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Successful implementation of inquiry-based physiology laboratories in undergraduate major and nonmajor courses

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Casotti G, Rieser-Danner L, Knabb MT. Successful implementation of inquiry-based physiology laboratories in undergraduate major and nonmajor courses. *Adv Physiol Educ* 32: 286–296, 2008; doi:10.1152/advan.00100.2007.—Recent evidence has demonstrated that inquiry-based physiology laboratories improve students' critical- and analytical-thinking skills. We implemented inquiry-based learning into three physiology courses: Comparative Vertebrate Physiology (majors), Human Physiology (majors), and Human Anatomy and Physiology (nonmajors). The aims of our curricular modifications were to improve the teaching of physiological concepts, teach students the scientific approach, and promote creative and critical thinking. We assessed our modifications using formative (laboratory exams, oral presentations, and laboratory reports) and summative evaluations (surveys, laboratory notebook, and an end of semester project). Students appreciated the freedom offered by the new curriculum and the opportunity to engage in the inquiry process. Results from both forms of evaluation showed a marked improvement due to the curricular revisions. Our analyses indicate an increased confidence in students' ability to formulate questions and hypotheses, design experiments, collect and analyze data, and make conclusions. Thus, we have successfully incorporated inquiry-based laboratories in both major and nonmajor courses.

pedagogy; curriculum; evaluation

INQUIRY-BASED LEARNING is an alternative pedagogical method of classroom teaching that is characterized by a focus on learning through discovery. It incorporates four approaches to teaching: *1*) a focus on ideas and concepts generated by students rather than by instructors, *2*) an activity component where students actively participate in performing tasks (experiments) to test their ideas, *3*) an emphasis on learning the methods of verifying and testing hypotheses, and *4*) an emphasis on the importance of both content and process as components of learning (7).

Some individual studies of the effectiveness of an inquiry-based approach have been reported. For example, DiPasquale et al. (2) modified the curriculum in an exercise physiology course at San Diego State University. The course was previously taught in a traditional style. Their new approach was to cover core exercise physiology topics in the first third of the course using the traditional teacher-centered style of learning while emphasizing the scientific process. In the last 9 wk of the course, students worked in small groups of three to four and completed independent research projects. In contrast, Myers and Burgess (11) redesigned an organismal physiology course centering on student-designed experiments throughout the course of the semester. Both studies reported an increase in student achievement of learning outcomes using student-designed experiments compared with a teacher-centered approach. Moreover, a recent review (10) published in *Advances of Physiology Education* summarized the evidence supporting the conclusion that forms of active learning, such as an inquiry-based approach, are more effective in enhancing student learning than traditional modes of teaching.

Problems With the Existing Curriculum

The physiology curriculum using a teacher-centered approach resulted in several problems related to student learning. One of the problems was that students in our nonmajor course failed to connect physiological concepts taught in lecture with the laboratory activities. In addition, the laboratories did not emphasize the scientific approach to problem solving, and students were restricted in the types of experiments they were able to perform (13).

Our old curriculum provided students with detailed step-by-step instructions for completing their experiments. As a result, students commented to the laboratory instructors that they lost sight of the educational purpose of the experiments. Furthermore, regimented instructions did not allow our students any flexibility to deviate from the experimental protocol, thereby impeding student creativity (14, 16, 18, 19). Student learning was further limited because laboratory topics were not directly linked to lecture topics (in the nonmajor course), thus reducing the likelihood that students would appreciate the relevance of the experimental procedures to the development of their knowledge of physiology (11).

Students had no opportunity to develop their own understanding of physiology using the scientific approach. Even though our majors were required to write laboratory reports in prerequisite courses such as Cell Physiology and Organic Chemistry, they did not communicate their ideas effectively in a scientific report. For example, students did not refer to the neural control of respiration when discussing irregular respiratory patterns when solving a math problem. This resulted in low scores on laboratory reports. Clearly, this called for the need to offer students more opportunities using the scientific method, from researching background information to developing a testable hypothesis using appropriate written communication and reporting of scientific findings. Similar problems in understanding the scientific approach were also evident in our nonmajor course (see *Precurricula Survey*).

Verbal comments from students in our physiology courses indicated a dissatisfaction with simply repeating experiments that had already been done by other researchers. Students could not see the purpose of performing some of the experiments, especially those involving animals, and often asked "Why are

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we conducting this experiment when we know that the outcome has already been documented?". Clearly, students did not appreciate the potential learning that can result from duplicating experiments, specifically the value of repeatability in regard to the scientific method. On the other hand, mere replication of known results was certainly not the best way to encourage critical thinking and scientific problem solving.

Precurricula Survey

Before changes to the curriculum were made, a student survey was administered at the end of the spring 2003 semester. Students were asked questions designed to assess three outcomes: *1*) whether the laboratory enhanced learning of physiological concepts, *2*) whether the laboratory enabled an understanding of how scientists approach problems, and *3*) whether the laboratory curriculum taught creative- and critical-thinking skills (http://darwin.wcupa.edu/~biology/casotti/inquiry/index.html).

Survey results were mixed depending on whether the students were majors or nonmajors. In the case of nonmajors, students did not perceive the laboratory experience to be useful for learning physiological concepts, with only 57% of students agreeing that "laboratory activities enhanced my ability to understand lecture material." The results of other items from this survey also indicated that students in our nonmajor course viewed the laboratory experience negatively, primarily because laboratory topics did not closely follow lecture topics. In contrast, 100% of majors responded positively (strongly agreed or agreed) to the statement "laboratory activities enhanced my ability to understand lecture material." In terms of questions on the scientific approach and creative and critical thinking, depending on the question, nonmajors responded positively (strongly agreed or agreed) only 38–49% of the time to statements dealing with developing a testable hypothesis and experimental design. In contrast, majors responded positively (strongly agreed or agreed) 92–100% of the time. Based on these results, substantial revisions needed to be made, particularly in the nonmajor course.

Course Demographics

To address the challenges discussed above, we adopted an inquiry-based teaching approach and modified our laboratory curricula in three physiology courses: a lower-division course, Human Anatomy and Physiology (nonmajors), and two upper-division courses, Human Physiology (preprofessional majors) and Comparative Vertebrate Physiology (Biology majors). Students in Human Anatomy and Physiology were from the disciplines of nursing, sports medicine, kinesiology, and nutrition. The annual class enrollment was ~300 students. Students in our preprofessional and pharmaceutical and product development programs take Human Physiology, while students in biology take Comparative Vertebrate Physiology. The annual enrollment for each of these latter courses is 12–20 students.

Goals

Laboratory sections for our upper-division physiology courses are designed to closely follow material covered in the lecture and are used to reemphasize these concepts. The usefulness of this approach is supported by results from the spring 2003 survey. In contrast, as mentioned earlier, laboratories for our lower-division course did not follow the lecture material closely. Thus, the first goal of our study was to address this problem in our nonmajor course laboratories by incorporating a set of interactive laboratory activities that directly corresponded to lecture topics.

Students in our major class did not have the flexibility to design and implement their own experiments and had difficulty writing their laboratory reports in a proper scientific manner. Problems in understanding the scientific approach were also evident in our nonmajor course. To address this problem, the second goal of our study was to revise the laboratory curricula to emphasize the development of scientific problem solving in students. In addition, curricula were redesigned to encourage creative and critical thinking, the third goal of our study.

In an effort to stimulate learning of physiology and the scientific approach, a modified version of an inquiry-based curriculum, as initially developed by DiPasquale et al. (2), was adopted. Their model proved very successful, with instructors reporting increased independent thinking, improved integration of information, and enhanced student ability to answer their own questions. Students reported a "tremendous ownership" of group projects, valued independence, and, most importantly, that the curriculum sparked an increased interest in scientific research and graduate programs (2). In DiPasquale et al.'s model, students participated in traditional teacher-oriented classes for the first third of the semester. Thereafter, students worked in small groups, using the knowledge obtained in the first third of the course, to complete independent research projects.

In the present study, laboratories throughout the semester were inquiry based (not just the latter portion), with the instructor providing students with a basic outline of the physiological principles. Students were required to read textbooks and articles from the primary literature before entering the laboratory and to use this background knowledge to design unique experiments. This approach of researching prior literature was used successfully by Chaplin (1). Once in the laboratory, students formulated hypotheses to test, designed experiments, and analyzed and interpreted data. Finally, students were asked to present the data in front of the rest of the class using an interactive whiteboard in what we called "show and tell" presentations.

Curricular Modifications

Nonmajor laboratories. To increase student understanding and learning of physiology, our nonmajor laboratory course was redesigned such that laboratory topics (and the order of laboratories) more closely followed the topics presented in lectures. Some prior laboratory activities were removed while a series of new laboratory activities were introduced, as shown in Table 1. Three laboratories involving computer simulations (senses, membrane physiology, and muscle contraction) were removed. Since computer simulations always work, we saw this as a problem because it does not accurately reflect the variability of physiological systems. Three new inquiry-based laboratories were introduced: Psychophysiology II, Cardiovascular Physiology II, and Exercise Physiology II, where students

Table 1. *Lecture schedule and previous (teacher oriented) and modified (inquiry based) laboratory curriculum for the Human Anatomy and Physiology course for nonmajors*

Week	Lecture Schedule	Previous Curriculum	Modified Curriculum
1	Introduction and the autonomic nervous system	Scientific notation and metrics	Introduction to inquiry-based learning and PowerLab tutorial†
2	Endocrinology	Senses (reflexes, taste sensation, and two-point threshold)	Psychophysiology I† (galvanic skin response parameters)
3	Cardiovascular physiology	Senses (computer simulations)	Psychophysiology II*† (inquiry experiments)
4	Cardiovascular physiology	Hematology	Hematology
5	Lymphatics/immunology	*Laboratory exam 1*	Cardiovascular Physiology I† (anatomy, ECG, heart sounds, pulse recording, and blood pressure)
6	Respiratory physiology	Membrane physiology (computer simulations)	Cardiovascular Physiology II*† (inquiry experiments)
7	Respiratory physiology	Cardiovascular physiology (ECG, heart sounds, pulse recording, and blood pressure)	*Laboratory exam 1*
8	Renal physiology	Muscle contraction (computer simulations)	Respiratory physiology† (anatomy and spirometry)
9	Renal physiology	*Laboratory exam 2*	Integrative Exercise Physiology I† (experiments measuring pulse, ECG, and breathing)
10	Digestion	Respiration (anatomy and spirometry)	Integrative Exercise Physiology II*† (inquiry experiments)
11	Digestion	Renal physiology (computer simulations)	Renal physiology (urine analysis and computer simulations)
12	Reproduction	Digestion (anatomy and computer simulations)	Digestion (anatomy and computer simulations)
13	Reproduction	*Laboratory exam 3*	*Laboratory exam 2*

*Show and tell presentations; †PowerLab experiments.

designed, tested, and presented experimental results to the rest of the class. These changes were made possible with the purchase of PowerLab, a powerful computerized data-acquisition system that enabled students to collect and analyze data easily. *Laboratory 1* provided a tutorial on how to use the equipment as well as an introduction to the inquiry-based approach to learning. In the subsequent weeks, laboratory topics followed 1 wk after the topic was finished in lecture (Table 1).

Major laboratories. Modifications were made to our major laboratory curriculum including an introductory laboratory on inquiry-based learning, a PowerLab tutorial, and the addition of six inquiry-based laboratories. In addition, a laboratory on how to effectively present scientific data and laboratories dedicated to independent projects and oral presentations were also included (Table 2). Two laboratory exams were removed, and laboratory questions were incorporated into lecture exams, thereby allowing time for the addition of an independent project to the laboratory curriculum at the end of the semester (*week 12*).

Curricular modifications in all courses involved students working in groups of three or four. Since studies on peda-

Table 2. *Lecture schedule and previous (teacher oriented) and modified (inquiry based) laboratory curriculum for the Comparative Vertebrate Physiology course for majors*

Week	Lecture Schedule	Previous Curriculum	Modified Curriculum
1	Homeostatis	Membrane physiology (diffusion, osmosis, and tonicity)	Introduction to inquiry-based learning and PowerLab tutorial
2	Nervous system	Neuromuscular blockade (effect of tubocurare)	Presenting scientific information
3	Nervous system	Nerve-muscle physiology (irritability, threshold, tetanus, length-tension, and fatigue)	Action potentials† (threshold, refractory period, and conduction velocity)
4	Muscle physiology	Hematology (hemoglobin, blood counts, and blood typing)	Nerve-muscle physiology*† (graded response, load, tetanus, fatigue, neuromuscular blockade, and temperature)
5	Muscle physiology and circulatory physiology	Cardiovascular Physiology I (heart sounds, blood pressure, electrical axis, and pulse recording)	Hematology (hemoglobin, blood counts, and blood typing)
6	Circulatory physiology	*Laboratory exam 1*	Cardiovascular Physiology I*† (ECG, heart sounds, pulse recording, and blood pressure)
7	Circulatory physiology	Cardiovascular Physiology II (refractory period, Starling's law, temperature, and heart block)	Cardiovascular Physiology II*† (effects of drugs and temperature on heart rate and ECG)
8	Respiratory physiology	Respiratory physiology (hyperventilation, rebreathing, and spirometry)	Respiratory physiology*† (spirometry and chest movement)
9	Respiratory physiology	Renal physiology (urine volume, specific gravity, Cl^- concentration, and osmolality)	Renal physiology* (urine volume, specific gravity, Cl^- concentration, and osmolality)
10	Renal physiology	Metabolism (oxygen consumption)	Metabolism*† (effects of thermy, temperature, activity, and diet)
11	Metabolism	Digestion (insulin and glucagon)	Digestion (insulin and glucagon)
12	Digestive physiology	Reproduction (effect of gonadotropin)	Independent projects
13	Reproductive physiology	*Laboratory exam 2*	Oral presentations

*Show and tell laboratories; †inquiry-based laboratories.

gogical practices have demonstrated that a group size of three to four students enhances learning, a group size of four students was chosen as part of the curricular modification (6, 8, 12, 14, 17).

New laboratory activities developed for each physiology course were designed to enhance student inquiry, help students learn skills to "think like a scientist," and promote creative and critical thinking. These activities enabled students to acquire familiarity with the data generated using PowerLab. Once familiar with data generation, students read the literature (i.e., primary literature or textbooks), came up with hypotheses to test, and then designed experiments to test predictions.

Teaching Methodology

The previous teacher-centered mode of instruction involved the professor spending the first 30 min of the laboratory discussing the physiological principles of the laboratory topic and instructing students on how to use the equipment to achieve the desired result. The remainder of the laboratory was spent performing all of the assigned experiments as outlined in the laboratory manual with each group of students repeating the same experiments.

The new student-centered model using the inquiry-based approach involved the following 2-wk process.

Week before the laboratory. Students were assigned to groups of four in the laboratory. Each group was asked to find literature appropriate to the topic and design experiments based on readings and from material presented in lecture. For the nonmajor physiology class, 2 wk were devoted to each inquiry-based laboratory (i.e., Psychophysiology I, Cardiovascular Physiology I, and Integrative Exercise Physiology I). In the first week, students conducted directed experiments aimed at learning what types of variables could be tested (Table 1). This was the same strategy used by Stratton (9). Major students, being more independent, did their background research before the laboratory. Both majors and nonmajors reviewed experimental ideas with their instructors, thus enabling them to arrive to class prepared and ready to conduct their own independent experiments. Instructors often guided the students' thinking by asking them probative questions to improve their experimental design. All students were asked to prepare a PowerPoint presentation with slides on the title, background, purpose, hypothesis, and materials and methods before the next laboratory session. Other slides, such as results and discussion, were completed in the laboratory after students had gathered and analyzed their data.

Time spent in the laboratory. Students performed their experiments in the time allocated. In the case of the nonmajor class (2-h laboratories), students had 1 h to conduct their experiments and 30 min to analyze their data as well as prepare their results and discussion slides. The final 30 min were used for oral presentations using an interactive whiteboard (Smart Technologies). Since major laboratories are 3 h long, these students had 2.5 h to complete their experiments, analyze data, and finalize their presentations and 30 min to present the results of their findings as oral presentations.

Examples of nonmajor psychophysiology laboratories. LABORATORY 1. Our equipment enabled students to measure the galvanic skin response (GSR), a change in skin conductivity associated with sweating, and skin temperature, both mediated by the sympathetic nervous system. A preliminary lab (Psychophysiology I) was used to introduce students to the GSR response, and student groups conducted simple predetermined experiments to measure changes in the GSR and temperature (Table 1). They discovered that increased stress increased the GSR response and decreased skin temperature. After this laboratory, students researched the GSR literature and designed a unique experiment that was reviewed by their laboratory instructor. For example, students chose an article where investigators studied the effects of music on GSR in college students (18). Data from that GSR study were used to develop a new testable hypothesis that was conducted in *week 2*. Between *weeks 1* and *2*, students prepared their PowerPoint presentation with the exception of their results and discussion slides.

LABORATORY 2. Students investigated the effects of different music genres on GSR and skin temperature. After data analysis, they discovered that rap music increased GSR and decreased skin temperature more than slow relaxing music. They concluded that rap music stimulated the sympathetic nervous system. Activities such as these allow students to gain an appreciation of the physiological effects of the autonomic nervous system and develop the critical-thinking skills necessary to plan and conduct a scientific investigation.

Example of the major action potential laboratory. In the week before the laboratory, students were asked to read ahead in the laboratory manual and thus were aware of variables they would test in the next laboratory. For an action potential (AP) laboratory, they read an article such as "The refractory period of fast conducting corticospinal tract axons in man and its implications for intraoperative monitoring of motor evoked potentials" (15). This article demonstrates the effect of factors such as threshold voltage, stimulus strength, and frequency of stimulus on the rate of AP generation. These variables were all discussed in lecture as affecting the probability of generating APs. Student groups showed their background materials to the professor, who reviewed their proposed experiments. They then began to prepare a PowerPoint presentation, as was described above for the nonmajor class. These PowerPoint presentations promoted sharing of the data and knowledge gained by the group with the rest of the class.

Students in our major classes were expected to answer questions at the end of every laboratory and write two scientific laboratory reports in the course of the semester. At the conclusion of the laboratory, each student took electronic data and analyzed it independently, graphed the findings, and wrote a report in proper scientific format.

Overcoming Obstacles

Achieving successful curricular reform inevitably presented some obstacles. More problems were associated with incorporating changes in the large enrollment, nonmajor course, and several strategies were developed to overcome them. Other teaching faculty members, both full time and temporary, were assigned to teach the nonmajor laboratories. Most of these faculty members had no previous experience with inquiry-based laboratories, so we required that all faculty members meet once a week to discuss the planned experiments and address classroom management challenges. At these meetings, participating faculty members had an opportunity to work with the equipment, discuss concerns about engaging students in the inquiry process, and provide feedback on inquiry-based questions on the laboratory exams. Instructors were educated on how to ask probative questions, such as the following:

- What is your idea?
- What do you think will happen and why?
- How do you plan to test your ideas?
- How many subjects will participate?
- Can I see the data you collected?
- Does your graph show your results in the best way?
- How do your results relate to what you learned in class?

It would have been impossible to accomplish these curricular changes without the cooperation of our colleagues.

Students also voiced concerns about the changes in the laboratory experience. Important components to our first laboratory meeting with students was an introduction to the PowerLab equipment as well as our expectations for student-designed experiments and presentations. Thus, in addition to a short tutorial using PowerLab, students were required to share their contact information with their laboratory group (so they could meet outside of regular laboratory hours), work on a data set to prepare a graph using Excel, and view a template for a PowerPoint presentation. The laboratory instructors emphasized and explained the resources available online, such as the rubrics included in the laboratory manual and practice laboratory exam questions. For more information about the laboratory materials, see http://darwin.wcupa.edu/~biology/casotti/inquiry/index.html.

The most critical components to the success of this approach were effective time management by the students and instructor flexibility. The instructors played a crucial role in keeping students on track and aware of time limits. For example, in the nonmajor course, the students needed to execute, analyze, and present their results in 2 h. Students were expected to perform background research and prepare their PowerPoint presentations in the week before the laboratory. A problem of lack of resources arose when the groups, consisting of four students, needed to perform their experiments and work on their presentations simultaneously. It became clear that two computers were needed for each group: one for conducting the experiment and one for data analysis and presentation preparation. The inquiry laboratories ran more efficiently and within the time constraint of the laboratory with the additional computers. In the major courses, students preferred to have 1 wk to work on their presentations. Thus, the schedule was modified so that students conducted their experiments in the first week and made their presentations at the beginning of the next laboratory period.

The rewards of incorporating inquiry-based learning were worth the effort. Not only did the instructors gain insight into student interests but they were surprised at the students' novelty and diversity of ideas. A faculty laboratory meeting sometimes turned into a "bragging session" about which project was the most creative the previous week. Thus, although modification of the laboratories from a traditional to an inquiry-based approach was challenging, it was a rewarding experience for both faculty members and students.

Assessment of Curricula Integration

Evaluation plan. The following student learning outcomes (SLOs), derived from the three goals of our curricular modifications (as outlined above), were developed:

SLO 1. Students will understand physiological concepts.

SLO 2. Students will develop an understanding of the scientific approach.

SLO 3. Students will engage in creative and critical thinking.

The success of our curriculum initiatives and the extent to which students reached our learning outcomes were evaluated using two broad forms of evaluation: formative and summative. Formative evaluations were those used to assess ongoing project activities (3). In our nonmajor laboratory, examples of formative assessment included exams and show and tell presentations; in our major laboratories, they included laboratory reports and show and tell presentations. Summative evaluations were used to assess the projects' overall success (3). Examples of summative evaluations in our nonmajor laboratory included survey data and in our major laboratories included an end of semester laboratory notebook, surveys, and an independent project.

For each of the direct measures of student learning that were included, grading rubrics were developed to aid in the evaluation of overall performance and individual SLO performance, with individual items of each rubric linked to one of the three SLOs. Each of the grading rubrics are available online at http://darwin.wcupa.edu/~biology/casotti/inquiry/index.html. Direct measurement of student learning and specific performance goals for each included the following:

1. Laboratory exams (nonmajors only). Students will obtain an average score of 70% on items measuring each SLO.

2. Show and tell presentations. Overall percentage scores and percentage scores for each SLO will increase as the semester progresses.

3. Laboratory reports (majors only). A minimum of 80% of students will obtain a score of 80% of total possible points and 80% of points measuring each SLO by the second report of the semester.

4. Laboratory notebook (majors only). A minimum of 80% of students will obtain a score of 80% of total possible points as well as 80% of points measuring individual SLOs.

5. Final group project (majors only). All students (100%) will obtain a grade of at least 80% on items measuring each SLO.

Surveys were included as indirect measures of student learning in an attempt to obtain information about student perceptions of the degree to which we met our objectives in the course. Copies of each of our surveys are available online at http://darwin.wcupa.edu/~biology/casotti/inquiry/index.html. Surveys and specific expectations regarding the outcome of these surveys included the following:

1. Precourse/postcourse survey. Students were asked a set of 10 survey questions at the beginning and end of each semester. Questions were designed to assess students' confidence in their abilities to engage in and/or their understanding of the scientific approach (*SLO 2*). We expected to see an increase in student confidence ratings (i.e., ratings of "somewhat confident" or "strongly confident") over time.

2. Postcourse survey. Students completed a second survey at the end of the semester, designed to assess student perceptions of the degree to which the course met all three SLOs (i.e., to learn physiological concepts, understand the scientific approach, and develop creative- and critical-thinking skills). We expected that a minimum of 80% of student responses to items associated with each SLO would be "agree" or "strongly agree." In addition, this postcourse survey included three open-ended questions designed to gather information about which laboratory activities students perceived to be most helpful in achieving each of the three SLOs. We hypothesized that presentation laboratories (those that include a presentation component; see Tables 1 and 2) would be reported as helpful more frequently by students than would laboratories that did not include a presentation component.

Results of assessment. NONMAJOR PHYSIOLOGY LABORATORIES. Assessment data were collected each semester from two laboratory exams (for three consecutive semesters), three show and tell presentations (for two semesters), precourse/postcourse surveys (for three semesters), and postcourse surveys (for two semesters). The results for laboratory exams by SLO are shown in Table 3. The results suggest that student performance clearly met our expectations for two of the three SLOs. Average student percentage scores for items measuring students' understanding of the scientific process (*SLO 2*) ranged from 74.5% to 86.7% (across two exams each semester) with an overall average of 80%. Average percentage scores for items measuring students' ability to engage in creative and critical thinking (*SLO 3*) ranged from 74.9% to 83.4% (across two exams each semester) with an overall average of 78.3%. Average student percentage scores for items measuring students' understanding of physiological concepts (*SLO 1*) fell just short of our expectation, with average scores ranging from 67.3% to 68.0% and an overall average of 67.7%.

For the show and tell presentations, we expected that student performance scores for each SLO would increase across the semester. The results suggest that our expectation was met. For each semester, one-way repeated-measures ANOVA was calculated comparing each of the three show and tell SLO scores at three different time points (*presentation 1*, *presentation 2*, and *presentation 3*). Table 4 shows average initial and final presentation scores as well as the amount of change by SLO for each semester. For *SLO 1* (understanding of physiological concepts), the fall 2006 results, involving 20 lab groups, approached significance ($F_{2,38} = 3.09$, $P < 0.06$). Followup protected paired *t*-tests comparing initial with final presentation scores revealed that scores increased significantly from the initial to final presentation. The spring 2007 results, involving 15 lab groups, also revealed a significant effect for *SLO 1* ($F_{2,28} = 12.25$, $P < 0.001$). Followup protected paired *t*-tests again revealed that scores increased significantly from the initial to final presentation. Across both semesters, presentation scores increased by an average of 14.6% from the initial to final presentation.

Table 3. *Average SLO percentage scores by semester on laboratory exams for the Human Anatomy and Physiology course for nonmajors*

	Spring 2006	Fall 2006	Spring 2007	Average
SLO 1. Physiological concepts	67.8*	68.0*	67.3*	67.7
SLO 2. Scientific appoach	74.5	86.7	78.7	80.0
SLO 3. Creative and critical thinking	76.6	74.9	83.4	78.3

Values are percentages; n = 108–118 students in the spring 2006 semester, 105–106 students in the fall 2006 semester, and 113–117 students in the spring 2007 semester. SLO, student learning outcome. *Scores that did not meet our expected minimum of 70%.

Table 4. *First and final average show and tell presentation scores with the average percent change by SLO for the course for nonmajors*

	Fall 2006	Spring 2007
SLO 1. Physiological concepts		
Initial presentation	82.50 ± 16.4	81.67 ± 14.8
Final presentation	95.00 ± 10.3	98.33 ± 6.5
Percent change	12.50 ± 19.0*	16.7 ± 15.4§
SLO 2. Scientific approach		
Initial presentation	87.50 ± 6.2	91.11 ± 3.5
Final presentation	97.8 ± 6.2	97.22 ± 4.1
Percent change	9.60 ± 7.2§	6.10 ± 5.6§
SLO 3. Creative and critical thinking		
Initial presentation	87.00 ± 8.0	94.00 ± 6.3
Final presentation	97.50 ± 5.5	100.00 ± 0.0
Percent change	10.50 ± 10.5‡	6.00 ± 6.3†

Values are means ± SD; n = 20 groups and 3 presentations for the fall 2006 semester and 15 groups and 3 presentations for the spring 2007 semester. *$P < 0.06$; †$P < 0.05$; ‡$P < 0.01$; §$P < 0.001$.

For *SLO 2* (understanding of the scientific approach), the fall 2006 effect was significant ($F_{2,38} = 8.14$, $P < 0.001$). Followup protected paired *t*-tests again revealed that scores increased significantly from the initial to final presentation. The spring 2007 results were similar, with a significant overall effect ($F_{2,28} = 9.00$, $P < 0.001$) and protected paired sample *t*-tests revealing a significant change in scores from the initial to final presentation (see Table 4). Across both semesters, presentation scores increased by an average of 7.9% from the initial to final presentation.

A similar pattern of results was found for *SLO 3* (creative and critical thinking). An overall significant effect was found ($F_{2,38} = 6.23$, $P < 0.005$) for fall 2006 data. Followup protected paired *t*-tests indicated a significant increase in scores from the initial to final presentation (see Table 4). The spring 2007 results showed the same pattern, with an overall significant effect ($F_{2,28} = 5.21$, $P < 0.05$). Again, followup protected paired *t*-tests revealed a significant increase in scores from initial to final presentation (see Table 4). Across both semesters, presentation scores increased by an average of 8.3% from the initial to final presentation.

The results of the precourse/postcourse surveys indicated that students gained confidence over the course of the semester in their ability to engage in and/or understand the scientific process (*SLO 2*). An overall confidence score was calculated for both pre- and postcourse assessments by scoring each item on a Likert-type scale (from *1* to *5*, where *1* = completely doubtful to *5* = strongly confident) and adding item scores. This procedure of adding point values for items measured on Likert-type scales is commonly used in personality and temperament development research (4, 5, 21). With 10 survey items, the possible overall confidence scores ranged from 10 to 50 for each survey. From these, a confidence difference score was calculated (postcourse confidence score − precourse confidence score). Each semester, a positive confidence difference score, indicating an increase in overall confidence, was reported by a large majority of students (80.2% in spring 2006, 72.9% in fall 2006, and 86.1% in spring 2007). Average pre- and postcourse difference scores are shown in Table 5. Paired sample *t*-tests indicated that the change in overall confidence scores from pre- to posttest were statistically significant each semester ($t_{95} = 9.69$, $P < 0.001$; $t_{95} = 7.24$, $P < 0.001$; and $t_{107} = 11.08$, $P < 0.001$, respectively). In a review of student ratings for individual items, we calculated the percentage of confidence ratings for each item, i.e., the percentage of "somewhat confident" or "strongly confident" ratings (ratings of *4* or *5*) for each item at both the pre- and postcourse assessments. We then examined the degree of change in the percentage of confidence ratings given by students from pre- to postcourse assessment for each specific item. Percentages of confidence scores and changes in the percentages of confidence scores (across three semesters) for each of the 10 items are shown in Table 6. This analysis revealed that the greatest increase in confidence ratings occurred for those items that were specifically targeted by our curriculum modifications: formulating questions and hypotheses (*item 2*), designing an experiment and making predictions (*item 3*), communicating observations orally (*item 5*), summarizing scientific data (*item 9*), and reaching conclusions when presented with scientific data (*item 10*). Average changes in the overall percentages of confidence scores for these items across all three semesters ranged from 19.1% to 43.6%. The smallest change in confidence scores was found for items that students were likely to have more experience with from other, nonlaboratory classes [e.g., working cooperatively in teams (*item 7*)]. Average changes in the overall percentages of confidence scores for these items (items *1*, *4*, *6*, *7*, and *8*) across all three semesters ranged from 3.6% to 13.3%. McNemar tests were used to determine significant changes in the percentages of confidence scores. Significant changes are shown in Table 6. Individual items are available for review at http://darwin.wcupa.edu/~biology/casotti/inquiry/index.html.

Students also reported (via the postcourse survey) that the laboratory was, indeed, helpful in achieving each of the SLOs. Table 7 shows average percentages of "agree" or "strongly agree" responses to survey items linked to each of the three SLOs for two consecutive semesters for nonmajors. Our expectation of 80% of agree responses was clearly exceeded in all cases. Open-ended items of the postcourse survey (see http://darwin.wcupa.edu/~biology/casotti/inquiry/index.html) asked students to identify individual laboratories, if any, that they perceived to be most helpful in achieving each of the three SLOs. Responses were then tallied and categorized by type (presentation laboratories, where students prepared show and tell presentations, and nonpresentation laboratories). Figure 1 shows the results of this tallying procedure across both semesters. As Fig. 1 demonstrates, students more frequently identified presentation laboratories as being most helpful in achieving *SLO 2* (ability to engage in and/or understand the scientific approach) and *SLO 3* (creative and critical thinking). Nonpresentation laboratories were, on the other hand, identified more frequently as being most helpful in achieving *SLO 1* (learning physiological concepts). The reason why students viewed nonpresentation laboratories as being more helpful in understanding physiological principles may be that these labora-

Table 5. *Pre- and postcourse overall confidence scores and confidence difference scores for the Human Anatomy and Physiology course for nonmajors*

	Spring 2006	Fall 2006	Spring 2007
Precourse confidence score	38.13 ± 5.09	39.49 ± 4.61	38.54 ± 4.72
Postcourse confidence score	42.72 ± 3.80	42.99 ± 4.76	43.30 ± 3.93
Confidence difference score	+4.59 ± 4.65	+3.50 ± 4.74	+4.76 ± 4.47

Values are means ± SD; $n = 96$ students in the spring 2006 semester, 96 students in the fall 2006 semester, and 108 students in the spring 2007 semester. Possible confidence scores ranged from 10 to 50.

Table 6. *Percent student confidence ratings from precourse to postcourse for the course for nonmajors*

	Spring 2006	Fall 2006	Spring 2007
Item 1. Understanding science			
Precourse	77.0	86.4	83.3
Postcourse	92.7	93.7	94.5
Change	15.7	7.3	11.2
Item 2. Questions and hypotheses			
Precourse	68.8	76.0	76.9
Postcourse	95.9	91.7	93.5
Change	27.1‡	15.7	16.6‡
Item 3. Designing experiments and making predictions			
Precourse	39.6	52.1	49.1
Postcourse	94.8	90.6	86.1
Change	55.2‡	38.5‡	37.0‡
Item 4. Analyzing data			
Precourse	74.0	79.1	79.6
Postcourse	91.7	85.4	95.4
Change	17.7†	6.3	15.8
Item 5. Communicating orally			
Precourse	60.4	66.7	61.1
Postcourse	88.5	86.5	91.7
Change	28.1‡	19.8†	30.6‡
Item 6. Communicating in writing			
Precourse	74.0	78.1	76.0
Postcourse	85.5	83.4	95.3
Change	11.5	5.3	19.3‡
Item 7. Working in teams			
Precourse	90.6	95.7	91.7
Postcourse	97.9	93.8	97.2
Change	7.3	−2.0	5.5
Item 8. Using computers for experiments			
Precourse	57.3	68.8	65.8
Postcourse	71.8	82.3	77.8
Change	14.5*	13.5*	12.0*
Item 9. Summaring data			
Precourse	61.5	67.7	59.3
Postcourse	84.4	83.4	91.6
Change	22.9‡	15.7†	32.3‡
Item 10. Reaching conclusions			
Precourse	65.6	71.9	66.7
Postcourse	86.5	83.3	97.1
Change	20.9	11.4	25.0‡

Values are percentages; $n = 96$ students for the spring 2006 semester, 96 students for the fall 2006 semester, and 108 students for the spring 2007 semester. See http://darwin.wcupa.edu/biology/casotti/inquiry/index.html for individual items. Items were rated on a Likert-type scale from *1* to *5*, where *1* = completely doubtful to *5* = strongly confident; scores shown are from those students that answered "somewhat confident" and "strongly confident." *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

Table 7. *Percentages of "agree" or "strongly agree" responses to postcourse survey items associated with each SLO for both nonmajors and majors*

	Fall 2006	Spring 2007	Average
SLO 1. Physiological concepts (1 item)			
Nonmajors	92.0	94.9	93.5
Majors	100.0	100.0	100.0
SLO 2. Scientific approach (4 items)			
Nonmajors	93.8	95.5	94.7
Majors	98.6	100.0	99.3
SLO 3. Creative and critical thinking (3 items)			
Nonmajors	92.7	91.2	92.0
Majors	98.1	100.0	99.1

Values are percentages; n = 100 nonmajors and 18 majors for the fall 2006 semester and 117 nonmajors and 17 majors for the spring 2007 semester.

tories simply reinforced, rather than extended, lecture material and this direct connection was more obvious to the students. Alternatively, the presentation laboratories required students to identify a problem, design an experiment, and complete a project, and this process may have overshadowed the learning of the underlying physiological concepts.

MAJOR PHYSIOLOGY LABORATORIES. Assessment data, collected each semester, consisted of show and tell presentations (four, five, or six presentations across three semesters), two laboratory reports (for two semesters), a laboratory notebook (available for only one semester), a final oral project presentation (for two semesters), precourse/postcourse surveys (for two semesters), and postcourse surveys (for two semesters). As was true for the nonmajor course, we hypothesized that student SLO scores on the show and tell presentations would increase across the semester. For each semester, one-way repeated-measures ANOVA was calculated comparing each of the show and tell SLO scores at multiple time points (*presentation 1* and *presentations 4*, *5*, or *6*). There were no significant changes in SLO scores

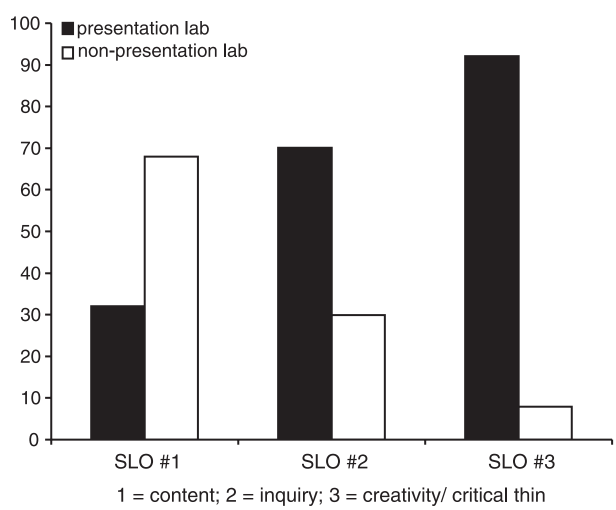

Fig. 1. Postcourse survey results (open-ended items) for the Human Anatomy and Physiology course for nonmajors. There were 213 total responses. Student learning outcomes (SLOs) were as follows: *SLO 1*, physiological concepts; *SLO 2*, scientific approach; and *SLO 3*, creative and critical thinking. Students responded positively 92%, 96%, and 96%, respectively, to each of the SLOs.

across the semester for any of the three SLOs during any of the three semesters for which data were available. Table 8 shows average initial and final presentation scores by SLO for each semester.

All majors were required to complete two laboratory reports each semester. Reports were graded using a standard rubric that allowed us to measure overall performance. We hypothesized that 80% of students would achieve an overall score of 80% as well as minimum scores of 80% for each SLO by the second laboratory report. Overall performance scores exceeded our expectations, with 94.4% of students achieving a minimum overall score of 80% by the second laboratory report during the fall 2006 semester and 82.3% of students achieving a minimum overall score of 80% by the second laboratory report during the spring 2007 semester. We further hypothesized that overall performance would improve from the first to second laboratory report. Results here were somewhat mixed. Paired *t*-tests supported significant improvement from the first laboratory report (mean = 80.97, SD = 10.6) to the second laboratory report (mean = 87.36, SD = 6.50) during the fall 2006 semester ($t_{17} = 3.38$, $P < 0.01$). However, no significant change occurred from the first laboratory report (mean = 85.76, SD = 9.48) to the second laboratory report (mean = 84.75, SD = 11.52) during the spring 2007 semester ($t_{16} = 0.31$, $P = 0.76$).

Majors also turned in a laboratory notebook at the end of each semester, and grading rubrics allowed instructors to assess overall performance. We hypothesized that 80% of students would achieve a minimum overall score of 80%. During the fall 2006 semester, our expectation was met, with 100% of students achieving a minimum overall score of 80%. During the spring 2007 semester, however, only 70.6% of students achieved a minimum overall score of 80% (but 94.1% did obtain a minimum score of 75%). Although the average grade for the laboratory notebook during the spring 2007 semester was 83%, five students did not achieve a minimum of 80%.

Results for the final project were very encouraging. We hypothesized that all laboratory groups would obtain a minimum score of 80% on items measuring each of the three SLOs. During the fall 2006 semester (n = 5 laboratory

Table 8. *First and final average show and tell presentation scores with the average percent change by SLO for the courses for majors*

	Spring 2006	Fall 2006	Spring 2007
SLO 1. Physiological concepts			
Initial presentation	87.50 ± 25.0	76.00 ± 8.9	80.00 ± 11.18
Final presentation	93.75 ± 12.5	72.00 ± 11.0	95.00 ± 11.18
Percent change	6.25 ± 12.5	−4.00 ± 8.9	15.00 ± 22.4
SLO 2. Scientific approach			
Initial presentation	97.92 ± 4.2	85.00 ± 14.9	94.17 ± 3.7
Final presentation	96.00 ± 4.6	91.80 ± 10.2	99.20 ± 1.8
Percent change	−1.92 ± 4.1	6.8 ± 18.2	5.03 ± 3.5
SLO 3. Creative and critical thinking			
Initial presentation	92.50 ± 9.6	84.00 ± 8.9	98.00 ± 4.5
Final presentation	100.00 ± 0.0	92.00 ± 8.4	98.00 ± 4.5
Percent change	7.50 ± 9.6	8.00 ± 13.0	0.00 ± 0.1

Values are means ± SD; n = 4 groups and 4 presentations for the spring 2006 semester, 5 groups and 6 presentations for the fall 2006 semester, and 5 groups and 5 presentations for the spring 2007 semester. There were no significant changes in the presentation scores for majors.

groups), all groups did achieve a minimum of 80% of total points for items measuring each SLO. During the spring 2007 semester (n = 5 laboratory groups), all groups received a minimum of 80% of total points for items measuring *SLO 2* (scientific approach) and *SLO 3* (creative and critical thinking). Average scores for each SLO are shown in Table 9.

Results of the precourse/postcourse surveys among majors indicate that they too gained confidence over the course of the semester in their ability to engage in and/or understand the scientific process (*SLO 2*). As with the nonmajor surveys, an overall confidence score was calculated for both pre- and postcourse assessments (with possible overall confidence scores ranging from 10 to 50 at each time point). From these, a confidence difference score (postcourse confidence score − precourse confidence score) was calculated. Each semester, a positive confidence difference score, indicating an increase in overall confidence, was reported by a large majority of students (80.0% in spring 2006, 76.5% in fall 2006, and 88.2% in spring 2007). Average pre- and postcourse difference scores are shown in Table 10. As with nonmajors, paired sample t-tests indicated that the change in overall confidence scores from pre- to posttest was statistically significant (or very closely approached significance) for majors each semester ($t_9 = 4.62$, $P < 0.06$; $t_{16} = 4.21$, $P < 0.001$; and $t_{16} = 5.21$, $P < .001$, respectively). In a review of confidence ratings for individual items, we again calculated the percentage of confidence ratings for each item, (i.e., the percentage of "somewhat confident" or "strongly confident") at both the pre- and postcourse assessments. We then examined the degree of change in the percentage of confidence ratings given by students from pre- to postcourse assessment for each item. Percentages of confidence scores and changes in the percentages of confidence scores (across three semesters) for each of the 10 items are shown in Table 11. The results suggest that students responded with relatively high increases in confidence with regard to designing experiments and making predictions (*item 3*), communicating scientific results orally (*item 5*), using computers for experiments (*item 8*), and reaching conclusions (*item 10*). Average changes in the overall percentages of confidence scores for these items across all three semesters ranged from 22.3% to 34.1% (Table 11). McNemar tests were used to determine significant changes in the percentages of confidence scores. Note that the differences were less pronounced for majors versus nonmajors because majors had a higher level of confidence initially.

Majors reported (via the postcourse survey) that the laboratory experience was helpful in achieving each of the SLOs. As shown in Table 7, >98% of majors marked "agree" or "strongly agree" to the survey items linked to each of the three SLOs. When asked, via open-ended survey items, to identify laboratories that they perceived to be most helpful in achieving each of the three SLOs, majors more frequently identified presentation laboratories as being most helpful in achieving all three SLOs (Fig. 2).

Table 9. *Average presentation scores by SLO for the courses for majors*

	Fall 2006	Spring 2007	Average
SLO 1. Physiological concepts	100.00 ± 0.0	88.33 ± 11.2	94.17
SLO 2. Scientific approach	93.82 ± 3.4	92.35 ± 2.6	93.09
SLO 3. Creative and critical thinking	97.06 ± 2.9	91.76 ± 7.9	94.41

Values are means ± SD (in %); n = 5 laboratory groups in the fall 2006 semester and 5 laboratory groups in the spring 2007 semester.

Table 10. *Pre- and postcourse overall confidence scores and confidence difference scores for the courses for majors*

	Spring 2006	Fall 2006	Spring 2007
Precourse confidence score	41.40 ± 4.86	39.71 ± 3.26	38.18 ± 5.46
Postcourse confidence score	47.00 ± 2.58	43.53 ± 3.36	46.00 ± 2.78
Confidence difference score	+5.60 ± 3.84	+3.82 ± 3.75	+7.82 ± 6.19

Values are means ± SD; n = 10 students in the spring 2006 semester, 17 students in the fall 2006 semester, and 17 students in the spring 2007 semester. Possible confidence scores ranged from 10 to 50.

Summary and Final Thoughts

The results of our SLO assessment indicate that an inquiry-based curriculum enhances student understanding of physiological concepts, increases understanding of the scientific approach, and enhances creative and critical thinking. Among nonmajors, before the curricular revision, 57% of students stated that the laboratories enhanced understanding of the lecture material. After the curricular modification, >92% of students responded positively to the same statement. In addition, before our modifications, <50% of students stated that the laboratory allowed them to develop hypotheses and design experiments to test their predications. After the curricular modifications, this number increased to >96%.

With the inquiry-based curricular modifications, nonmajors showed an increased understanding of physiological concepts, as was evidenced by a significant improvement in show and tell presentation scores across the semester. Among majors, students exhibited an excellent understanding of physiological concepts with an overall average score of 94% on final project items measuring this SLO.

With regard to students' understanding of the scientific method, all assessment results support the conclusion that our new curriculum is indeed associated with above-average levels of both their understanding and performance in this area. Among nonmajors, student performance on exam items designed to measure this SLO averaged 80%, and significant improvements in show and tell presentation scores were also found. Laboratory report and final project scores for majors also demonstrated above-average levels of understanding of the scientific approach.

Similar results were found for students' engagement in creative and critical thinking. Among nonmajors, students earned an average performance of 78% on exam items designed to measure this SLO. Significant improvements were also seen in show and tell presentation scores. Among majors, final projects scores suggested that students engaged in creative and critical thinking, with scores averaging 94%.

There are, as one might expect, areas in which students did not meet our performance expectations, suggesting the need for additional curricular improvements. For example, nonmajors did not meet our performance expectation on exam items

Table 11. *Percent student confidence ratings from precourse to postcourse for the courses for majors*

	Spring 2006	Fall 2006	Spring 2007
Item 1. Understanding science			
Precourse	100.0	100.0	94.1
Postcourse	100.0	100.0	100.0
Change	0.0	0.0	5.9
Item 2. Questions and hypotheses			
Precourse	100.0	76.5	82.4
Postcourse	100.0	88.3	100.0
Change	0.0	11.8	17.6
Item 3. Designing experiments and making predictions			
Precourse	80.0	64.7	47.1
Postcourse	100.0	94.1	100.0
Change	20.0	29.4	52.9
Item 4. Analyzing data			
Precourse	80.0	70.6	76.5
Postcourse	100.0	94.1	100.0
Change	20.0	23.5	23.5
Item 5. Communicating orally			
Precourse	70.0	82.3	47.1
Postcourse	100.0	100.0	100.0
Change	30.0	17.7	52.9†
Item 6. Communicating in writing			
Precourse	80.0	76.4	70.6
Postcourse	100.0	82.4	94.1
Change	20.0	6.0	23.5
Item 7. Working in teams			
Precourse	90.0	100.0	94.1
Postcourse	100.0	100.0	100.0
Change	10.0	0.0	5.9
Item 8. Using computers for experiments			
Precourse	80.0	94.2	52.9
Postcourse	100.0	88.3	100.0
Change	20.0	−5.9	47.1†
Item 9. Summaring data			
Precourse	80.0	70.3	76.5
Postcourse	100.0	94.1	100.0
Change	20.0	23.8	23.5
Item 10. Reaching conclusions			
Precourse	80.0	64.7	58.8
Postcourse	100.0	100.0	100.0
Change	20.0	35.3	41.2*

Values are percentages; $n = 10$ students for the spring 2006 semester, 17 students for the fall 2006 semester, and 17 students for the spring 2007 semester. See http://darwin.wcupa.edu/biology/casotti/inquiry/index.html for individual items. Items were rated on a Likert-type scale from *1* to *5*, where *1* = completely doubtful to *5* = strongly confident; scores shown are from those students that answered "somewhat confident" and "strongly confident." $*P < 0.05$; $†P < 0.01$.

designed to measure their understanding of physiological concepts, achieving an average score of only 67.7%. A post hoc review of individual exam items suggested that the items included to measure this SLO were not evenly distributed across exams and, furthermore, were not representative of the laboratories that incorporated the new inquiry-based procedures and/or student presentations. Thus, exams are being revised with these issues in mind to better assess students' understanding of physiological concepts after participation in the revised laboratory procedures. It appears that we need to improve our efforts with regard to helping nonmajors establish connections between physiological concepts and inquiry-based laboratories. Students reported, via the open-ended items of the postcourse survey, that nonpresentation laboratories aided their understanding of physiological concepts better than laboratories where they were asked to present experimental findings to the rest of the class. These results, in conjunction with the exam score results discussed above, suggest a need to identify strategies that enable students in nonmajor classes to recognize inquiry laboratories as important mechanisms for understanding content.

Students in all our physiology courses seemed to enjoy the freedom of the new curriculum and the opportunity to engage in the inquiry process. When asked for any additional end of semester thoughts on the new curriculum on postcourse surveys, student comments can be summarized as follows:

> We learned how to explore problems by allowing us to create our own variations in the lab. By allowing us to do our own individual group projects we were able to explore how different factors affected an animal. An example of this would be how a drug affected our frog heart such as acetylcholine and epinephrine.
>
> The exercise labs helped us understand the lecture material. It accomplished this because we had to design our own experiments and understand the results.
>
> I felt that I was able to perform my own experiments and get my own results. I thought it was great

Inquiry-based curricula are challenging to write, maintain, and coordinate. They are also more challenging for the students than are more traditional teaching approaches, but they offer clear benefits in terms of the development of student skills and critical thinking. As educators, we have a responsibility to provide our students with the best possible building blocks for their future careers in science. Inquiry-based curricula enable us to meet this responsibility.

GRANTS

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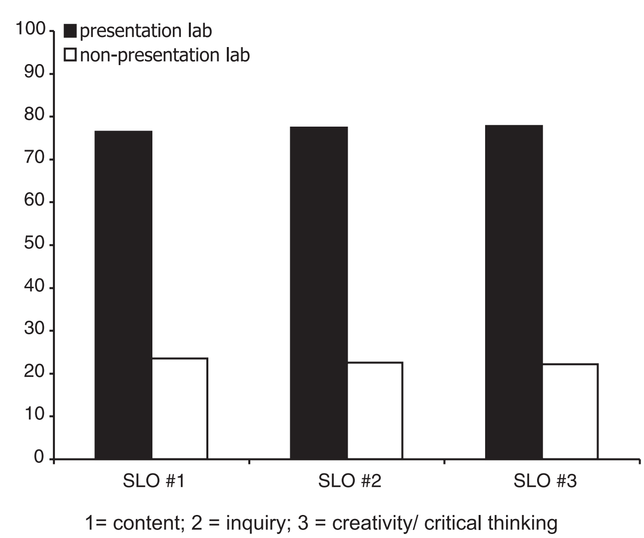

Fig. 2. Postcourse survey results for the Human Physiology and Comparative Vertebrate Physiology course for majors. There were 35 total responses. Students responded positively 100%, 100%, and 94%, respectively, to each of the SLOs.

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