

Revisiting Inquiry and Prescriptive Laboratory Experiences in Introductory Physics

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Abstract

The study reported here was designed to substantiate the findings of previous research on the use of inquiry-based laboratory activities in introductory college physics courses. The authors sought to determine whether limited use of inquiry activities as a supplement to a traditional lecture and demonstration curriculum would improve student achievement, as measured by test scores and course grades, and student attitudes toward the course, as reported in course evaluations and interviews. Female students in the introductory survey and general education courses who participated in the inquiry activities outperformed those in the traditional curriculum, especially on test questions related to the topics investigated in the inquiry activities. Further, the inquiry group students as a whole outperformed non inquiry students, even those from the algebra and calculus based introductory courses, on a common conceptual exam problem.

I Introduction

In recent years a substantial and growing body of research has demonstrated that a more active, inquiry based, way of learning brings students to a more robust understanding of physics concepts than does the traditional lecture approach.¹⁻⁵ Students in university physics programs that engage them in hands-on, active construction of knowledge have been shown to outperform those in traditional lecture/demonstration classes even on quantitative (as opposed to conceptual) assessments⁶⁻⁸; however, there are conflicting results on whether such activities are more valuable when performed by the students themselves (active inquiry) than when performed by an instructor (vicarious inquiry).^{9,10}

There is also evidence that some groups of students may benefit more from the inquiry method than others. While most studies have not disaggregated data by gender or by race, one study of high school students in the Netherlands found that girls did not perform as well as boys under the active inquiry approach but did under vicarious inquiry¹¹. Priscilla Laws also reports that college women in her Workshop Physics courses sometimes expressed frustration with the time and effort required for inquiry learning, in spite of having done well in the courses¹². On the other hand, a study of fourth and fifth grade students found that, while all students expressed increased enjoyment in doing science after inquiry activities involving batteries and bulbs, the girls in the study showed a more dramatic increase in enjoyment¹³. More studies with results disaggregated by gender (and ethnicity) are needed to determine whether the inquiry method is most appropriate for all students.

The inquiry method has also been criticized for its lack of coverage¹⁴ and lack of correspondence to social and cultural expectations¹⁵. The in-depth coverage of some topics, required by the constructivist approach, results in the elimination of coverage in other areas. Modern physics, in particular, is difficult to approach from a hands-on standpoint. The Physics Education group at the University of Washington has developed a successful computer-based inquiry tutorial on the photoelectric effect for upper division courses¹⁶, but does not include material on atomic structure, relativity or other such topics in its material for preservice teachers and general education students.¹⁷ The inquiry method, in general, has been shown to be particularly appropriate for those groups.¹⁸⁻²¹

Finally, most inquiry-based programs call for smaller class sizes and student-to-instructor ratios, classrooms with tables or other adequate space for performing the activities, and more equipment, as compared with traditional lecture classes. These resources are often unavailable, especially for large enrollment classes. Such constraints have led some physics educators to consider a third possibility: a combined approach in which limited inquiry activities supplement traditional lectures. Such a combined approach allows a smaller commitment of resources, and has also been shown to be successful when inquiry-based tutorials replace traditional recitation sessions (problem solving led by a teaching assistant)¹⁶ and when guided inquiry laboratory experiments replace traditional (prescriptive) laboratory experiments.²²

We chose to test the combined approach in two different ways. First, during selected school terms we replaced the prescriptive laboratories that accompanied our survey class with inquiry based labs. Second, during selected terms we replaced one lecture every other week for the general education students (who previously had no laboratory activities) with hands-on inquiry-based activities (a shortened version of the inquiry labs for the survey students). The success of both forms of limited

inquiry implementation was assessed using a variety of methods.

II Objective

The objective of the experiment was to determine whether limited exposure (1.5 hours or 50 minutes) to inquiry activities every two weeks would affect students' mastery of the introductory physics curriculum and students' attitudes toward the introductory course. In particular, the experiment was designed to answer the following questions.

- (1) Are outcomes (mastery and appreciation) different for students engaged in inquiry or prescriptive laboratory exercises?
- (2) Are outcomes different for students who replace one lecture every other week with a 50-minute inquiry session vs. students who do not and are assigned approximately 25 minutes of extra homework each week?
- (3) Do inquiry activities affect male and female students differently?
- (4) Do inquiry activities affect prospective elementary school teachers and other students differently?
- (5) How does the performance of students with minimal mathematical skills and limited inquiry training compare with that of students in the algebra and calculus based classes on physics concept application?

III Description of the Experiment

The research reported here consisted of three elements: (1) a causal-comparative analysis of formative and summative assessment data for control (non-inquiry) and experimental (limited inquiry activities) groups from our survey and general education physics class, (2) comparison of achievement between students experiencing inquiry-based activities with that of students in algebra and calculus based (non-inquiry) classes on a common physics application problem on resistive circuits and (3) classroom observations and pre- and post- treatment focus-group interviews conducted by an external evaluation specialist.

A. Populations

The experimental and control group students were drawn from two populations: students in a general education introductory physics class and students in an introductory physics service course, primarily for elementary education majors. Students from both classes served as controls during some quarters and as the experimental group during others. The two courses have a joint lecture. The survey course students are predominantly female (71%), while the general education students are 53% male and 47% female. Utah State is a land grant college and entrance requirements are minimal. There are no prerequisites for either course. Many of the general education students have never had an algebra course and have only rudimentary mathematics skills. Elementary education majors have a required minimum grade point average prior to their acceptance into the program and must take a college algebra course (although not necessarily prior to taking the physics survey course.)

B. Procedure

Control Treatment

The survey class students in the control group (n=47) attended lectures (with demonstrations) five days a week and completed six traditional physics labs outside of lecture hours. These laboratory exercises were prescriptive in nature, listing a series of experimental steps to be performed and calling for a well-described data analysis procedure (for example, measure this, graph this, etc.). The labs did not call for any qualitative conclusions and were not designed with a constructivist approach in mind. The general education students in the control group (n=43) attended the same lecture and demonstrations five days a week, but had no laboratory activities. These students were assigned additional weekly homework problems that were similar in nature to problems that were used on exams. These problems were both quantitative (requiring a calculation) and qualitative (requiring a verbal explanation) in nature.

Experimental Treatment

The experimental group students received the same lecture and demonstration as those in the control group with one exception. During some quarters, six lecture periods out of approximately 50 were dedicated to inquiry exercises for the general education students, who were then serving as the experimental group, and for whom no regular laboratory time outside class is scheduled. Thus, during these quarters all students were exposed to slightly less lecture time. The students in the experimental survey class (n=33) participated in inquiry-based activities rather than traditional prescriptive labs during their assigned laboratory periods. Students in the experimental general education class (n=48) performed a shortened (50 minute rather than 1 hour and 50 minute) version of the same activities. These activities took place in either the lecture auditorium or in the surrounding halls or outdoor open spaces. All experimental activities were performed in self-selected groups of five or fewer students.

The inquiry exercises were designed to develop concepts in the areas of motion (velocity and acceleration), energy, electric circuits, light (reflection and refraction), standing waves, and heat transfer. A description of the exercises for each unit is given in Table I. The motion, energy, and heat transfer exercises required quantitative calculations; the others did not.

Table 1: Inquiry-based Exercises

Unit	Activity
Motion	Determine average velocities and accelerations of marbles using meter sticks and stop watches.
Circular Motion	Model a carnival ride with string washers and straws
Energy	Construct model roller coasters with plastic tubing and BBs,
Heat transfer	Make an ice cream sundae, determine the specific heat of chocolate syrup
Electric circuits	Construct simple physical circuits with batteries and bulbs
Light	Trace light rays using laser pens
Standing waves	Draw standing waves formed from superposition of traveling waves on transparencies

Although the activities contained open-ended questions, they were designed to guide students rapidly

to the creation of certain concepts and the refutation of common misconceptions. Time limits and the large student-to-teacher ratio ruled out the painstaking approach of the University of Washington group and meant that only selected concepts could be treated in the inquiry lessons. The instructor presented these same topics in lectures and illustrated them with demonstrations.

C. Assessments

Student outcomes were measured in several ways. Class grades, grades on individual tests, and scores on individual problems that dealt with the concepts investigated in the inquiry activities were used to assess student mastery of concepts. All tests were created by the same instructor and contained parallel questions designed to test the same concepts. A causal comparative analysis was performed for matched control and experimental students during two quarters in 1996.

In an effort to describe and distinguish between traditional and inquiry-based instructional practices, an external evaluation specialist made non-participant observations of twenty lecture-demonstration classes and twenty laboratory (both prescriptive and inquiry) sessions during Winter and Spring of 1996. This specialist conducted eight focus group interviews during Fall 1996 and Winter 1997 to assess student appreciation of the course and student opinion on the value of the inquiry-based exercises. The instructor also asked students to comment on the inquiry activities on final class evaluations.

Finally, one test question dealing with simple resistive circuits (taken from Reference 3, Figure 3) was included on the final exam for , including the experimental . Following Reference 6, we asked instructors for the algebra and calculus based introductory classes to pose the same question to their students for comparison. Students in those classes typically major in science areas (for example; physics, pre-medical, engineering, and physics backgrounds), and have more mathematical preparation than the survey and general education students. The question was administered to the algebra-based class during a lecture period and on a voluntary basis, and to the calculus-based class on the final exam. Instructors for both classes had covered the topic of resistive circuits in lecture and agreed that the question was suitable and that students in their classes should have been able to respond to it correctly. The instructor for the calculus based course did point out that his students, having been exposed to real electric circuits extensively in the laboratory associated with their class, may have been reluctant to treat the batteries as ideal. However, the problem instructed students to treat batteries as ideal.

III Results

Course grades for students in the four sections comprising the experimental and control groups were based on a percentage of homework and/or laboratory scores (30%), three midterm examinations (50%), and a final examination (20%). While individual class and laboratory sessions, as well as specific homework and exam questions, varied from term to term, the instructor made every effort to ensure the physics concepts covered were consistent. Specific concepts for which assessment questions were designed included: velocity, acceleration, relation between distance and acceleration, circular motion, transfer of energy from potential to kinetic, reflection, refraction, standing waves, and resistive DC circuits. Efforts to increase content validity of all assessment measures included a pre- and post-hoc analysis for construct validity by colleagues in physics education.

As seen in Table 2, mean percentages of accumulated points on all outcome measures for students experiencing inquiry-based laboratory exercises were higher than those for students not experiencing inquiry based activities, but not by a very significant amount ($p = .151$).

Table 2: Cumulative Percentage of Points

Group	Number of Cases	Mean	SD	SE of Mean
Control Group	90	81.42	12.17	1.28
Inquiry Based Group	81	83.77	8.75	.96

$t = -1.44, p = .151$

To investigate whether students who participated in inquiry-based laboratory exercises had higher achievement on specific outcome measures, we initially compared means from experimental and control groups on outcome measures using multivariate analysis of variance (MANOVA). Controlling for group variances in grade point average (GPA) and gender, results suggested the possibility that group means varied by assessment instrument (See Table 3).

Table 3: Comparisons of Experimental and Control Group Means on Dependent Measures

Measure	Control	Experimental	F	Sig. of F
Homework Avg.	85.2	85.2	0.03019	.862
Test 1	76.0	77.9	1.84501	.176
Test 2	81.8	84.9	4.48219	.035*
Test 3	84.3	86.5	1.81871	.179
Final Exam	74.5	75.2	0.12423	.725

* $p < .05$

The fact that these differences were most apparent on Test #2, which had a high percentage of laboratory-based questions, suggested that additional investigation into achievement on test questions directly related to the topics covered in the inquiry exercises was warranted. Two external physics educators identified questions that were valid indicators of achievement on concepts covered in the laboratory exercises. Any questions that dealt directly with concepts investigated in the inquiry sessions were included in the analysis, while those on other topics were not. For example, any question dealing with electric circuits was included, while questions on static electricity or magnetism were not. All of these problems required the application of reasoning strategies, and thus met the criterion for tests of procedural knowledge. A previous study showed that hands-on laboratory methods of instruction yielded greater achievement on such tests than did teacher demonstration oriented instruction¹⁰.

Results from comparisons of experimental and control students indicated group differences greater than those that might be expected by chance. Students who participated in the inquiry-based laboratory experiences had much higher achievement on questions designed to assess mastery of laboratory based concepts (See Table 4).

Table 4: Comparison of Group Means on Laboratory-based Examination Questions

Variable	Number of Cases	Mean	SD	SE of Mean
Prescriptive Lab	47	67.6596	15.954	2.327
Inquiry-based Lab	81	83.4215	15.769	1.752

$t=-5.41, p<.001, ES = .99$

As mentioned earlier, prior research has suggested that younger female students may benefit from inquiry-based laboratory strategies¹³. Our study provided support for the conjecture that women at the college level have higher achievement on some measures when they participate in inquiry exercises (See Table 5).

Table 5: Comparisons of Mean Scores of Female Students on Dependent Measures

Measure	Control	Experimental	F	Sig. of F
Homework	88.5	89.7	.51284	.475
Test 1	74.7	78.1	1.37729	.242
Test 2	81.3	85.6	1.44606	.231
Test 3	83.1	87.4	1.75933	.186
Final Exam	73.1	76.6	3.63720	.058
Cum. Grade	81.9	85.4	1.38154	.241
Lab-based	74.5	86.5	9.15026	.003*

* $p<.01$

Analysis of data from female students revealed that those who experienced the inquiry-based laboratory exercises also had higher achievement on both the laboratory-based questions and the second test when compared with women experiencing the prescriptive laboratory exercises (See Tables 6 and 7). In comparison, differences between means on all dependent measures for the corresponding two groups of male students were not significant.

Table 6: Comparisons of Achievement on Laboratory-based Questions for Female Students in Inquiry-based and Prescriptive Laboratory Classes

Variable	Number of Cases	Mean	SD	SE of Mean
Prescriptive Lab	43	68.1728	16.444	2.508
Inquiry-based	58	84.9261	16.205	2.128

$t=-5.09, p<.001, ES = 1.02$

Table 7: Comparisons of Achievement on Test 2 for Female Students in Inquiry-based and Prescriptive Laboratory Classes

Variable	Number of Cases	Mean	SD	SE of Mean
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Prescriptive Lab	43	80.7907	11.738	1.790
Inquiry-based	58	85.3448	8.196	1.076

t=-2.18, p=.033, ES =.39

Elementary Education majors who participated in inquiry activities also had much higher achievement on laboratory-based questions than did their General Education counterparts (See Table 8).

Table 8: Comparisons of Achievement on Laboratory-based Questions for Education and General Education Majors Experiencing Inquiry-based Activities

Variable	Number of Cases	Mean	SD	SE of Mean
General Education	48	77.5000	15.678	2.263
Education Majors	33	92.0346	11.468	1.996

t = -4.82, p < .001, ES = .93

This difference in achievement on specific laboratory-based concepts was more pronounced among female students (See Table 9).

Table 9: Comparisons of Achievement on Laboratory-based Questions for Female Education and General Education Majors Experiencing Inquiry-based Activities

Variable	Number of Cases	Mean	SD	SE of Mean
General Education	29	75.9606	15.972	2.966
Elementary Education	29	93.8916	10.628	1.974

t = -5.03, p < .001, ES = 1.12

B. Comparison with Algebra and Calculus-based Courses on a Common Exam Problem.

Following references 4 and 6, we administered the problem shown in Figure 1, which was taken from Reference 3 Figure 3, to all students in the survey and general education classes, as well as those in the algebra and calculus based classes. The problem asks students to rank the order of brightness of bulbs in three different circuits. All bulbs are identical and all batteries are ideal; one circuit has a single bulb, one has two bulbs in series, and one has two bulbs in parallel. Initial comparisons of achievement for students in the inquiry group (general education and survey experimental groups) and the non inquiry group (general education and survey control students and algebra and calculus based classes) revealed a distinct difference between means of correct responses.

Table 10: Comparisons of Achievement Between Groups on the Resistive Circuit Question

Variable	Number of Cases	Mean	SD	SE of Mean
Non-inquiry	344	.6708	.220	.012
Inquiry based	310	.7980	.188	.011

t = -7.97, p < .001, ES = .58

C. Attitude correlations: Interviews and survey results

Findings from causal-comparative analysis of quantitative assessment data suggested that limited inquiry-based laboratory activities likely contributed to an increase in student understanding of selected laboratory-based concepts. Improved performance on several outcome measures, including the broad cumulative grade index, was particularly evident among female students. Anecdotal comments from the focus-group interviews and classroom observations provided additional insights on these findings.

Students who volunteered to participate in the focus-group interviews agreed to attend a pre- and post-course session in place of one homework assignment. All 22 interview participants experienced inquiry-based activities. Questions asked by the external evaluator during the four pre-, and four post-treatment interviews were designed to assist interpretation and validation of quantitative data^{23,24}. Information from the interviews and observations were analyzed and codified by the external evaluator based on content consistent with benefits associated with laboratory-based activities.

An emergent theme from discussions about the laboratory component of the introductory physics classes was value associated with concept confirmation. Concrete activities, regardless of whether they were laboratory experiences or classroom demonstrations, were perceived as beneficial, particularly when concepts were directly linked to previous lecture topics. A previous study had found that open-ended inquiry sessions were most beneficial when they followed lecture/demonstration sessions.²⁵

"I love to actually be able to work with the material and actually see how it comes out. Also I think it's not just working with it, it's also the examples she gives, like seeing is believing." (female general education student)

"It makes it easier to remember how it works when you can visualize it. For me it's easier to visualize it in my head after I've seen it." (female education major)

"I felt sorry for those people that had hands-on or their laboratory at the beginning of the week when we didn't cover the material in class until later...I have to see it on paper and see it in the laboratory. It's a reinforcing experience for me." (male general education major)

As previously noted, hands-on experiences conceptually linked to written or oral aspects of educational experiences are integral to improved understanding. There was some indication from interview information that students in classes experiencing the longer inquiry-based exercises in the laboratory valued those experiences more than students who participated in abbreviated classroom activities. However, findings from the interviews suggested that this value was attributed more to "increased time" and "being in a lab setting" than a fundamental difference in instructional strategies.

"Our labs are two hours long, and in every typical two hours, it always takes about an hour to get the instructions right. They (general education students who performed inquiry exercises during the lecture hour) only have 50 minutes; I don't know how you could ever accomplish the same amount of stuff." (female education major)

"I think if I would have been in the lab environment (rather than the classroom or hallway), it would

have been a lot easier. Because when you're in a lab setting you're always constantly doing experiments. (female general education major, inquiry-based exercises in the lecture room)

A second emergent theme from interview and observation information was value associated with inquiry-based strategies of concept acquisition. Students approached the introductory physics classes with common expectations of what goes on in a science classroom. These perceptions were illustrated when students were asked to describe differences between scientists and science teachers:

"The scientist is actually involved. They have a lot more knowledge of the deeper stuff, the more scientific things that you wouldn't explain to a student. A science teacher has to cover a lot of material in a short period of time, so I would think that they would have more of a basic knowledge. One knows a lot about a little and the other knows a little about a lot." (female general education student, pre-course)

"If I were a science teacher, I would be going for the right answer, the right experiment, the right conclusion or ending to my experiment whereas if I was a scientist, I would be looking for what's going wrong or what you know about all the different things, ... the teacher might just want the experiment to turn out." (female education major, pre-course)

"Science teachers want students to measure something that is going to be a certain weight... a scientist working in a lab can try and discover new things." (male general education major, pre-course)

While students at the beginning of each quarter were very clear that science teaching consisted of transmission of known facts and prescriptive laboratory exercises, comments at end of the quarters were less definitive. This narrowing of a perceived gap between doing science and learning about science was attributed to several variables.

"In an idealistic sense, I think of myself as more of a scientist in her class. I think her being a woman teacher affected me a lot; and because it (the lab) was more realistic." (female education major)

"There's different ways people learn. A lot of people may have learned through what scientists did...she tried to cover all the different ways that people could learn. She gave us reading material, lectures, she gave us pictures to look at, she had hands-on days. We had every way available to us to learn, and I think that's important." (female education major)

It was evident that some students participating in the inquiry-based exercises had begun to challenge their earlier perceptions about the nature of science teaching and learning. Factors that may have contributed to these changes included teacher gender, more realistic nature of inquiry-based approaches, and use of a variety of instructional mediums to complement the inquiry-based exercises.

At the same time, some students who experienced the inquiry-based exercises were reluctant to challenge their perceptions of a distinction between learning science and doing science. One noticeable characteristic of inquiry-based exercises that reinforced this distinction was the absence of time devoted to detailed outline of procedure. For several students with strong prescriptive expectations of science labs, a perceived lack of direction resulted in frustration and withdrawal, rather than challenge and

active involvement in problem solving.

The value students place on concept discovery appears to influence their acquisition of selected laboratory-based concepts. Comments from students involved in inquiry-based activities within this theme were characterized by words such as "dynamic", "exciting", and "alive", and lab groups were typically active and verbal.

"You could see the field and how it's progressing. It gets you excited. It makes the field come alive. Whereas my chemistry class is just the same old, same old. It's like a drill." (female, education major)

Student comments about the inquiry exercises on course evaluations were very nearly universally positive, providing anecdotal evidence that these activities improved student attitudes toward the course. There were infrequent comments indicating that students preferred to have lecture coverage of a topic prior to their inquiry investigations. Course evaluation scores and instructor evaluation scores were both higher during quarters when inquiry exercises were included in the curriculum.

One interpretation of comments related to the value of concept discovery is that these students view the content as more dynamic and themselves as more active participants in the learning process. In this scenario, concept discovery is closely linked to responsibility for learning. For students involved in this project, the aspect of discovery in the inquiry-based exercises was one motivating factor that contributed to acceptance of responsibility in the learning process.

IV Conclusions and Implications

Results from this study indicate that implementation of limited inquiry-based laboratory exercises on certain concepts into introductory physics classes increases understanding of those concepts among female students and female elementary education majors in particular. Possible reasons for these observed differences include the validation or confirmation value of hands-on activities, and value associated with alternative ways of acquiring knowledge in science, particularly discovery.

Our study was not able to distinguish in the MANOVA analysis between students experiencing 50 minutes of inquiry exercises as a replacement for a lecture once every two weeks and students experiencing one hour 50 minutes of inquiry activities as a replacement for traditional prescriptive laboratory activities once every two weeks. Student comments did provide some anecdotal evidence that students perceived the longer exposure to be more beneficial. Further study of the effectiveness of inquiry activities vs the length of exposure time is needed to determine which method, if either, provides a greater enhancement to achievement.

These findings were strengthened by use of multimethod data and information gathering strategies. Reference 26 suggests that interpretations from triangulation of information collected using multiple methods on different samples at different times can be more credible than conclusions based upon one-dimensional data collection techniques. It should be noted, however, that differences in the control and experimental groups were significant only assessment measures that dealt directly with concepts investigated in the inquiry exercises, and that these assessments were subjectively identified. Further, some subgroups of students did not show a significant difference when exposed to inquiry exercises.

Clearly, the possibility that participation in limited inquiry-based laboratory activities effects different groups of students in different ways also warrants further investigation.

Recognizing risks inherent in interpretation of findings from any social research, we suggest that college or university Physics educators with introductory physics teaching responsibilities consider the importance of including inquiry-based exercises into their courses, even if it is only possible to do so on a limited basis. Activities such as those described earlier may be of particular value to the largely female population of prospective elementary teachers. Efforts to increase future teachers' conceptual understanding and attitudes toward science are of particular importance in that they may result in improved elementary science instruction, thus affecting large numbers of future science learners.

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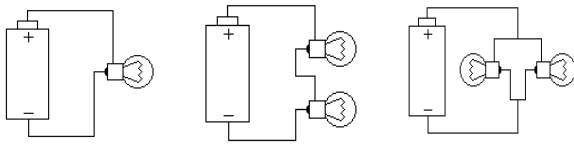


Fig. 1. Students were asked to rank the five bulbs in the circuits shown here by brightness, assuming that all bulbs are identical and all batteries are identical and ideal. (After Fig. 3 in Reference 3)