Engaging Students in Authentic Microbiology Research in an Introductory Biology Laboratory Course is Correlated with Gains in Student Understanding of the Nature of Authentic Research and Critical Thinking †

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Recent recommendations for biology education highlight the role of authentic research experiences early in undergraduate education as a means of increasing the number and quality of biology majors. These experiences will inform students on the nature of science, increase their confidence in doing science, as well as foster critical thinking skills, an area that has been lacking despite it being one of the desired outcomes at undergraduate institutions and with future employers. With these things in mind, we have developed an introductory biology laboratory course where students design and execute an authentic microbiology research project. Students in this course are assimilated into the community of researchers by engaging in scholarly activities such as participating in inquiry, reading scientific literature, and communicating findings in written and oral formats. After three iterations of a semester-long laboratory course, we found that students who took the course showed a significant increase in their understanding of the nature of authentic research and their level of critical thinking skills.

INTRODUCTION

Educational studies and assessments have found that the engagement and retention of potential Biology majors in introductory courses is low and that this is true nationwide; the retention of all Science, Technology, Engineering, and Mathematics (STEM) majors through graduation is also low as fewer than 40% of students who enter college as a STEM major graduate with a STEM degree (29). This is likely due to academic and social reasons, as many students struggle with the transition to college because of increased academic rigor and the novelty of independence (30, 39). Higher levels of expectation in college compared with high school are intimidating, particularly in STEM disciplines that often are perceived as “hard.” Additionally, the larger class sizes and often dry lecture style of teaching are not conducive to a good learning environment for first-year students (27). Though there have been improvements in the use of educational technology to remedy the inherent problems associated with large lecture courses, many professors have not found the same level of improvement in the thinking and learning abilities of their biology students (23). In particular, students’ critical thinking skills, their abilities to analyze, interpret, and evaluate information; solve problems and apply course material to achieve a specific outcome; and effectively communicate remain subpar (4, 7, 8, 12). Since the development of critical thinking skills and scientific literacy produces strong leaders and better prepares students for work in the 21st century (8), it is a primary goal of teaching that has recently received support from educational recommendations (1, 24, 40).

One potential way to accomplish this and improve the quality of Biology majors is to involve students in undergraduate research early in their education. Laboratory courses are a natural place to build critical thinking skills because successful critical thinking instruction requires active engagement of students (25). Furthermore, research experience can promote better learning of course material (43), improved data collection and analytical skills, enhanced scientific reasoning and teamwork abilities (10), and a healthier understanding of the nature of science (31). Open-ended investigations allow students to learn how science is performed by allowing them to do real research projects (17, 37, 44). Students learn more when they are given the freedom and opportunity to actively discover why and how things are the way they are (5, 33), and the earlier students get involved in research, the more benefits they will receive (9, 38).

Inquiry-based learning is the method used to integrate scientific inquiry into students’ learning, based on the idea of “science-as-a-verb” instead of “science-as-a-noun” (3). The identified best practices for inquiry-based learning include activities that are student-driven and involve students in scientifically-oriented questions where they are allowed...
to formulate hypotheses, make observations, analyze data, evaluate explanations from the evidence, and communicate their findings and ideas (2, 28). These activities lead to the development of the desired critical thinking skills, specifically enhancing the ability of students to analyze data, evaluate information, formulate hypotheses, solve problems, and communicate clearly, all of which fall under the various domains of critical thinking (7, 34). Students can gain a better understanding of scientific concepts when they are involved in the same activities as practicing scientists (3). Involvement in these types of exercises improves students' attitudes toward science (11, 13, 16, 18) and understanding of the scientific process (26).

A variation of inquiry-based learning is research-based inquiry, where inquiry-learning takes the form of an authentic research project. Because involvement in this type of course can improve critical thinking skills and increase students' enthusiasm for science and belief in their ability to perform scientific research (19, 21, 22), we created a novel microbiology research-based module that involves second semester freshman Biology majors at Purdue University in research early in their academic careers, similar to modules that have been described recently (5, 6, 13, 20). Within this module, we provided students with the same laboratory skills they would learn in traditional lab classes (pipetting, spectrophotometry, use of balance, preparation of dilutions, and basic statistics), but within the context of an actual research project. The objectives for this module were to increase students' enthusiasm for science and research, increase the number of students with early research experience, improve their understanding of the nature of authentic scientific research, improve the retention of Biology majors, enable student proficiency in scientific understanding and communication, and improve critical thinking skills. After implementing this module for three years, we have found that students showed significant gains in critical thinking skills and demonstrated an increased understanding of research and the scientific process.

METHODS

Student demographic

A total of 53 second semester freshmen (36 females and 17 males; 39 Caucasians, 3 African-Americans, 6 Asians, 3 Latino, and 2 classified as other) participated in the semester-long laboratory module over the course of three semesters. Students from all three semesters were Biology majors as indicated by their enrollment in the concurrent introductory biology lecture course and second semester Chemistry course. All students self-selected into this course which met once a week for four hours over the entire 15-week semester. Students' reasons for enrolling in the course are shown in Table 1. Students were asked to provide their motivation for enrolling in the class on an informal survey administered on the first day of class in all three semesters that the course was offered. Two independent reviews of the responses were done to establish categories of responses and the number of responses that fell into each category. There was ≥ 80% agreement between the reviewers on the coding of the responses. Each student's response was allowed to fall into more than one category if multiple reasons were given. Enrollment in the first semester (Spring 2010) was limited to Honors Biology students while the second and third semesters of instruction, comprising the bulk of this report, were open to both Honors and non-Honors Biology majors. Honors students were determined by high school GPA and SAT/ACT standardized test scores per Purdue University designations. Initial findings from a longitudinal study on the students who enrolled in this class suggest that students who chose to take this class in the Spring of 2011 had a higher GPA in their science classes before enrolling in our class which, in turn, suggests that our self-selecting students might not accurately reflect the general student population. All student data reported here were collected and analyzed in agreement with human studies protocols approved by the Purdue University Institutional Review Board.

Course outline

The course was designed to be a 15-week module divided into three sections as indicated in Table 2. Students were provided with weekly laboratory manuals containing applicable background information and the specific laboratory protocol for the experiment(s) of that week. When procedures were repeated in later weeks, the students referred back to the manuals and their notes to complete the procedures.

During the first portion of the semester, students developed the skills and concepts required to understand and proceed into the research portion of the course as well as the basic lab skills normally taught in an introductory lab module. Techniques were demonstrated to the students as they were relevant to the lab activities and research project and students would then copy and practice them. After acquiring background skills such as proper use of micropipettes, aseptic technique, spread plating, quadrant streaking, and spectrophotometry during the first portion of the course, students worked in teams to devise a hypothesis and design a mutagenic scheme to produce mutations in the proP gene of Salmonella typhimurium. They were given the option to use different mutagenic conditions so long as they used a strain capable of genetic mapping with the established technique. After designing a scheme, students generated mutants that were able to grow in the presence of high concentrations of glycine betaine and used classical genetic techniques to map which mutations were linked to proP. In order to identify the location of the mutation, students PCR amplified proP and sequenced the gene.

Student assessment within the course/module

Assessment of student performance was completed through a mix of group and individual assignments in the
TABLE 1.
Student motivation for enrolling in research-based module.

<table>
<thead>
<tr>
<th>Reason</th>
<th>Spring 2010 (n = 15)</th>
<th>Spring 2011 (n = 13)</th>
<th>Spring 2012 (n = 19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research experience</td>
<td>4/15 (26%)</td>
<td>5/13 (39%)</td>
<td>11/19 (58%)</td>
</tr>
<tr>
<td>Sounded interesting</td>
<td>3/15 (20%)</td>
<td>1/13 (8%)</td>
<td>2/19 (10.5%)</td>
</tr>
<tr>
<td>Improve lab skills</td>
<td>3/15 (20%)</td>
<td>2/13 (15%)</td>
<td>3/19 (16%)</td>
</tr>
<tr>
<td>Major requirement</td>
<td>1/15 (7%)</td>
<td>2/13 (15%)</td>
<td>1/19 (5%)</td>
</tr>
<tr>
<td>Better than alternative</td>
<td>3/15 (20%)</td>
<td>2/13 (15%)</td>
<td>2/19 (10.5%)</td>
</tr>
<tr>
<td>Other</td>
<td>1/15 (7%)</td>
<td>1/13 (8%)</td>
<td>–</td>
</tr>
</tbody>
</table>

*Student motivations obtained from beginning semester surveys. All student responses were classified into the six categories shown on the chart. If a student response fell into multiple categories, the response was included in the score for both categories. A “–” indicates that no students gave a response that fit that particular category.

TABLE 2.
Outline of activities and desired outcomes over the 15-week semester.

<table>
<thead>
<tr>
<th>Weeks</th>
<th>Activities</th>
<th>Desired Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–3</td>
<td>• Learn basic laboratory techniques</td>
<td>1. Demonstrate proficiency with bacterial cultures.</td>
</tr>
<tr>
<td></td>
<td>• Learn and practice the scientific method</td>
<td>2. Describe <em>proP</em> transport system.</td>
</tr>
<tr>
<td></td>
<td>• Learn requirements for growth and maintenance of pure cultures</td>
<td>3. Apply hypothesis-driven inquiry.</td>
</tr>
<tr>
<td></td>
<td>• Learn basic genetics</td>
<td>4. Practice accurate note-taking.</td>
</tr>
<tr>
<td></td>
<td>• Learn how to keep a laboratory notebook</td>
<td></td>
</tr>
<tr>
<td>4–5</td>
<td>• Perform mutagenesis/select mutants</td>
<td>1. Demonstrate ability to select mutants.</td>
</tr>
<tr>
<td></td>
<td>• <em>Paper Discussion #1</em> (Mutations and osmotic regulation)</td>
<td>2. Summarize points from review articles.</td>
</tr>
<tr>
<td></td>
<td>• <em>Lab Report #1</em></td>
<td>3. Write lab report in scientific paper format.</td>
</tr>
<tr>
<td>6–11</td>
<td>• Learn transduction technique and genetic linkage</td>
<td>1. Apply mutation mapping and selection techniques.</td>
</tr>
<tr>
<td></td>
<td>• <em>Lab Report #2</em></td>
<td>2. Describe transduction as molecular biology tool.</td>
</tr>
<tr>
<td></td>
<td>• <em>Paper Discussion #2</em> (student-selected)</td>
<td>3. Demonstrate ability to read and discuss primary literature articles.</td>
</tr>
<tr>
<td>12–13</td>
<td>• PCR and gel electrophoresis</td>
<td>1. Amplify and sequence <em>proP</em> with PCR.</td>
</tr>
<tr>
<td></td>
<td>• Identify mutations</td>
<td>2. Demonstrate ability to run an agarose gel.</td>
</tr>
<tr>
<td></td>
<td>• <em>Lab Report #3</em></td>
<td>3. Utilize online bioinformatic tools.</td>
</tr>
<tr>
<td></td>
<td>• <em>Paper Discussion #3</em></td>
<td></td>
</tr>
<tr>
<td>14–15</td>
<td>• Informal PowerPoint presentation on preliminary data</td>
<td>1. Summarize and interpret a large data set.</td>
</tr>
<tr>
<td></td>
<td>• Poster preparation and presentation</td>
<td>2. Demonstrate effective oral communication of results.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Explain the difference in format between research papers and posters.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Construct a clear poster for public presentation.</td>
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<tr>
<td></td>
<td></td>
<td>5. Communicate data with scientific community.</td>
</tr>
</tbody>
</table>

form of standard classroom evaluations and assignments related to the research projects (see below). Students were grouped into teams of two or three on the first day of class based on their responses to online personality and learning styles inventories, the Myers-Briggs type indicator (http://www.humanmetrics.com/cgi-win/jtypes2.asp) and the VARK
Peer Led Team Learning workshops (PLTL)

Students in the class during the 2011 and 2012 offerings were divided into small groups (four to six students/group) that met with a peer leader for five to six workshops during the semester. The material explored in the workshops complemented and extended concepts and activities covered in the course. The topics were: 1) how to keep a laboratory notebook, 2) data analysis and evaluation, 3) how to write a scientific paper, 4) how to read a research article, 5) ethical conduct in science, and 6) how to make a research poster. The peer leaders were Biology majors who had taken the class the previous semester and were chosen based on their interest in the position, performance in the class, and ability to work well as leaders in a group based on observations by the instructors. The students were required to read a brief document(s) and occasionally answer a few questions prior to each workshop. Students worked on guided-activities in pairs and as a whole group during the workshops. These workshops were required but not graded to give the students a setting in which to work on the material without a grade. The peer leaders kept electronic journals and reported that participation was high. The workshops were all adapted from workshops designed and implemented in research-based lab classes in the chemistry department (Varma-Nelson et al., unpublished data).

Student feedback

Student interest in and satisfaction with the course were determined by anonymous end-of-semester online course evaluations, a postsemester focus group interview (Spring 2010), and an attitudinal survey administered using an online survey tool (Qualtrics Labs Inc., Provo, UT) issued pre- and postsemester to students enrolled in the spring of 2011 and 2012. The first installment of the module in the spring of 2010 was evaluated by participation of all students in a focus group session held by an assessment coordinator at the Discovery Learning and Research Center (DLRC) at Purdue University. This session was held after the formal poster presentation and focused on four evaluative questions: 1) What benefits accrued to participants from their participation in the module? 2) What are the impacts of the module on students’ research and laboratory skills and understanding of research publications? 3) What are the impacts of the module on students’ educational and career aspirations, especially aspirations for research-oriented careers in the biology field? 4) What are the challenges associated with participation in the module and what are participants’ suggestions for improvement?

The attitudinal survey used in the spring of 2011 and 2012 was a 37-item, 6-position Likert-type survey developed for use within the chemistry CASPiE classes (41, 42). The survey prompted the students to rate their agreement with the 37 items reflected on their most recent laboratory course in biology. Presemester responses therefore reflect their feelings about their high school biology laboratory experience and postsemester responses reflect the laboratory module. An external evaluator for the chemistry CASPiE program found that the pretest responses to 26 of the items reduced into five factors (32): 1) Interest in Chemistry/Science, 2) Perceived connection between real life and science, 3) Lab perceived as similar to real scientific lab practices, 4) Perceived learning of chemistry content through laboratory (self-assessment), 5) Belief that they can understand and do scientific research (self-efficacy). The Cronbach’s $\alpha$ was > 0.800 for all five factors. A total of 26 of our biology students from the spring of 2011 and 2012 responded to both the pre- and postsemester attitudinal surveys indicating their level of agreement with statements probing various aspects of their interest and confidence in science and research. Our sample size of matched pairs was too small to perform exploratory factor analysis to determine the validity of the survey and previously identified factors in our population of biology students. Therefore, we determined the Cronbach’s $\alpha$ for each of the previously defined factors in our pre- and postsemester data to evaluate the reliability of the survey items in measuring the factors. We found Cronbach’s $\alpha > 0.700$ for all five factors suggesting that the items making up the factors identified previously were reliable for our context.
A one-way ANOVA with Bonferroni correction for multiple comparisons was used to compare the pre- and postsemester surveys using SPSS statistical software.

**Critical thinking**

We utilized the Critical thinking Assessment Test (CAT) developed by Tennessee Technological University (34–36) to evaluate the development of critical thinking skills in students from the Spring of 2011 and 2012. The CAT instrument was administered in a pre-/postsemester design during regular class time in accordance with an approved protocol for human studies. The pretest was taken by all students enrolled in the class in the second week of the semester and the posttest was administered in week 14 of the semester. Students were given one hour to complete the test but they were free to take longer, if desired. The tests for 2011 were scored by Tennessee Tech University and the tests for 2012 were scored on-site at Purdue in a session led by faculty who had given official training for scoring the instrument (http://www.tntech.edu/cat/training/). Tests scored at Purdue were returned to Tennessee Tech University for accuracy checking and final-score summaries. The pretest scores were not significantly different between 2011 and 2012 semesters (two-sample t-test) so the data were lumped. Differences between pre- and postsemester scores were statistically analyzed with a one-way ANOVA with Bonferroni correction for multiple comparisons.

**RESULTS**

**Student assessment of research-based module**

Students’ motivation for enrolling in the course remained relatively constant over the three semesters (Table 1), though there was a steady increase in the proportion of students taking the course because they were interested in obtaining research experience. As part of the standard Purdue course evaluations, students were urged to submit written comments pertaining to what they liked about the course or what they disliked with suggestions for improvement. Many students wrote comments reflecting how much they learned and how they believed they gained a lot from the research-based activities and teaching methods used. The most common complaint students had dealt with the workload of the course. Students felt the amount of work required was higher than the two credits awarded for completion of the course. Comments are shown in Appendix 2.

After the first semester of this research-based lab course was taught, we wanted to gain more information on students’ real feelings about the course and how it helped improve their interest in science and understanding of the nature of scientific research. To accomplish that, we needed an assessment that went into more detail than the standard Purdue student course evaluations. A focus group session with four preselected evaluative questions was led by an assessment coordinator of the DLRC at Purdue. These questions and the results from the focus group session with selected student quotations are shown in Table 3. Much like the course evaluations, the focus group survey results show students appreciated the course. Even the minority of students who indicated they did not wish to continue on to graduate school felt they learned a lot and had increased interest in taking upper level biology courses.

Students from the second and third installment of the course voluntarily took an anonymous attitudinal survey in a pre- and post fashion with some prompts that were analogous to the focus group session questions. The students indicated their level of agreement with statements probing their experience in five areas: 1) Interest in biology/ science, 2) Perceived connection between real life and science, 3) Lab perceived as similar to real scientific lab practices, 4) Perceived learning of biology content through laboratory (self-assessment), 5) Belief that they can understand and do scientific research (self-efficacy). Presemester responses indicate students’ opinions of their high school biology lab experience while postsemester responses reveal students’ feelings toward the laboratory module. Figure 1 shows select pre- and postsemester results from the attitudinal survey. An increased number of students agreed they had a better understanding of the process of scientific research, that lab experiences were very similar to real research, and that lab experiences increased their appreciation for the role of scientists in society postsemester compared to presemester. These results were statistically significant (Appendix 3). There was a trend toward increased interest in the process of science in the postsemester, though the data were not significant (Appendix 3). Mixed results were seen for the number of students interested in earning a PhD in a scientific field. More students felt strongly interested in earning a PhD postsemester, but more students also felt strongly disinterested in earning the degree postsemester. When asked about their confidence in explaining a biology experiment from the course to an instructor, students showed little increase postsemester; however, students were already confident in their ability to accomplish this at the beginning of the semester.

**Critical thinking Assessment Test**

One of the objectives we had for this class was to develop students’ critical thinking skills. As has been noted by many educators and postgraduate employers, a lot of emphasis is placed on developing students’ critical thinking skills during their undergraduate careers. However, the actual teaching of them in undergraduate courses is lacking (4, 12). To determine how well the activities in this course led to increased critical thinking skills, students in the second and third installments of the course took the CAT (Critical thinking Assessment Test) in a pre-/postsemester format. The CAT instrument divides critical thinking into four domains that encompass previously defined domains (7, 8): problem
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TABLE 3.
Student responses to evaluative questions asked during focus group session.

<table>
<thead>
<tr>
<th>Evaluative Question</th>
<th>Student Data</th>
<th>Select Student Quotations</th>
</tr>
</thead>
</table>
| What benefits accrued to participants from their participation in the research-based module? | • All felt the module was a positive learning experience.  
• A majority described the module as intense, rewarding, illuminating, informative, or helpful.  
• All indicated the module increased their interest in taking higher-level classes in biology. | • I thought it was really nice because we got to learn some of the basic laboratory techniques that we are going to need in the future, like pipetting and aseptic technique and things like that, but at the same time we were working on research that hadn’t been done before and contributing to furthering knowledge.  
• It’s not research just for the sake of research, or experiments for the sake of experiments. We actually did the experiments with a research goal in mind. |
| What are the impacts of the module on students’ research and laboratory skills and understanding of research publications? | • Students felt that they successfully:  
• acquired basic/technical laboratory skills.  
• enhanced research skills and communication of research findings.  
• enhanced understanding and interpretation of scholarly publications. | • Being able to read papers and really get into the literature and then write your own papers that basically sound like those papers. When at first you start reading them and you think every other word is a foreign word . . . but now that we have done the poster session, we said...those words, and . . . gaining that familiarity with a foreign language was really cool for me.  
• The process of writing lab reports . . . was also good practice, because it helped in understanding reading other people’s research papers.  
• The figures and graphs really developed throughout our lab reports. |
| What are the effects of the module on students’ educational and career aspirations, especially aspirations for research-oriented careers in biology fields? | • Some students’ career plans were impacted by the course, others were not.  
• A majority indicated they would like to go to graduate school. | • I think just the fact that it’s research can tell you whether or not you’d like to do research in the long run.  
• I know I’m actually planning on also doing a major in micro thanks to this class, so I probably wouldn’t have, so I found it to be really interesting. |
| What are the challenges associated with participation in the module and what are participants’ suggestions for improvement? | • Students thought the module would be too intense and time-consuming.  
• Students felt the module was too much work for the amount of credits. | • The only negative thing I can think of, as far as expectations, is it was only a two-credit hour course and was like a lot of time.  
• This is probably one of my most work-intensive classes.  
• It definitely took the most time out of all my classes. |

...solving, creative thinking, evaluating information, and effective communication. Figure 2 shows the comparison of pre- and post-test scores from students taking the CAT test in our classes. Students showed a significant increase in their total postsemester CAT scores compared to presemester (p < 0.05, one-way ANOVA with Bonferroni corrected alpha). When broken down into specific questions, students also demonstrated a significant increase in their scores for two questions, one probing the ability of students to evaluate information and the other probing two domains—creative thinking and effective communication.

DISCUSSION

The goals of our research-based module were to: increase students’ enthusiasm for science and research, increase the number of students with early research experience, improve their understanding of the nature of authentic scientific research, improve the retention of Biology majors, enable student proficiency in scientific understanding and communication, and improve critical thinking skills.

Student assessment of research-based lab module

The feedback has shown that students generally have a positive view of the course. Given that these are first-year students who are actively designing and executing an authentic research project that would be performed in a real scientific laboratory, it is not unexpected that the class would be perceived as difficult and the workload significant. The majority of students felt that while this was the case, the benefits of the course made the effort worthwhile.
On the informal survey issued on the first day of class, the majority of students (40/45) indicated that they were interested in attending some form of graduate studies (graduate school, medical school, veterinary school, dental school, or a combination). Over half of those 40 students (22/40) expressed an interest in graduate school. While encouraging, convincing students to pursue research careers is not a goal of the course and given that students self-select into the research-based course, we recognize there may be a bias toward the enrollment of students already committed to graduate school. Previous studies suggest that students' preexisting interests are not often shifted by research class experience (38). We wanted to expose students to an original research experience early in their education to increase their interest in science and knowledge of how real scientific experimentation works. All scientists know that research is not for everyone, and it is better for students to learn whether they enjoy research earlier rather than later. Concerns over whether student interest in the course would be affected by disinterest in the specific research topic are not justified. Comments from the focus group indicate even those students who were not interested in the microbiology research project still felt that the fact that it was research made the course worthwhile and provided them with valuable lab skills that have prepared them well for future biology courses (data not shown).

FIGURE 1. Comparison of student responses to select questions from a pre-/postsemester attitudinal survey. The number of student responses to select questions from a Likert scale attitudinal survey where 6 = Strongly Agree, 5 = Agree, 4 = Barely Agree, 3 = Barely Disagree, 2 = Disagree, and 1 = Strongly Disagree.
We observed significant gains in students’ understanding of the nature of scientific research based on responses to all prompts that contributed to that factor on the attitudinal survey, which was one of our objectives for this project. However, we did not observe significant gains in student responses to prompts regarding the other four themes targeted by the survey. Student interest in biology and science did not significantly change. This could be due to a variety of reasons including: not being interested in research, the specific topic of the class, or the realization of what science and scientific research really are. Alternatively, it is also possible the self-selecting students already had a high interest in science prior to the start of the semester as noted earlier; these students are already planning to be Biology majors. The slight negative trend in the theme of perceiving a connection between real life and science suggests to us that we need to target that area of our instruction and activities as it is important for a scientifically-literate society to see connections with what they know and the world of science and research.

We did administer our attitudinal survey to students participating in the traditional lab class, but the number of matched pairs for pre- and postsemester surveys was too small for a valid analysis of the data. However, data gathered from the other research-based class taught in the fall (13) indicate that there are significant differences in the postsemester (data not shown).

Critical thinking Assessment Test

We saw a significant gain in student critical thinking as measured by the CAT instrument (Fig. 2). Students were engaged in all four critical thinking domains probed by the CAT instrument in all blocks of the semester (Table 2). The practice of critical thinking skills was implicit in many of the activities and assignments that students completed during our course and in the PLTL workshops (Table 2). The skills and strategies learned from the explicit instruction and guidance were expected to be employed in assignments such as lab reports and the research poster. Students use critical thinking skills in the discussion section of lab reports in evaluating and interpreting data as well as thinking creatively to think of the next steps in their projects. We have begun more carefully analyzing the discussion sections of the lab reports over the course of the semester (Spring 2012) to identify areas of gains and areas where targeted instructional interventions would be helpful.

Upon reflection of our instructional approaches with respect to critical thinking skills development, the majority of our activities and assessments are embedded. There is evidence of higher gains in critical thinking with the use of explicit instruction with practice (25). We intend to devise more explicit instruction on how to solve problems, such as providing students with step-wise strategies and practice for evaluating information and data. These approaches will hopefully become tools that students will internalize and transfer to subsequent classes and situations.

Obviously students were enrolled in other classes which could contribute to the gains we observed. Our efforts to recruit a comparison group have been unsuccessful and we are revising our human studies protocols to offer a more enticing compensation for participation. However, given the activities and feedback that the students received, it is likely that at least some of the gains are due to activities in our class. Significant gains on the CAT have not been observed in a single semester unless there are focused instructions that would foster critical thinking development (Barry Stein, personal communication).

CONCLUSION

Early research experiences are beneficial to students in a number of ways (21, 22). We are currently evaluating the long-term impact of introductory lab classes by following students who have enrolled in these classes as well as students who did not throughout their time at Purdue. We are tracking students’ choice of major, persistence in science, participation in other research experiences, and academic performance at Purdue.

From the perspective of the instructors and researchers, this class has also been a tremendous success. While this type of course requires more instructional time and management than cookbook lab classes, the benefits far outweigh the costs. This course was recognized for its educational merit and was one of the 2012 AAAS/Science Prize winners for Inquiry-Based Instruction (15). Further, the data generated by the students in the 2010 and 2011 spring semesters led to a scientific publication with all of the students as authors (14)!
Involving introductory biology students in authentic research experiences in their classes is one of the recommendations for improving biology education for undergraduate students (1). With our class we have demonstrated that this model can be successful and that a genetic screen provides a feasible project for first-year students to engage in. This class has generated research-quality data, improved critical thinking skills, increased student understanding of the nature of scientific research, and engaged and excited students.

**SUPPLEMENTAL MATERIALS**

Appendix 1: Confirmatory factor analysis for attitudinal survey  
Appendix 2: Representative quotes from written comments section of Purdue course evaluations  
Appendix 3: Pre-/Postsemester changes in attitudes

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