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INQUIRY-BASED LABORATORY COURSE IMPROVES STUDENTS' ABILITY TO DESIGN EXPERIMENTS AND INTERPRET DATA

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We redesigned our intermediate-level organismal physiology laboratory course to center on student-designed experiments in plant and human physiology. Our primary goals were to improve the ability of students to design experiments and analyze data. We assessed these abilities at the beginning and end of the semester by giving students an evaluation tool consisting of an experimental scenario, data, and four questions of increasing complexity. To control for nontreatment influences, the improvement scores (final minus initial score for each question) of students taking both the laboratory and the companion lecture course were compared with those of students taking the lecture course only. The laboratory + lecture group improved more than the lecture-only group for the most challenging question. This evidence suggests that our inquiry-based curriculum is achieving its primary goals. The evaluation tool that we developed may be useful to others interested in measuring experimental analysis abilities in their students.

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There now is a great deal of evidence that student achievement, persistence in science courses, and attitudes toward science are enhanced by having students work in small groups on appropriate intellectual tasks (5). Furthermore, a large number of reports summarizing the state of science education emphasize that inquiry-based approaches are essential (1, 3, 4). The *National Science Education Standards* (3) states, "Inquiry is central to science learning. When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others."

Even though many of us are convinced that inquiry-based laboratories improve students' critical thinking skills and their understanding of the process of science, it is difficult to obtain data that demonstrate this (6). We describe here our laboratory course and the tool that we used to evaluate students' ability to analyze data and experimental design. Our course structure is similar in many ways to the physiology course based on student-designed experiments described by Kolkhorst et al. (2), although we arrived at it independently. However, our assessment method is different and measures the development of thinking and analysis skills.

DESCRIPTION OF THE LABORATORY COURSE

Organismal Biology constitutes the third semester of the four-semester Biocore honors sequence at the University of Wisconsin-Madison. It follows

TABLE 1
Progression of experiences throughout the semester

Gravitropism in *Brassica rapa* (3 wk)
Structural: form (permanent) research teams; review scientific method; discuss experimental design issues; discuss format of scientific papers
Specific: teams observe response of seedlings to gravity (experiment set up previously by instructors) and brainstorm possible explanations for responses (*week 1*); teams plan and execute experiment to test their explanation for observed gravitropic response: formulate hypothesis, draw expected results graphs, design and execute experiment, collect data, perform simple analysis (*week 2*); teams write short paper, present their results to class (*week 3*)
EMG experiments (1 wk)
Structural: discuss data analysis/statistical issues (includes worksheet); help students use Excel for data entry and graphing; introduce data acquisition system (Biopac Student Lab and Lab Pro Software)
Specific: teams plan and execute a simple experiment using EMG measurements
ECG and EEG experiments (1 wk)
Structural: work on critiquing published scientific papers; discuss statistical concepts and simple tests
Specific: teams learn either ECG or EEG measurements; teams finish EMG analysis and write a paper
Demo Day (2 wk)
Structural: discuss how to respond to written reviews of papers; continue discussion of statistical issues
Specific: teams develop (*week 1*) and give (*week 2*) a 10-minute "demonstration experiment" for their peers that involves either EEG, ECG, or EMG measurements
Cardiovascular experiments (2 wk)
Structural: work on determining appropriate sample size; discuss how to compare results with those in the literature
Specific: teams plan and pilot-test an experiment involving the cardiovascular system (*week 1*) and then execute the refined design, analyze resulting data, and begin writing paper (*week 2*)
Proposal+ project (5 wk)
Structural: discuss how to perform a full literature search; discuss what makes a research question "novel," help students learn PowerPoint to create presentations
Specific: teams search literature and brainstorm ideas for a novel research question (*week 1*); teams refine their hypothesis and pilot-test methods (*week 2*); teams collect data and begin to analyze it (*week 3*); teams finish data collection and analysis, begin writing paper and preparing presentation (*week 4*); teams give PowerPoint presentation for peers and guests (*week 5*)

EMG, electromyogram; ECG, electrocardiogram; EEG, electro encephalogram.

courses that deal with evolution, ecology, and genetics and with cell and molecular biology. Students can elect to take the lecture class by itself (3 credits) or the laboratory-lecture combination (5 credits). Those who enroll in the laboratory course tend to be either students who need another laboratory class to meet degree requirements or students who are especially interested in organismal physiology.

For the laboratory course, each student attends one 50-minute discussion period per week and one three-hour laboratory. In addition to the learning of physiological principles, the primary goals of the course are to improve the ability of students to design experiments and analyze data. To promote these objectives, students work all semester in research teams of three or four on some stage of designing or carrying out their own experiments. Early in the semester, they focus on plant physiology, later on aspects of their own physiology. As the semester progresses, we stress increasingly complex elements of experimental design (hypothesis formation, literature review, randomization, blinding, controls, sample size estimation) and analysis (data manipulation, graphing, statistical tests, comparison with previous findings). As Table 1 illustrates, the course is designed to provide students with the raw materials to ultimately develop a complete understanding of the experimental process. By the end of the semester, most research teams are functioning quite independently, consulting with instructors only when necessary.

Many of the experiments developed by students make use of a computerized data acquisition system that transduces, records, and displays physiological responses in real time (Fig. 1). The system allows students to immediately analyze their data, to work together to solve problems and decide what to do

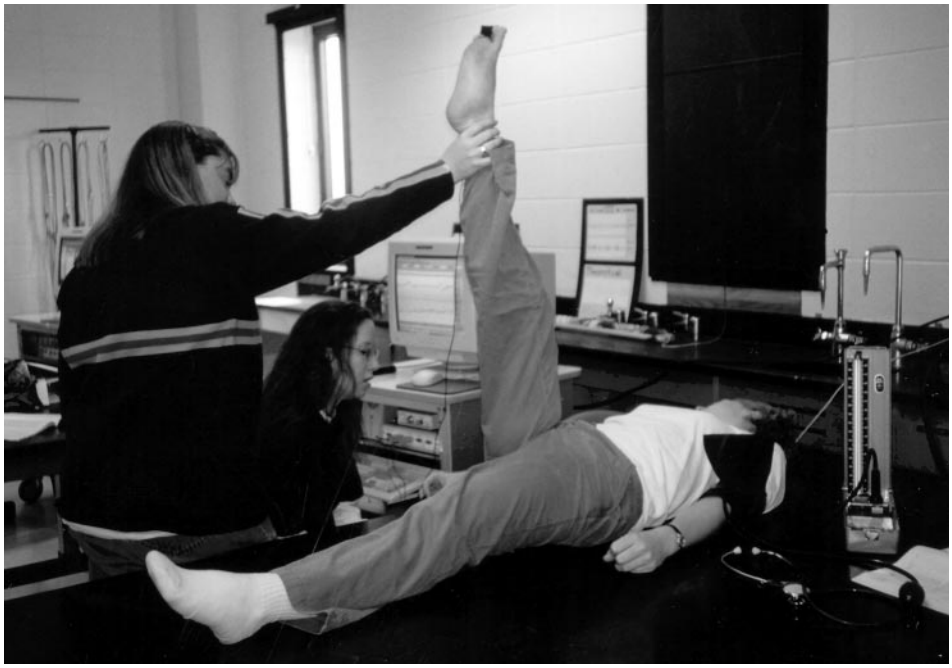

FIG. 1.
Research teams use sensors that interface with a computer data acquisition system to test their ideas.

next, and finally to draw conclusions from their results. Several times during the semester, the research teams report their findings through oral presentations or by writing, peer reviewing, and revising papers following the format of scientific journal articles. The last five weeks of the semester are devoted to the "Proposal+" project. During this period, each research team develops a detailed proposal on a novel research question, including literature review, testable hypotheses, detailed (and pilot-tested) methods, and preliminary results. If research teams definitively answer their experimental question by the end of the semester, they write up and present this final project as a scientific paper. If, on the other hand, there is no clear answer (as frequently happens), but they have developed a better method to test the original idea, the research team writes up and presents its efforts as a pilot-tested proposal for future work (hence the name Proposal+). Some of the Proposal+ projects conducted by student teams are shown in Table 2.

TABLE 2
Examples of Proposal+ projects conducted by Organismal Biology student teams

- Talking ourselves to death: the distracting effect of music and conversation on response time to a visual stimulus
- Effect of accelerated evaporative cooling during exercise on change in heart rate
- Effects of exercise on respiratory sinus arrhythmia
- Physiological responses to emotional stimuli
- Effects of coffee on heart rate and blood pressure under conditions of mental stress in habitual coffee-drinking college students
- Effects of preexercise stretching on power output in the hamstrings muscle group
- Determining the cumulative effect of step cadence and step height on heart rate
- Effect of intense cycling on biceps fatigue
- Effect of time of day on reaction time
- Learning a time interval: how does mode of learning (audio vs. visual) and frequency of time interval affect human ability to learn?

ASSESSMENT OF COURSE GOALS

Administration of Evaluation Tool

To assess how well students in the course were achieving our primary learning objectives, we developed a customized evaluation tool. The tool consisted of an experimental scenario and data, followed by a series of four questions of increasing complexity (described below). This tool was administered at both the beginning and the end of the semester to students taking the lecture course only (n = 65) and to students taking the laboratory + lecture combination (n = 43). Students were given the evaluation during a discussion session for the lecture course and had no idea of the purpose of the exercise or that they would see the same evaluation again at the end of the semester. Students were given 20 minutes to work on the evaluation and were simply asked to "put a good effort" into the assignment and to show as much of their work and thinking as possible.

The evaluation tool was scored (using criteria described below) by a biostatistician who did not know whether a particular test was from the beginning or end of the semester or whether it was from a student who took the lecture course only or the laboratory + lecture combination. For each student, an improvement score was calculated for each question on the evaluation as the difference between the student's final and initial scores. We expected some pre-to-post improvement in scores because students were seeing the evaluation for a second time at the end of the semester. Furthermore, they had the opportunity to learn about physiology experiments and data analysis in lecture and may have become more sophisticated in their thinking with the passage of time. The strength of our approach is that students enrolled in lecture alone served as the control group for students taking the laboratory and lecture together. Improvement scores in the lecture-only group were attributed to all factors *other* than the laboratory curriculum (e.g., seeing the evaluation for a second time). Thus any difference between the improvement scores for laboratory + lecture students and those for students taking only the lecture course can be considered a consequence of the laboratory experience. We tested for such differences between groups with Student's *t*-test.

Evaluation Tool: Investigation of the Effect of Step Cadence on Heart Rate

Scenario/Hypothesis. Three Biocore 324 students, Terry, Tonya, and Taliz, did their group research project on the factors that influence heart rate during stepping on an exercise step. Taliz suggested the topic because she teaches a step aerobics class and wanted to know what routines are likely to elicit adequate (but nonlethal!) heart rate responses in her students.

The students hypothesized that the cadence (rate) of stepping would affect heart rate. To test this hypothesis, they performed the experiment described below. Read how they conducted their study, examine the data they collected, and then answer the questions about the meaning of the findings.

Methods. The group selected Taliz to be the subject for the experiment, as she was in the best aerobic shape of the three. A metronome was used to provide the appropriate beat for stepping. Heart rate was monitored with a pulse plethysmograph that was attached to Taliz's index finger.

The experiment used four different step cadences: 92, 98, 102, and 108 steps/min. Taliz performed three trials at each of the four step cadences (12 trials in all). During each of these trials, she started by standing still for 30 s (to get a preexercise value for heart rate), and then she stepped up and down on the step at the appropriate cadence for 2 min. A trial did not begin until Taliz's heart rate while standing varied 3 beats/min or less over a 30-s period.

Data. Table 3 shows the order in which the trials were conducted. It also gives Taliz's average heart rate during the last 5 s of each standing and stepping period.

Analysis. [Be sure you explain the reasoning behind your answers. Show all calculations and logic on this sheet OR the attached blank sheet.]

Create a graph to help you visualize the effect of step cadence on heart rate (do this on the attached graph paper).

TABLE 3

Trial No.	Step Cadence	Average Heart Rate (beats/min)	
		Standing	Stepping
1	92	75	107
2	92	74	106
3	92	74	108
4	98	75	111
5	98	74	114
6	98	75	113
7	102	77	119
8	102	78	121
9	102	77	123
10	108	79	133
11	108	81	137
12	108	80	139

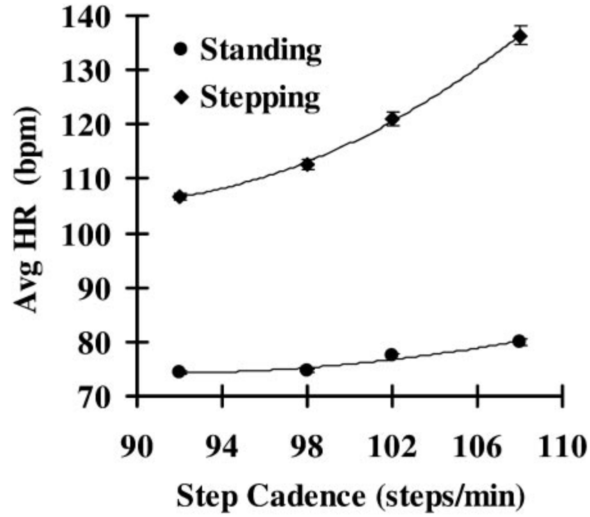

FIG. 2.
Example of a well-designed graph in response to *question 1*. Effect of cadence on stepping and standing heart rate (HR) during the last 5 s of the measurement period. Each point represents the average of 3 trials at that cadence for the single subject (Taliz). Error bars, ±1SE.

What is the nature of the relationship between step cadence and heart rate?

On the basis of your analysis, what advice would you give Taliz about the step cadences she should use in her routines if she wants to keep the heart rate of her students between 110 and 120 beats/min during the 45-min class?

If you wanted to predict heart rate from step cadence with great precision, how would you improve the experimental design?

Evaluation Scoring Criteria

Each of the four questions on the evaluation was scored on a scale from 0 to 3 points, using increments of 0.25 point. For each question, the scorer assigned points for elements of answers that reflected key aspects of the expected answer. In some cases, students could also lose points for adding incorrect elements to otherwise correct answers. The general criteria used in scoring each question are described below.

Question 1: Create a graph to help you visualize the effect of step cadence on heart rate. For *question 1*, students needed to create a well-labeled and appropriately sized scatterplot illustrating the relationship between step cadence and heart rate (an example is shown in Fig. 2). Students could have shown a separate line for heart rate while stepping and while standing or a line representing the difference between stepping and standing heart rate at each cadence. Their graph could have included individual points for each trial or the mean (of the 3 trials) for each cadence and error bars representing the variability.

Question 2: What is the nature of the relationship between step cadence and heart rate? For *question 2*, students needed to note the nonlinear (higher cadences had disproportionally higher heart rates), positive relationship between step cadence and heart rate. They also should have noted whether their answer concerning stepping heart rate took into account the increase in standing heart rate as trials progressed.

Question 3: On the basis of your analysis, what advice would you give Taliz about the step cadences she should use in her routines if she wants to keep the heart rate of her students between 110 and 120 beats/min during the 45-min class? For *question 3*, students needed to state in detail the limitations in their ability to generalize from the data given. They could have said that a person

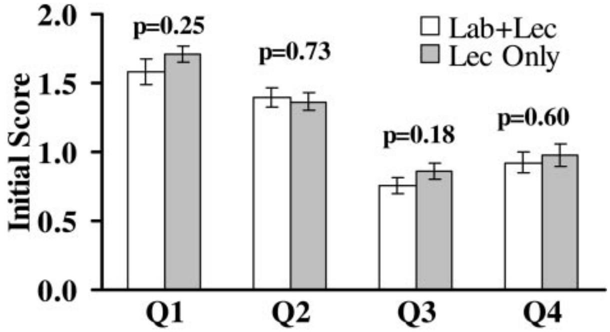

FIG. 3.

Average group initial (beginning of the semester) score for each question on the evaluation tool. The maximum possible score for each question was 3 points. Error bars, ±1 SE. *P* values represent significance level of Student's *t*-test for differences between groups.

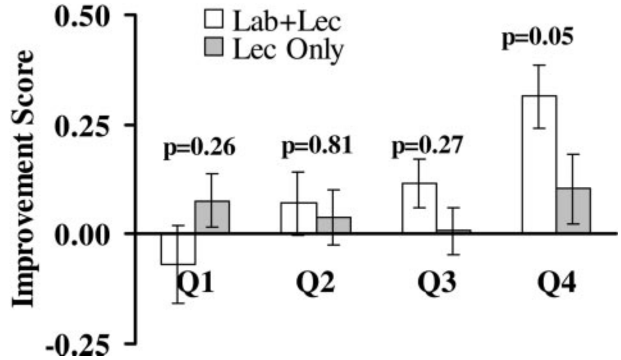

FIG. 4.

Average group improvement score (final score minus initial score) for each question on the evaluation tool. The maximum possible score for each question was 3 points. Error bars, ±1 SE. *P* values represent significance level of Student's *t*-test for differences between groups.

similar to Taliz in fitness level and other characteristics should be able keep her/his heart rate between 110 and 120 beats/min with cadences of ~98–102 *if* their stepping duration was ~2 min. Students needed to say that the data from the experiment do not allow predictions about heart rate based on step cadence for stepping periods much greater than 2 min or for people much different from Taliz in fitness level, body proportions, gender, etc. Students could also have said that they could not make reasonable predictions because of problems with the experimental design (see below).

Question 4: If you wanted to predict heart rate from step cadence with great precision, how would you improve the experimental design? For *question 4*, students had to point out the significant flaws in the design of the experiment and discuss how they would account for other influences on heart rate. For example, the trials were not performed in random order. In fact, the cadence was systematically increased throughout the experiment, potentially confounding the effects of fatigue, body temperature change, etc., with cadence effects. A better design would have ensured that test conditions were constant (initial standing heart rate, time of day, humidity, temperature, etc.), used trials long enough in duration to ensure that subjects had achieved a steady state, used a more precise instrument for measuring heart rate (e.g., a heart rate monitor), and included a larger range of step cadences. Students should have noted that more trials per cadence would have improved the precision of predictions based on the data. They also needed to suggest increasing the number of subjects, but they had to appreciate that subject characteristics (such as fitness level, gender, body proportions, previous stepping experience) could increase variability if not accounted for (without necessarily saying *how* they would account for such variation).

RESULTS AND DISCUSSION

Although it was not possible to assign students randomly to the laboratory + lecture or lecture-only groups, we did look for evidence of comparability between the two groups. Students in the laboratory + lecture and lecture-only comparison groups did not differ significantly ($P = 0.68$) in the final grades they received for the previous lecture course in the sequence (Cellular Biology). In addition, the two groups also did not differ significantly in their initial scores (from the beginning of the semester) on any of the four evaluation tool questions (Fig. 3). When the improvement scores (final minus initial scores) for the two groups were compared, the laboratory + lecture group had a statistically significant ($P = 0.05$) improvement score for the hardest question, *question 4* (Fig. 4). This finding suggests that participating in the laboratory course did improve students' abilities to meaningfully interpret data and critique flaws in experimental designs.

We noted that some students in the laboratory + lecture group scored *less* well on *question 1* at the

TABLE 4
Sample student comments

From evaluations at the end of the Organismal Biology laboratory course

- *We learned how to learn, how to question, how to design appropriate experiments to adequately answer that question.*
- *I like designing my own experiments tremendously more than following a protocol. Recipes are for cooking.*
- *Designing my own experiments made me more interested in the outcome of the experiment. Since the beginning of the semester. I've improved a lot at designing a good experiment and knowing how to analyze the results and figure out what they mean.*
- *I learned more in this lab course than in any other I've taken so far. I think my greatest improvement was in problem solving. We were responsible to note experimental error and to think about how to avoid it.*
- *The fact that this lab is "ours" is my favorite aspect. We discuss and peer review everyone's experiment, design our own experiments, write up our own papers on stuff we actually did, and are treated like independent intelligent thinkers. We interact with our teachers like [they are] mentors.*
- *At the beginning of the semester, the entire science world appeared foreign and mystical to me. This course has helped me realize science is doable and has taught me to do it effectively. I have a fuller understanding of the research process; my thought process has been more adapted to critical thinking and analysis.*

From evaluations at the end of the four-semester Biocore sequence

- *I really liked [Organismal Biology Lab]. The hands-on applications and the writing of lab reports were very helpful. Plus I think the way everything is set-up lends itself to a much better way of learning. I actually remember things from previous semesters such as concepts even if the details are fuzzy at times.*
- *In [Organismal Biology Lab], I learned a lot about designing experiments and testing hypotheses. In addition, I know how to critically read scientific papers.*
- *[Organismal Biology Lab] gave a lot of freedom to design experiments, yet required you to use knowledge gained from previous courses. It allowed you to apply your knowledge.*
- *[Organismal Biology Lab] was the best class out of all of them. It was fun and we were really given a chance to enter into our own individual thinking.*

end of the semester compared with the beginning. We believe that this may be due to the exclusive use of Microsoft Excel for creating graphs in the laboratory course. Students in the laboratory course may not have fully understood how to create graphs by hand because they could get by using computer software, or they may have had little patience, at the end of the semester, for making a graph by hand when they knew there was an "easier way." In any event, we now allow students to use the computer to generate graphs only *after* they have shown they know how to make appropriate graphs by hand.

Qualitative data from student evaluations show that students value the chance our laboratory course gives them to plan and conduct their own experiments, and many look back on this experience as the highlight of the four-semester sequence (see representative comments listed in Table 4). Students particularly value the Proposal+ project that takes up the last five weeks of the semester because they conduct research on a novel question. Often what is novel about their experiments is fairly incremental (e.g., the subject populations being tested), but now and then students come up with truly original ideas to investigate. Some research teams definitively answer their experimental question and present this final project as a scientific paper. Those who are not able to do this succeed in developing a better method to test their original idea, and they present their efforts as a pilot-tested proposal for future work. This strategy is particularly affirming for the numerous teams who spend five weeks solving one important problem after another but do not obtain enough useful data in the end to draw conclusions about their hypothesis.

To summarize, we developed an experimental analysis evaluation tool and used it to assess whether an inquiry-based organismal physiology laboratory course helped students improve their ability to analyze data and experimental design. The evaluation showed that students enrolled in both laboratory and lecture improved more than students taking only the lecture course for the most complex question. We conclude that our new inquiry-based curriculum is accomplishing its primary goals. We have described our evaluation tool in considerable detail so that others interested in measuring experimental analysis abilities in their students may use it.

We thank Kathleen Daniels for the many hours spent scoring student responses to the evaluation tool. We are also grateful to the students in the Organismal Biology course who participated in this evaluation.

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