab type.

Self-efficacy Survey

A self-efficacy survey, created and validated by Baldwin *et al*. (1999), was used to measure how confident non-biology major students were in their ability to understand and do science (Baldwin, Ebert-May, & Burns, 1999). The self-efficacy survey, administered online within the first two weeks and the last two weeks of the semester, was composed of 25 questions (6 demographic + 19 confidence questions) that were scored on a Likert scale (ranging from 2, totally confident, to -2, not at all confident). Baldwin *et al.* (1999) conducted factor analysis to verify that similar items consistently factor together and to condense the answers into one single value for a particular skill set. The factor pattern was varimax orthogonally rotated, which increases the absolute values of large loadings and decreases the absolute values of small loadings on factors within the columns of the factor matrix, resulting in a greater distinction between significant versus non-significant variables loading on each factor. They found that questions addressed students' confidence in performing three types of skills: (1) confidence in explaining and writing about biological ideas, (2) confidence in writing and critiquing a lab report, and (3) confidence in using a scientific approach to solve problems, including using analytical skills to conduct experiments and general confidence for success in the course.

We repeated this varimax orthogonally rotated factor analysis to confirm whether our students' survey responses were organized by the skill set of Baldwin, *et al.* (1999). The orthogonally rotated factor pattern for both the Fall 2006 and Spring 2007 data were similar to what Baldwin, *et al.* (1999) observed in their initial validation of the instrument. The extracted factors from the Fall 2006 data and Spring 2007 data were analyzed using analyses of variance (ANOVAs), to determine whether students in inquiry and traditional labs differed in confidence in their ability to carry out certain types of scientific activities.

We used ANOVAs to assess differences in the pre-to-post change in total self-efficacy scores by lab type. Significant differences between lab types were examined using Tukey's Honestly Significant Difference (HSD) means separation test. In addition, we used ANCOVAs to determine whether all student populations (females, males, minorities) reported similar gains in confidence in scientific abilities.

Course Evaluations

Students completed online course evaluations at the end of semester in which they were asked to give an overall rating of the lab on a scale of 1-5 (1 being poor and 5 being excellent). Analysis of variance was used to determine whether student evaluations differed by lab type or by instructor. Significant differences in evaluation responses for each lab type were examined using Tukey's (HSD) means separation test.

Student Interviews

To assess student attitudes toward the inquiry and traditional lab courses, one co-author, conducted separate one-hour end-of-semester focus groups. Student volunteers for focus group were solicited from each laboratory section. Four focus groups were interviewed, two groups per lab type, each containing at least 5 students (inquiry N=10; traditional N=11). Students responded to questions designed to gauge their epistemological beliefs on the role of students and instructors in the learning process in general, as well as specific questions about their experience in the laboratory.

Findings

Student Demographic Information

Student demographic information was collected using items from the self-efficacy survey described above during both Fall 2006 and Spring 2007 (Table 1). Students in the inquiry and traditional labs shared similar demographics. They were primarily (~70%) Caucasian female students in their first to second semester of college (67-74%) and approximately 15% were minority students. On average, students in Biology 1103 reported a 3.13 GPA during Fall 2006 and 3.22 GPA during Spring 2007, and reported similar GPAs between both inquiry and traditional lab sections. For the most part, these students had little previous college science experience: 32-45% indicated this was their first college science course. Biology 1103 lab was possibly the only laboratory course taken to fulfill a science requirement for graduation from the university since most of these students do not intend to pursue further study in science (only 20% indicated possible interest in a science career).

Table 1. Student Demographics for the Traditional and Inquiry Sections

	Fall 2006		**Spring 2007**	
	Traditional	Inquiry	Traditional	Inquiry
Gender (% female)	79.0	74.6	66	74.7
Ethnicity (% minority*)	10.9	14.2	14.7	15.8
Class (% freshmen)	74.0	71.7	66.7	67.0
First College Science Course (%)	44.5	39.6	32.0	31.7
Interest in Science Career (%)	34.5	35.6	28.0	29.9
Self-reported GPA	3.1	3.2	3.2	3.3
Final Grade (%)	90.9	89.4	91.5	87.5

*Minority designation included African/African American, Asian/Asian American, Native American, Hispanic/Latino, and Other.

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Science Literacy Assessment

Inquiry and traditional lab students did not perform significantly differently on the pre-test for the science literacy assessment. ANCOVA results showed that students' science literacy assessment (SLA) post-test scores differed significantly depending on which type of lab instruction they received ($F_{(1, 383)}$ =12.21, N= 386, p>0.0005). Students in the inquiry labs showed an improvement of 4% in total correct responses while students in the traditional lab showed no significant difference from the pre-test (Figure 1).

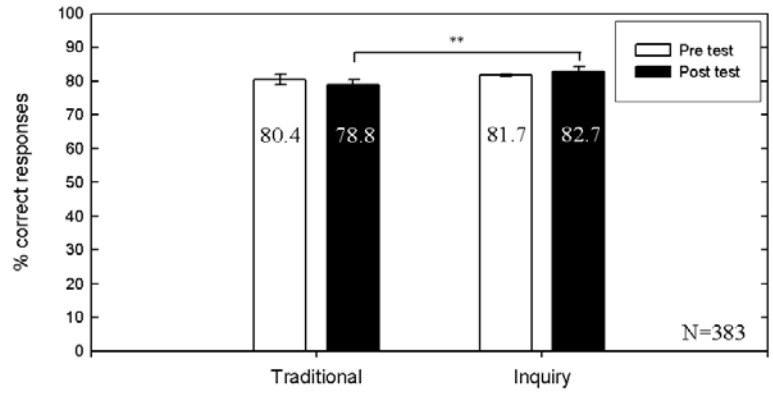

Figure 1. Science literacy assessment results from Spring 2007. Analysis of covariance (ANCOVA) results indicate that students in the inquiry labs answered 3.9% more questions correctly, consequently scoring significantly higher on the post science literacy assessment than traditional lab students ($F_{(1, 383)}$ =12.21, N= 383, p= 0.0005). (*** p < 0.0001; ** p < 0.001; *p < 0.05).

Science Process Skills Assessment

Pre-process skills scores differed by lab type for the Fall 2006 semester with students in traditional labs scoring slightly higher than students in the inquiry labs ($F_{(1, 393)}$ =4.56, N= 395, p> 0.0333), but pre-process skills did not differ by lab type for the Spring 2007 data. We found that inquiry lab students scored significantly higher (2%) on the post-test than traditional lab students across both semesters (Fall 2006: $F_{(1, 392)}$= 16.06, N=395, p<0.0001; Spring 2007: $F_{(1, 269)}$=6.85, N=272, p>0.0094) (Figure 2).

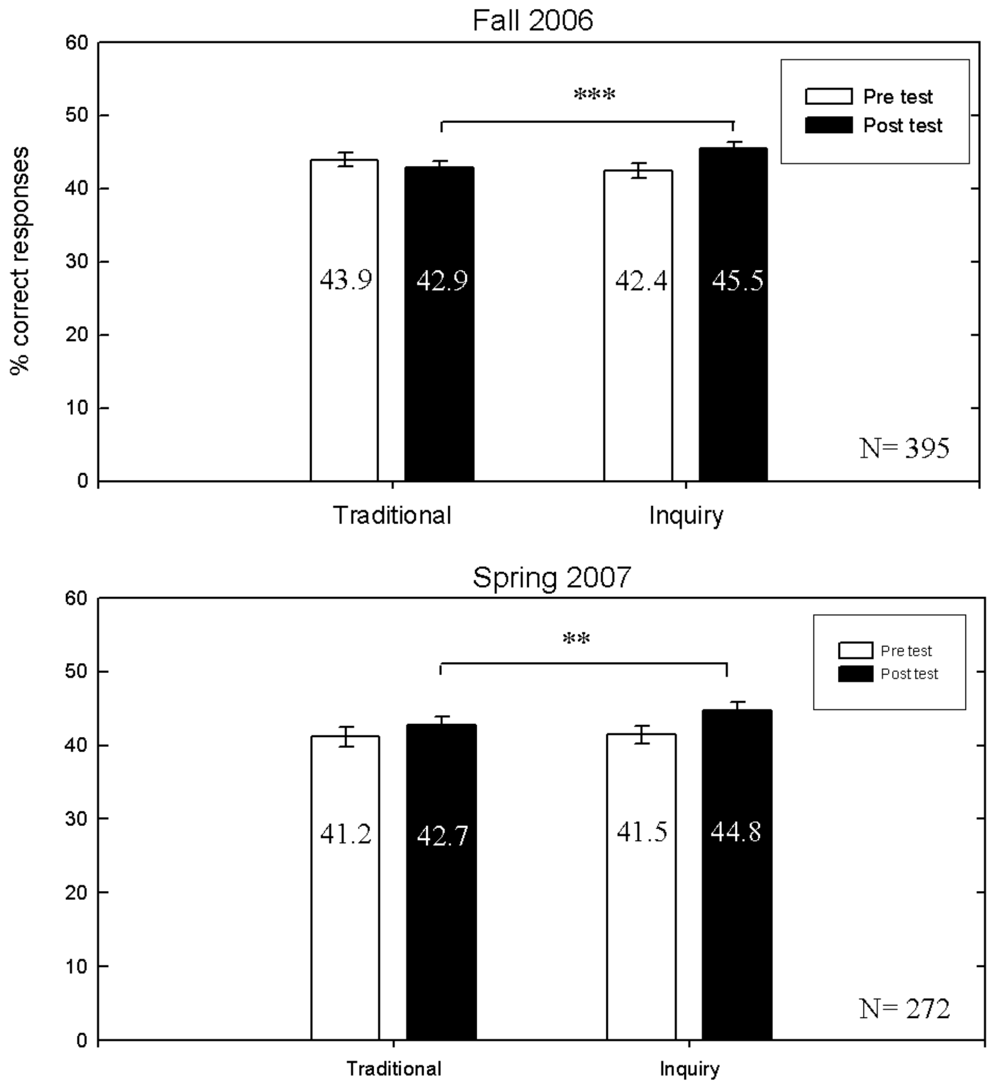

Figure 2. Science process skills results for Fall 2006 (A) and Spring 2007 (B). ANCOVA results indicate that across semesters, students in the inquiry labs answered at least 2% more questions correctly on the post process skills assessment than traditional lab students, resulting in significantly higher post process skills assessment scores (Fall 2006: $F_{(1, 392)}$= 16.06, N=395, $p<0.0001$; Spring 2007: $F_{(1, 269)}$=6.85, N=272, $p=0.0094$). (***=$p<0.0001$; **=$p<0.001$; *=$p<0.05$).

To be sure that post-assessment differences were due to participation in the particular lab, rather than prior exposure to the assessment, we also compared the scores of students who completed only the post-assessment with scores from students who completed both assessments. There was no indication that completion of the pre-assessment alone led to a higher post-assessment score for either semester.

Self-efficacy Survey

At the beginning of the Fall 2006 semester, students in both traditional and inquiry laboratories reported being fairly confident that they could perform scientific tasks and apply science skills in the context of daily life ($F_{(1, 294)}$= 2.25, N=296, p>0.1350). At the beginning of the Spring 2007 semester, however, traditional lab students reported being nearly totally confident, while inquiry lab students reported only being fairly to very confident that they could perform scientific tasks and apply science skills in the context of daily life($F_{(1, 414)}$=0.91, N=416, p>0.0341). At the end of both semesters, students attending both lab types showed increased confidence in their ability to perform the types of skills surveyed (Figure 3). However, across both semesters, students in traditional labs reported significantly greater gains in confidence than students in the inquiry labs (Fall 2006: $F_{(1, 293)}$= 5.56, N=296, p>0.0190; Spring 2007: $F_{(1, 414)}$=4.15, N=416, p>0.0423). There were no significant differences in gains from pre to post-test scores by gender (Fall 2006: $F_{(1,292)}$=0.25, N=296, p>0.6149; Spring 2007: $F_{(1,481)}$=0.33, N=485, p>0.5643) nor by ethnicity (Fall 2006: $F_{(1,289)}$=2.01, N=296, p>0.0931; Spring 2007: $F_{(5,363)}$=1.99, N=371, p>0.0789.

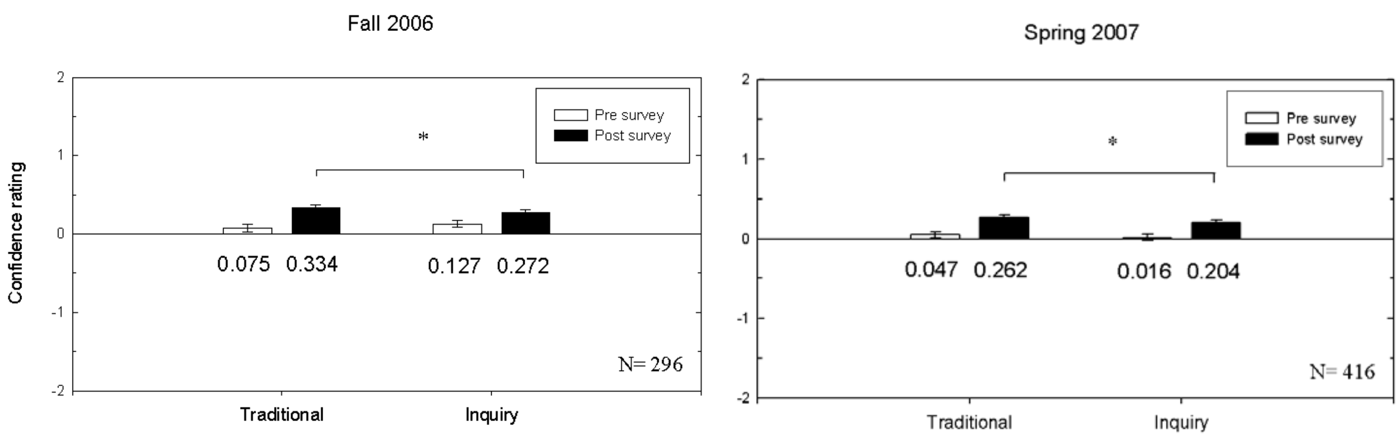

Figure 3. Self-efficacy survey (SE) results for Fall 2006 (A) and Spring 2007 (B). Students were asked to rate their confidence in their ability to perform specific scientific tasks on a Likert Scale (-2=not at all confident; -1=only a little confident; 0=fairly confident; 1=very confident; and 2=totally confident). Prior to the start of the lab course, students in both lab types reported being fairly to very confident in their ability to perform scientific tasks and take a scientific approach to activities in daily life. Students in both labs reported that their confidence in their scientific abilities increased by the end of the semester. However, ANCOVA results indicate that inquiry lab students reported significantly lower gains in confidence than traditional lab students ($F_{(1, 293)}$= 5.56, N=296, p=0.0190). (***=p<0.0001; **=p<0.001; *=p<0.05).

We used factor analysis and ANOVAs to examine differences in students' confidence to perform specific skill sets depending on lab type. The three factors we extracted using factor analysis were: (1) confidence in explaining and writing about biological ideas (factor 1); (2) confidence in writing and critiquing a lab report (factor 2); and (3) confidence in using a scientific approach to solve problems, including using analytical skills to conduct experiments and general confidence for success in the course (factor 3) (Appendix 3). Following factor analysis, we used ANOVAs to compare changes in confidence levels in each factor between students in inquiry and traditional labs. During Fall 2006, only one factor differed significantly between labs—students' confidence in explaining and writing about biological ideas. Students in the traditional labs reported gaining greater self confidence in their ability to explain and write about biology (factor 1, Table 2) ($F_{(1, 294)}$= 18.07, N=296, $p<0.0001$). In Spring 2007, students' confidence differed significantly between the labs for all three factors. Students in the traditional labs reported gaining greater self confidence in their ability to explain and write about biology (factor 1, Table 2) ($F_{(1,409)}$=25.11, N=411, $p<0.0001$), as well as in their ability to write and critique a lab report (factor 2, Table 3) ($F_{(1,409)}$=27.32, N=411, $p<0.0001$). Inquiry students, however, reported significantly higher gains in confidence than students in traditional labs in using a scientific approach to solve problems, using analytical skills to conduct experiments, and general confidence for success in the course (factor 3, Table 2) ($F_{(1,409)}$=8.02, N=411, $p>0.0049$).

Table 2. Self Efficacy Factor Analysis

	Fall 2006		Spring 2007	
	Traditional n=119	Inquiry n=177	Traditional	Inquiry
	Mean gain (standard error)	Mean gain (standard error)	Mean gain (standard error)	Mean gain (standard error)
Factor 1	0.293^{A}*** (0.089)	-0.197^{B} (0.073)	0.297^{A}*** (0.074	-0.210^{B} (0.0602)
Factor 2	-0.083^{A} (0.091)	-0.056^{A} (0.075)	0.165^{A} *** (0.076)	-0.116^{B} (0.064)
Factor 3	-0.022^{A} (0.092)	0.0144^{A} (0.075)	-0.286^{B} (0.075)	0.202^{A}*** (0.063)

(*p>0.05, **p >0.01, and ***p<0.0001)

Course Evaluations

Since we found no statistical differences between student evaluations for particular teaching assistants in each lab, instructors were not included in the ANOVA model. For both semesters, ANOVA results indicated that students in traditional labs rated their overall lab experience significantly higher (Figure 4) than inquiry students (Fall 2006 $F_{(1,34)}$=25.36 N=36 $p<0.0001$; Spring 2007 $F_{(1,31)}$=33.29 N=33 $p<0.0001$).

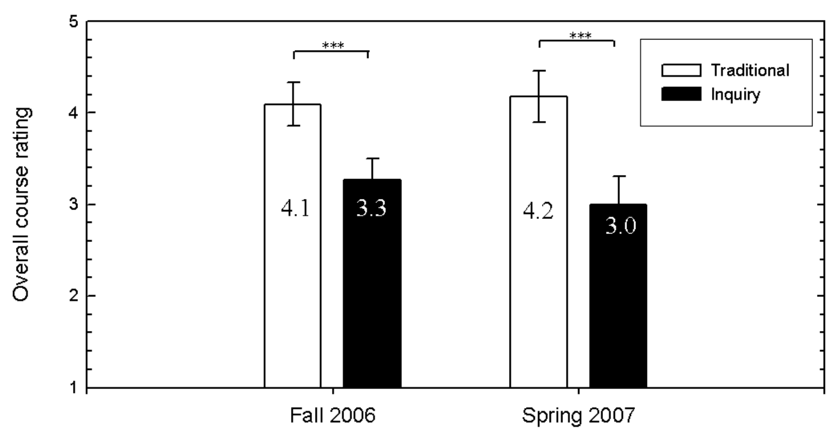

Figure 4. Lab evaluation results. Students were asked to rate their overall lab experience on a scale of 1 to 5, with 1=poor and 5=excellent. Analysis of variance showed that students in the traditional labs rated their overall lab experience significantly higher than inquiry lab students during both Fall 2006 and Spring 2007 semesters(Fall 2006 $F_{(1,34)}$=25.36, N=36, $p<0.0001$; Spring 2007 $F_{(1,31)}$=33.29, N=33, $p<0.0001$). (***= $p<0.0001$; **=$p<0.01$; *=$p<0.05$).

End-of-semester Interviews

In order to investigate more fully the reasons behind student's general level of dissatisfaction with the inquiry course compared to the traditional course, we conducted anonymous interviews at the end of the semester of Fall 2006. Negative impressions of the inquiry labs focused on frustrations, failures, and workload. Students participating in inquiry labs often cited experiencing frustration with the process of struggling to "figure out" what they were doing without directions when they were accustomed to being provided with exact details. They also commented that the inquiry lab was "too much work," especially when compared to other lab classes they had taken. These issues combined together to create a feeling of inadequacy and insecurity that every student in the interview group mentioned. In particular, they mentioned that as non-science majors they had not been trained to tackle the types of challenges they faced in the lab and indicated they lacked the commitment to surmount these challenges since they wouldn't be facing similar challenges later in their coursework. Positive comments about the inquiry labs focused on relevance and understanding. Students in the inquiry labs repeatedly mentioned their newfound abilities as learners and their ability to apply the material to the real-world. They also commented on how the collaborative aspects of struggling together were both rewarding and frustrating. However, in the end, several still indicated they would choose the easier rather than more rewarding path. One student summed it up best, stating, "I prefer it [the traditional lab]. I prefer just going in, looking at notes, taking a quiz and then having [the] procedure, this, this, and this. I think that's easier. But I wouldn't learn as much."

Students in the traditional labs also expressed feelings of frustration, but their complaints revealed a lack of enthusiasm (in themselves and their TA, and a lack of real learning) rather than frustration due to struggling to learn. This was also revealed in their positive comments that focused solely on the brevity, ease, and "cool" scientific equipment they found in labs, as well as how lab helped reinforce the content knowledge they could use for the lecture class rather than what they had learned for their own lives. Interestingly, student comments from the traditional lab clearly revealed that they really didn't understand what they were doing and admitted that they hadn't learned much, e.g., students in the traditional lab indicated they would not be able to answer practical questions about the labs at the end of the semester. In comparison, students in the inquiry labs answering the same question felt confident in their abilities.

Conclusions and Implications for Future Studies

Inquiry Lab Students Show Modest Gains in Literacy and Skills

We are one of many universities nationwide who have adopted an inquiry lab curriculum for their introductory courses (Sundberg, *et al.* 2005). However, we are one of very few who have systematically assessed the efficacy of this curriculum in comparison to more traditional lab curriculum. Rissing and Cogan (2009) found significant gains in student performance and attitudes when students participated in an inquiry enzyme laboratory, however, their study was limited to assessing one lab in an entire semester. Our results take into account the experience of students working in an inquiry based laboratory experience for an entire semester. Having clearly defined our instruction as a "guided inquiry" approach, we showed that students in our inquiry labs demonstrated a significant improvement in science literacy skills and process skills, consistent with the manner in which an average citizen would use them: 4% and 2% greater gains, respectively (Figures 1 and 2). At first glance, these gains may seem small considering that students in the inquiry labs spent substantially more time reading popular reports of science, designing their own experiments, and evaluating the results of their experiments in writing compared to the students in the traditional labs.

However, our observed gains of 2-4% are similar to the ranges of reported gains in conceptual understanding from prior studies of inquiry adaptation, albeit slightly larger than the gains we observed (Luckie, et al., 2004; Sundberg & Moncada, 1994; Udovic, et al., 2002). In comparison to a more traditional curriculum used in prior years (using scores on standardized exam questions from the MCAT), Luckie *et al.* (2004) reported a 10% greater improvement in student learning gains with their new "Teams and Streams" introductory biology curriculum for science majors that combined one week of traditional lab curriculum with a second week of more extensive, student-chosen, long-term, research projects. The research projects developed high-order thinking skills with the use of experimental designs and reflective critical analysis of multiple written drafts with additional assessments such as peer reviews. Sundberg and Moncada (1994) found that non-science majors taught with "I-Labs" inquiry lab curriculum showed improvements, ranging from 3-77% in different aspects of science literacy (defined by understanding of major concepts and misconceptions on a 36-item multiple-choice instrument), but did not report the overall mean gain. Finally, Udovic *et al*. (2002) made progressive changes over a three-year period to the curriculum of their "Workshop Biology" lecture and lab course, the difference in learning gains declined as more activities were added to the control comparison course each year, (measured by concept-tests developed by the instructors with no reliability or validity mentioned), with the inquiry and traditional groups differing in learning gains 20% the first year, 6% the second, and with no differences in year three.

In addition, our gains are the first observed in the "derived" science literacy skills of Norris *et al.* (2003) in which conceptual understanding is transferred to a new setting and students are challenged to interpret and evaluate texts dealing with scientific concepts. We would predict that participation in inquiry labs should have an impact on retention of these skills or greater long-term interest in biology, but these questions await future studies designed to track longitudinal learning gains from inquiry classrooms. The other question awaiting further study is which changes to our instructional materials or methods might improve science literacy skill acquisition in the short run. For example, it would be interesting to know if replacing or augmenting the Science Writing Heuristic template (Keys, et al., 1999) with its focus on improving conceptual understanding and experimental design with writing assignments would lead to greater skills in interpreting main-stream reports of science.

Since we recognized that student learning outcomes may be influenced by a confluence of factors, we incorporated multiple methodologies—science literacy and skills assessments, self-reported confidence surveys, and focus groups—in order to more accurately assess learning in the inquiry laboratory classroom. Future studies may consider study designs utilizing multivariate analysis, to account for other variables that may influence student performance, which is a limitation of our pre-post analysis of science literacy and skills gains. However, our qualitative results from student interviews may provide insights where statistical analyses alone cannot. Further, these results may serve to direct the focus of future studies, including potential variables to consider for inclusion in models.

Students' Confidence in Doing Science

We documented significant improvement in students' confidence to use science literacy skills after participation in the inquiry labs. We did not observe differences in self-efficacy in students of different gender or ethnicity. Interestingly, when we compared total confidence scores between students taught using the inquiry laboratories or a more traditional approach, we found that students in inquiry labs gained less confidence through the semester than students in the more traditional labs (Figure 3). In fact, inquiry lab students reported lower levels of confidence even for tasks such as explaining and writing about biological ideas, though they had much greater experience with these tasks (Table 3). There are at least two questions that we need to address to understand why students in the inquiry labs who demonstrated greater science literacy skills than students in the traditional labs don't feel confident using these skills: (1) whether the results of student's confidence levels are consistent with what we would predict due to their experiences in the two lab settings, and (2) what criteria do students use to define their own abilities.

Hopefully, students exposed to any lab course would have developed greater self-confidence in their ability to do science over the course of the semester, and some of the items, or scientific tasks, on the instrument were generic enough to increase equally in students in both labs. However, students would have practiced certain tasks significantly more depending on the type of lab in which they participated. For many of these items students responded in ways we would have predicted, e.g., students in the traditional labs had much more practice reading facts about biology from the introductory material in their lab manuals while studying for their weekly pre-lab quizzes. They also had much greater exposure to reading and following procedures from their manuals. It was therefore not surprising that traditional students showed higher gains in confidence for these types of tasks. The inquiry lab students were required to write numerous reports describing their findings, so it was not expected that they had higher gains in confidence in writing or critiquing a lab report.

We also encountered some unexpected and revealing results with the self-efficacy questions. Students did not have any experience in the traditional labs planning their own procedures for investigations, examining conflicting or complex data sets, or asking meaningful questions that could be addressed experimentally, yet they reported greater gains in confidence for these activities compared to inquiry students. Students in these labs also indicated significantly higher gains in confidence for items such as reading and then explaining or writing a summary of the main points from an article, public lecture, or television documentary compared to students in the inquiry labs. Neither inquiry nor traditional lab students had any extra exposure to documentaries or public lectures. In fact, inquiry students, rather than traditional students, had extra exposure to articles about biology. Finally, traditional lab students exhibited greater gains in confidence for the most general questions about how successful they felt they could be in a biology or physiology course.

Since it is unlikely that students in the traditional labs had greater abilities in the areas questioned on the self-efficacy survey, their confidence must have increased due to some other reason. One possibility is that success –or lack of failure in this case – bred over-confidence. Students in the traditional labs never had to grapple with failure or confusion, so they were never made aware of the difficulties of actually writing lab reports or asking meaningful experimental questions. Self efficacy is by definition subjective; it depends on a person's perceptions of their own ability (Bandura, 1986). In our case, actually doing the activities described in the self-efficacy survey, such as explaining the design of a biology experiment to another person and receiving critical feedback, some of it inevitably negative, would obviously bring about a more realistic impression of that ability. We propose that exposure to the actual challenge of attempting and sometimes failing in these activities gave inquiry students a more accurate impression of their abilities. Students in the traditional labs were encouraged by the simple but successful activities of the traditional curriculum into a state of comfortable, but naïve, over-confidence.

The only reason to be concerned about the relatively lower self-confidence in students participating in inquiry labs is the troubling thought that they may feel less competent to do these activities in their own lives. We would argue, however, that an accurate evaluation of one's own abilities would always be preferable to an ignorant over-estimation, especially when these skills are critical to the decision-making processes needed to evaluate evidence such as that relating to health and disease. In fact, this is exactly the impression we got from student interviews where multiple students expressed an appreciation for their own abilities to apply what they had learned to real-life problems.

Student Resistance to Innovative Instruction
We were not surprised to observe that inquiry students rated their lab experience lower than traditional students (Figure 4). Although several studies have reported higher levels of satisfaction in students working in inquiry lab classrooms at the college level (Ajewole, 1991; Kern & Carpenter, 1984; Luckie, et al., 2004; Merritt, 1993), most of the larger, more quantitative studies have instead reported frustration and resistance from college students engaged in inquiry activities (Sundberg & Moncada, 1994; Udovic, et al., 2002; Volkmann, Abell, & Zgagacz, 2005). For example, student attitude toward the "I- labs" curriculum developed by Sundberg and Moncada (1994) was similar to what we observed, reporting pride in their ability, mixed with some frustration and poor self-evaluation. They interpreted students' very strong initial negative reaction to the course as stemming from the increased demand for them to learn in a new and more rigorous way that was ameliorated over time, very similar to our results.

There are several additional factors that may have contributed to the high level of resistance to inquiry observed in both the interviews and end-of-course evaluation assessments in this study. The most commonly mentioned impediments to inquiry implementation are the challenges faced by students as well as instructors in accepting their new roles as facilitators and active learners respectively (Anderson, 2002; Sundberg, 1992; Sundberg & et al., 1992). Students don't like the extra work required to think through problems on their own (Loughran & Derry, 1997) and reveal a preference for memorization and regurgitation of knowledge rather than deep understanding (Hughes & Wood, 2003; Watters & Watters, 2007). Instructors often mention the extra time and effort required by students in inquiry labs (Moss, 1997). In our case, teaching the labs simultaneously led to problems of perception from the students that may have influenced their comparisons of the workload in the different courses. Since the traditional and inquiry lab sections were taught concurrently in adjacent rooms, it was obvious when students from the traditional labs were finished with their activities—sometimes in about half the time of the inquiry students. Both student groups were also enrolled in the lecture course that accompanied the lab, so they had ample opportunity to compare workload and difficulty level of the two labs.

The argument has been made that inquiry instruction may not be the best approach for increasing science literacy, particularly for students who are not cognitively equipped to meet the challenges it provides (Heppner, Kouttab, & Croasdale, 2006; Yerrick, 2000; Zohar & Aharon-Kravetsky, 2005). Berg et al (2003) categorized first-year college chemistry students according to their attitude toward learning using Perry's Scheme (Perry, 1999) including: their view of knowledge, role of the teacher, the student's role in learning, and the student's perception of assessment and experiments. Comparing groups with high and low levels of cognitive development, they found that students with a high level of cognitive development were more open to inquiry, while students with lower levels of cognitive development still valued the open format of the lab, but needed special attention and more guidance. It would have been interesting to determine if self-efficacy levels were correlated with attitude toward learning in the students in our inquiry labs, as this seemed to come across for many students in the interviews. If these attitudes and confidence were shown to correlate with each other, it could help explain some of the lower self-confidence and resistance expressed by students in the interviews. Administration of an attitude toward learning questionnaire at the beginning of the semester could help guide instructors in identifying students upon which to focus this extra guidance.

Role of the Instructor in Inquiry Laboratories

Another issue affecting students' attitudes toward inquiry labs –that of teacher preparation, motivation, and attitudes– was not analyzed in this study. Although there were no significant differences in student evaluations of their TA instructors, we did not systematically observe and evaluate TA teaching effectiveness. Students' perception of the instructor's role in science labs may be confounded in the inquiry labs since students needed to modify their role from passive follower to active designer. Students were given little written instruction in the inquiry labs and were expected to design their experiments under the active questioning of their instructors. Our TAs engaged in an extensive inquiry teacher-training course that lasted two days prior to the start of the semester and were observed and critiqued several times during the semester by two experienced instructors, however, inquiry instruction is notoriously difficult to implement by novice instructors, and only one of the TAs had any prior experience teaching in an inquiry classroom (Crawford, 1999; Gallagher, 1989). The degree of implementation of inquiry tasks has been shown to vary across a teaching population (Luft, 2001), and this has been shown to have a significant effect on student learning outcomes (Akkus, Gunel, & Hand, 2007). We are currently engaged in further work to determine the effect of quality of instruction on learning outcomes in our inquiry labs.

Inquiry instruction has been widely incorporated into college science laboratories in recent years and lauded for enhancing student learning. Our study supports these claims: inquiry lab students demonstrated small but significant gains in science literacy and science process skills compared to students enrolled in the traditional cookbook labs. Instructors following in our footsteps should be aware of the challenges, however. Adopting an inquiry-based laboratory curriculum requires a substantial investment not only in curriculum development but also in new training for instructors to facilitate the shift in instructional practices. In addition, inquiry instruction is often met with resistance from students as they are challenged to approach scientific problems at a higher level. Administrators evaluating the success of a course cannot simply use student evaluations as the sole indicator of the quality of instruction. Our inquiry lab students rated their experience lower on course evaluations but exhibited an interesting trend toward a more honest appraisal of their own abilities and an increased appreciation of their accomplishments.

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