Inquiry-based Laboratory Instruction Throws Out the "Cookbook" and Improves Learning

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1.0 Abstract

We designed an inquiry-based pre-laboratory on energy metabolism, applying research on how people learn, toward improving undergraduate biomedical engineering students' learning and experience. We hypothesized that such instruction would improve students' capacity to apply core concepts from metabolic physiology and enhance their ability to solve novel problems. Students in the experimental group addressed a challenge: how much food must an astronaut consume daily to keep her or his weight constant? The students' pre-laboratory was explicitly redesigned to be "learner centered" (students uncovered prior conceptions and debated), "knowledge centered" (students applied knowledge to a real-world problem), "assessment centered" (students discussed their thinking and evoked instructor feedback), and "community centered" (the instructor established cooperative searching for understanding as an in-lab norm). Students then performed the laboratory during which they measured their own metabolic rates. The control group's experience was similarly challenge-themed and employed the same indirect calorimetry apparatus, but the pre-laboratory instruction was "cookbook" and did not contain the explicit learner-, assessment-, and community-centered aspects. Our assessment included a final exam item constructed to assess students' ability to apply core energy metabolism concepts in a new context: mass balance and stoichiometry among glucose, respiratory gas values, and energy. This exam item was coded by an evaluator blind as to the condition of each subject, and showed that students who received the experimental pre-laboratory instruction demonstrated a greater ability to apply core concepts, with effect sizes ranging from 0.41 to 0.75. In addition, students completed a survey designed to capture their experience of the course. This survey independently verified the increased learner-, community-, and knowledge-centeredness of the experimental group's redesigned pre-laboratory. The experimental group also reported a higher degree of satisfaction with the redesigned learning experience.

2.0 Introduction

2.1 Why Teach Undergraduate Biomedical Engineers to Apply Systems Physiology's Core Concepts?

Grounded in the biological and medical sciences, the undergraduate Biomedical Engineering (BME) curriculum has systems physiology at its core, reflected by the extent to which most undergraduate BME curricula include one or more formal courses in systems physiology.

Learning systems physiology, undergraduate BME students should develop some of their unique competencies: a specialized vocabulary in biology or medicine, a specialized knowledge of the problem-solving techniques of biology or medicine, a capacity to deal effectively with the uncertain behavior of biological systems, and/or a generalized knowledge of how to apply engineering techniques to biological or medical topics [1]. But beyond what appears to be the agreed-upon potential merit of teaching systems physiology to BME undergraduates, there is little consensus on the best ways for BME students to learn systems physiology, and what part of this material to emphasize.

As the knowledge base of biology and medicine changes with ever increasing speed, one could argue that BME pre-professionals are best served by learning to apply systems physiology's governing principles to addressing unforeseen challenges. The Accreditation Board for Engineering and Technology's (ABET) "new" EC-2000 criteria support this focus on learning to *apply* knowledge in relevant situations, emphasizing higher-order cognitive skills ("An ability to identify, formulate, and solve engineering problems"), procedural skills ("An ability to use the techniques, skills, and modern engineering tools"), and combinations of these two kinds of knowledge as applied to investigations ("An ability to design and conduct experiments as well as to analyze and interpret data") [2]. In fact, the perception that engineering graduates are unable to apply their knowledge to solve novel problems is part of the motivation for the new engineering instructional paradigm embodied by EC-2000 [3]. This sentiment is echoed by Silverthorn [4]. She remarks how, "…we [know] more than we could possibly hope to teach within the confines of a structured physiology course," and as a result how, "…the basic themes and principles of physiology [get] lost in the morass of detail. [Students can] recite pathways but [are] unable to tie together disparate bits of information to solve a problem." This is the same problem that ABET's EC-2000 criteria aim to address. Silverthorn suggests employing findings from education research to improve undergraduates' ability to apply systems physiology's core concepts.

2.2 What Does Education Research Say about Teaching Learners to Apply Core Concepts?

Based on modern research on how people learn, learning environments that meet certain criteria may promote learners' ability to apply knowledge to solve novel problems. Consistent with the literature on this topic, we will describe this ability to identify, retrieve, and appropriately apply knowledge to solving novel problems as "meaningful understanding," in contrast to "inert knowledge." [5] The recent National Research Council publication, "How People Learn," [6] summarizes four attributes relevant to the design of instructional environments that effectively promote "meaningful understanding." Such an instructional environment must be learner-centered, knowledge-centered, community-centered, and assessment-centered. Learner-centeredness tells us that in order to build bridges to new understandings, teaching and learning activities must be based on the relevant knowledge that students bring to the classroom, and must also take into account what interests students. This is in contrast to a notion of teaching as telling, organized solely around the experts' taxonomy of the discipline. We must build from what students know and are able to do, as well as from what students care about and want to do. Knowledge-centeredness says that improving learners' problem solving requires conveying a well-organized body of knowledge organized for problem solving. All told, students can work toward "meaningful understanding" when they are given the opportunity to learn the content as it relates to their solving a motivating problem. Community-centeredness says that learning is enhanced by social norms that encourage discourse, and by connections to a broader community of practice. Lastly, assessment-centeredness requires instructional environments to define clearly what will pass as evidence of the learning that's been targeted. These four attributes are interrelated and the learning environment must be designed such that these attributes mutually support one another.

Designing instruction around a challenge is one way to organize a learning environment that is simultaneously learner-, knowledge-, community-, and assessment-centered. [7] However, not all learning "challenges" are necessarily of this ilk. Huang and Carroll [8] describe student teams addressing "challenges" in self-learning exercises in physiology, but we should not necessarily assume that their fill-in-the-blank, short answer, numerical calculations, figures to sketch, graphs to draw and interpret, and tables to complete are equivalent to the challenges we are describing here. For this reason, we will describe in detail those aspects of our challenge-based learning environment that achieve the aforementioned learner-, knowledge-, community-, and assessment-centeredness. However, before we do so, we will in the next section discuss which core concepts from systems physiology we chose to address in our learning environment, and where in the course we decided to intervene with our challenge-based instruction.

2.3 Around What Systems Physiology Core Concepts Should We Design Our Challenge-based Instruction?

We needed to select a core concept from systems physiology with which we knew college students had significant conceptual difficulties. For us to have the most impact, these conceptual difficulties should be significant enough for understanding systems physiology that leaving them unresolved might hinder students' problem solving in this area. In addition, these core concepts should be suggestive of challenges that would be motivating and relevant to learners and about which learners could draw from their own conceptions and experiences. We identified energy metabolism and cellular respiration to meet this standard. These concepts are critical to understanding systems physiology's unifying ideas such as energy flow as well as metabolic activities such as digestion, respiration, and circulation. Songer and Mintzes [9], using concept maps, clinical interviews, and an open-ended instrument, found that students in introductory and advanced college biology commonly held alternative explanations for deep breathing prior to underwater diving that were resistant to instruction. These alternative conceptions included using oxygen at levels other than the cellular, and using oxygen in ways other than as the terminal electron acceptor. [9] Songer and Mintzes also asked students about what to eat before a six-mile hike. This time, commonly held alternative explanations that were resistant to instruction included failing to recognize the need for digested food to enter the circulation, as well as the idea that vitamins and minerals could be broken down for energy. Related difficulties were identified by Michael *et al.* in undergraduate students enrolled in a variety of life science courses that included significant components of physiology. Michael *et al.*, using an inventory instrument, asked students to predict what would happen to ventilation when the metabolism of the body increases, and to choose from a list of explanations. The most common source of conceptual difficulty answering this question was that students believed there to be no connection between metabolism and ventilation. [10] Michael *et al.* also found an even greater degree of conceptual difficulty when students predicted that the exhaled amount of carbon dioxide would increase when breathing pure oxygen.

While neither study reports what percentage of subjects were engineering students (or specifically biomedical engineering students), the results of these studies do point to college students harboring a host of other-than-scientific understandings about the basic processes of cellular respiration, ideas that persist in the face of traditional instruction. In addition, taken together, these specific conceptual difficulties add up to students' inability to seek cellular explanations for organism-level phenomena. This is perhaps an even deeper core systems physiology concept without which a learner's effective problem solving in systems physiology might well be hindered. For all these reasons, our decision to design challenge-based instruction to promote meaningful understanding of energy metabolism and cellular respiration was well warranted. In addition, designing instruction in this area suggested instructional challenges focused on exercise or nutrition that might be relevant and motivating to young adult learners.

One might reasonably expect to find in traditional laboratory exercises challenges that require learners to apply core energy metabolism concepts. However, not all laboratories are necessarily challenges of this sort. Laboratory exercises can be "…'cookbook' experiments that [do] not require the students to think."[4] Modell *et al.* adapt the "cookbook" laboratory protocol that they describe as being largely "observe and record" by requiring students to complete a prediction table and also verbalize their predictions before running the experiment, and discussing with the instructor afterwards how their results compared to their predictions.[11] In so doing, Modell *et al.* essentially added learner-centered, knowledge-centered, and community-centered elements that the "cookbook" laboratory lacked. They found that in so doing they were able to double the remediation rate of an alternative conception in respiratory physiology. (They did not alter the laboratory exercise, just the preview of the laboratory protocol.) In the end, Modell *et al.* determined it was the *way* in which students participated that was critical, not their participation *per se*. Although Modell's intervention was not designed around a challenge that incorporated the learner-, knowledge-, assessment-, and community-centered elements into the revised laboratory protocol, this study spoke to the potential of redesigning a pre-laboratory to be appropriately challenge-based and promote the meaningful understanding of energy metabolism.

3.0 Methods

3.1 Energy Metabolism Pre-laboratory was Redesigned to Promote Meaningful Understanding

We developed a new pre-laboratory for a laboratory exercise that was part of a biomedical engineering (BME) systems physiology course taken primarily by juniors in BME, but including BME and a few biology majors ranging from sophomores to graduate students. In the laboratory itself, students measured their metabolic rate under both nearly basal conditions and while riding an exercise bicycle. Metabolic rate was measured using indirect calorimetry. This procedure involves performing a mass balance on inspired and expired oxygen in order to determine the amount of oxygen used per unit time. The stoichiometric relations between moles of oxygen and moles of substrate utilized, and between substrate utilization and energy release, allow for the calculation of energy utilization in kilocalories, given liters of oxygen consumed.[12] To obtain oxygen consumed, students collected into a Douglas bag their expired respiratory gases for a measured time interval. They then measured both the volume and oxygen content of the gas in the Douglas bag. Because the total volume of gas inspired and expired are almost the same, expired gas alone is sufficient as a basis for the mass balance required to determine oxygen consumed when the oxygen content and humidity of the inspired gas are known. These procedures were not discussed in the lecture part of the class. Instead all students attended a pre-laboratory in which the experimental work to be conducted in the laboratory was framed in the context of a challenge: How much food per week must be taken into space by two astronauts so that they do not gain or lose weight?

The control pre-laboratory consisted of a lecture about how the technique of indirect calorimetry could be used to provide information about metabolic rate of the astronauts, which could then be used to compute the necessary amount of food. In conjunction with this lecture, students received the protocol for the laboratory exercise to follow. During the pre-laboratory lecture, students asked questions, but the instructor (R.A.L.) employed no explicit instructional strategies to probe for students' conceptions. Similarly, he used no explicit instructional strategies to encourage students to generate or share their ideas about the solution to this problem in advance of explaining the solution, nor were students plainly asked to note or challenge the assumptions inherent in the measurements or calculations described. However, any such questions that the students posed were discussed without reservation. Nevertheless, the control pre-laboratory was left a "cookbook" experience.

In contrast, the experimental pre-laboratory employed explicit instructional strategies to add learner-centered, knowledge-centered, assessment-centered, and community-centered elements. Both the experimental and control pre-laboratories were organized around the stated challenge (How much food per week must be taken into space by two astronauts so that they do not gain or lose weight?), but only the experimental pre-laboratory was truly challenge-based as we have defined it in this paper, adding learner-, knowledge-, assessment-, and community-centeredness. In the experimental pre-laboratory, the students did not initially receive the laboratory protocol. Also, the presentation of the astronaut challenge was followed immediately, without any lecturing or description of the laboratory protocol, by the presentation of the first of four questions important to solving the challenge, this question being: what factors do we need to consider to solve the challenge? The instructor then had students brainstorm answers to this question in small groups, and each small group reported out their ideas to the class. The instructor guided the discussion to insure that each group had an opportunity to present its ideas. Groups were also encouraged to critique one anothers' ideas. Then, based on the students' responses to the first question, the instructor directed the students to consider what they'd need to know next, and thereby led them to the second question: given that one consideration is the metabolic rate of the astronauts, how can we measure metabolic rate in a laboratory setting? Students again brainstormed in small groups and then discussed their ideas among the whole class. The sequence of questions was designed to arise naturally out of the discussion of each preceding question. The third question was: given that indirect calorimetry is the most practical method, what do we need to do experimentally in order to obtain a value for liters of oxygen used? The fourth question was: how do we relate the amount of oxygen consumed to kilocalories of energy used? Not all interesting lines of thinking could be followed this way, but the essential elements of energy balance, the relation between respiration at the system and cellular level, and alternate ways of measuring energy consumption were all explored.

After this discussion, which was designed to take about 1.5 hours, the students were given the laboratory protocol, which recapitulated the ideas they had just "uncovered" for themselves. Like the control group, they then returned to complete the laboratory experiment. As opposed to the control pre-laboratory, this experimental pre-laboratory cultivated small group interactions and intra-actions (community-centered) to get the students' own ideas on the table for discussion (learner-centered) and to reveal and work with students' prior conceptions (knowledge- and assessment-centered).

3.2 Quasi-experimental Design

At the beginning of the term, students were informed of the opportunity to earn extra credit points for completing an optional laboratory and pre-laboratory that would take up to an additional 5 hours of their time. Approximately 90% of students in the course volunteered to participate and indicated their availability to the instructor. Four pre-laboratory and laboratory sessions were sufficient to accommodate all students, who were then randomly assigned to each session to create an equal numbers of participants in each session. This procedure allowed us to create two "experimental" sessions in which students received the redesigned pre-laboratory and two "control" sessions in which students received the traditional pre-laboratory. One strength of this experimental design is that it reduces of the likelihood of selection bias by using random assignment to condition given available times. This is not a true experiment, however. Students who volunteered for the study may possess unique characteristics such as higher motivation or ability level, making them qualitatively different from the larger class of all students. However, 90% of the students in the course did volunteer for this quasi-experiment, thus reducing the impact of this self-selection bias in this particular case.

3.3 Evaluation Instruments

To assess the impact of our intervention, data were collected on both student understanding of the material and student experience. Student understanding was assessed by evaluating responses to a final exam item that asked them to calculate metabolic rate given respiratory data about CO_2, rather than O_2, which is what they had measured in the laboratory. This question provided evidence of students' meaningful understanding by asking them to apply what they had learned to a new problem context. Students who had a deeper understanding of the core concept of the connection between pulmonary and cellular respiration were expected to perform better on this question. Responses were evaluated by a coder who was unaware of students' identities or conditions. Responses were evaluated on three dimensions: 1) recognition that the solution relied on the concept of mass balance on CO_2; 2) recognition of the stoichiometric relation between CO_2, O_2, glucose, and ATP; and 3) understanding of the conversion from liters of gas to kilocalories of energy. Responses to the exam item were rated on a 3 point scale, with 0 representing no evidence of using the concept in question, and 2 representing a completely correct employment of that concept

Student experience was assessed using a survey that was administered after students turned in their final laboratory reports. This survey attempted to capture student satisfaction and perceived learning from their experience in the pre-laboratory, the laboratory, and the laboratory report. In addition to its value as an evaluation tool, this survey also provided information about the extent to which our redesign of the pre-laboratory learning environment was successful. Students rated their agreement with 26 statements that described aspects of their experience. Agreement was measured using a 5 point Likert-type scale with 1 indicating little agreement, and 5 indicating much agreement with each statement.

3.4 Hypotheses and Analytic Strategy

We expected that adhering in the design of the pre-laboratory to the aforementioned principles would help students acquire a more meaningful understanding of the novel concepts practiced in the laboratory exercise. In addition, we expected that students exposed to the experimental condition of the redesigned pre-laboratory would report a higher degree of satisfaction with their overall laboratory experience

Two procedures were used to evaluate the potential differences between groups on measures of understanding and experience. First, an analysis of variance procedure (ANOVA) was used to detect differences. However, because of the small number of subjects (37) and resulting low statistical power, measures of effect size were evaluated. This procedure helped to uncover the magnitude of experimental effects without regard for sample size.

4.0 Results

4.1 Performance Item Results

Three one-way analysis of variance procedures were conducted. Experimental condition served as the independent variable and coded score on each concept served as dependent variables. The experimental group significantly outperformed the control group on one outcome, understanding the conversion of liters of gas to kilocalories (F, 1,36 = 4.85, $p<0.05$). A marginally significant difference was noted for recognition of the stoichiometric relation among CO_2, O_2, glucose, and ATP, (F, 1,36 = 3.63, $p=0.065$). There were no statistically meaningful differences for the recognition that the solution relies on the concept of mass balance on CO_2. While traditional statistical tests may be limited by power, effect size may point to the magnitude of observed differences. When using this standard, the experimental group outperformed the control group with effect sizes of 0.75, 0.62, and 0.42 respectively, these differences being in the moderate to large range (see Figure 1).

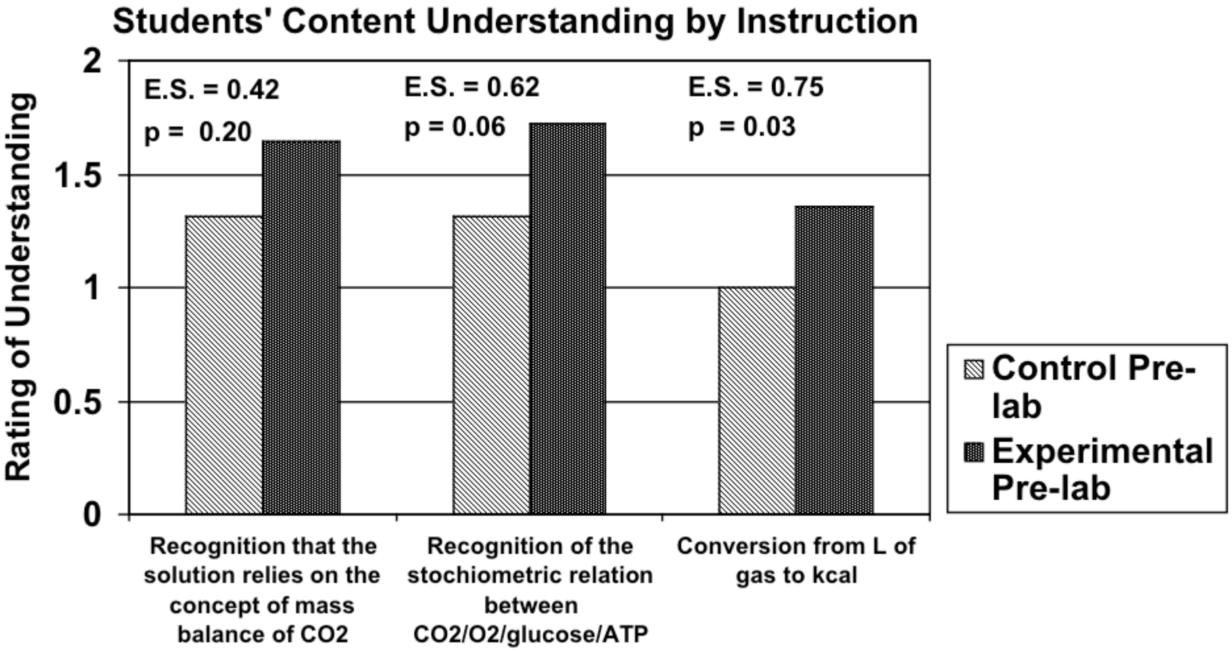

Figure 1: Students' Content Understanding Improves with Inquiry-based Pre-laboratory Experience

4.2 Experiential Item Results

Although the students completed 26 items, only those items that demonstrated the impact of our intervention, positively or negatively, will be discussed here. An analysis of variance procedure, with condition serving as the independent variable and item as the dependent variable was conducted on each item. No statistically significant differences were detected, in part because not all students complied with the request to submit the survey, so data were collected on even fewer students (n=25). However, analysis of one item demonstrated marginally significant differences. Students in the experimental group agreed with the following statement: "I enjoyed listening to other students ideas during the pre-lab session," slightly more than those in the control condition (F, 23,1=3.95, p=0.059). The effect size of this difference (E.S. = 0.80) was relatively large. Analysis of three other items, although not meeting traditional statistical criteria, revealed moderate effect sizes, although not always in the predicted direction: "Completing the pre-lab helped me learn about solving open ended problems" (E.S. = 0.47), "The experience of the pre-lab session helped me communicate my ideas" (E.S. = 0.68), and "The lab assignment helped me to integrate different topics in physiology" (E.S. = -0.64). Note that analysis of the last item revealed an advantage for control students (see Figure 2).

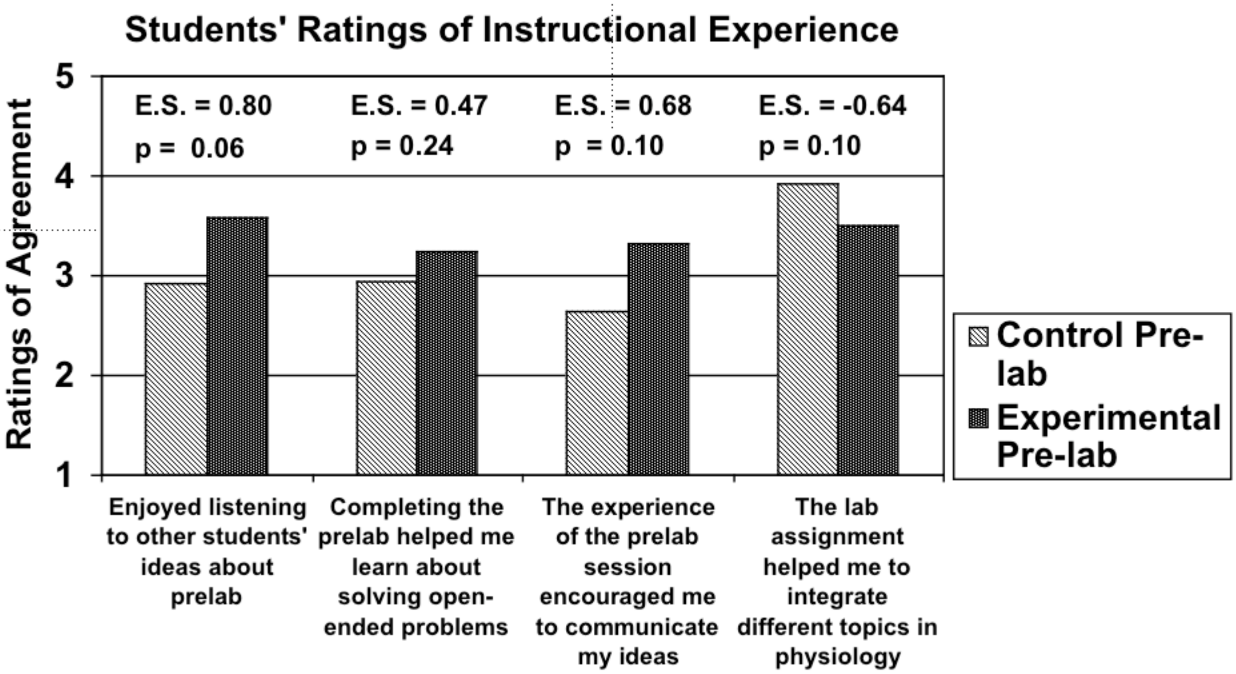

Figure 2: Students Rate the Inquiry-based Pre-laboratory Experience More Highly Than the Control

5.0 Discussion and Conclusion

5.1 Discussion of Performance Data

The performance-oriented question tested the depth of conceptions about indirect calorimetry and the connections between pulmonary and cellular respiration. When considering effect size, the students in the redesigned pre-laboratory outperformed those in the traditional pre-laboratory on all of the individual elements necessary to solve a problem in the same general area that the laboratory had covered. Students in both the traditional and redesigned pre-laboratories received essentially the same written description of the laboratory, including the relevant equations, had completed the same laboratory experiment, and had written a laboratory report with the same requirements. The main difference between groups was therefore the design of the pre-laboratory. This supported our hypothesis that a different learning environment could improve learning of core material. Two additional points deserve comment. First, the performance measure did not ask the students to simply regurgitate the principles, but forced them to apply their knowledge in a slightly new way, albeit in the general domain on which the laboratory focused, suggesting that they were better at one of the higher elements on the taxonomy of knowledge. “Transfer task” performance measures designed to assess whether this enhanced problem-solving capability also extended to other systems physiology domains have not yet been analyzed. Second, the performance measure test question reported here was integrated into the final exam, about 6 weeks after the students had completed the 1.5 hour pre-laboratory. Therefore, this assessment followed the teaching of a large number of unrelated topics in renal, digestive, and endocrine physiology, indicating that the effect of our modest manipulation lasted over a considerable period of time.

In redesigning the pre-laboratory, we tried to conceive of ways that would make it more learner-, knowledge-, community-, and assessment-centered, but there may be other ways of describing the manipulation that would capture the difference between groups equally well, perhaps the most obvious being that the redesigned pre-laboratory was “more active” or “more interactive.” However, such descriptions are insufficiently precise to help other instructors design challenge-based learning environments to promote meaningful understanding. After all, one would have said that the laboratory itself for both groups was “more active” than learning the same material via lecture, but we were still able to find a way to enhance learning for one group.

5.2 Discussion of Experiential Data

Student experience was generally positive across conditions. However, analysis of four questions revealed strong differences between groups. Three of those questions demonstrated a clear advantage for the experimental group who received the redesigned pre-laboratory, with effect sizes in the moderate to large range (E.S. = 0.47- 0.80). Each of these questions asked students about their experience in “pre-lab.” Two questions directly assessed student satisfaction with aspects of communication in class, (“I enjoyed listening to other students ideas during the pre-lab session,” and “The experience of pre-lab encouraged me to communicate my ideas”). This finding is encouraging, for it provides confirming evidence for the presence of attributes we hoped we had designed into the experimental manipulation, as well as pointing to areas that may need improvement in future endeavors. In addition, students were more likely to agree with the statement “Completing the pre-lab helped me learn about solving open-ended problems” in the experimental condition, pointing to another strength of the manipulation that we feel is especially important for engineering students. Unfortunately, one item demonstrated a disadvantage for the experimental students. Students in the control condition reported higher agreement with the statement “The lab assignment helped me to integrate different topics in physiology,” indicating that the manipulation, while encouraging communication among students, may sacrifice breadth of learning over depth. We have not yet analyzed whether any performance measure, such as grades for the course, supports this attitude of the students.

In general, student surveys indicated some success in our effort to make the course more community centered (communication-related items), but point toward improvement needed specifically in the area of information integration, an aspect of knowledge centeredness. While only four items are discussed here, analysis revealed an advantage for experimental groups in ratings of 8 of the 11 items that captured the pre-laboratory experience. The effect sizes of the remaining items were in the small range (E.S. = 0.30- 0.39). This finding may indicate that our manipulation was somewhat successful, but that we still have room for improvement.

5.3 General Discussion

Overall, our efforts have provided evidence for the effectiveness of an inquiry-based pre-laboratory in facilitating student learning and promoting a positive experience. Performance measures pointed to an advantage for students who encounter the redesigned pre-laboratory, with effects considered moderate to large. Experiential measures suggested that students not only detected a difference between the conditions, but that these differences contributed to their enjoyment and enhanced their learning. These effects point to particular success in encouraging communication among students, an aspect of community centeredness. However, the advantage of the redesigned pre-laboratory was not seen across all questions asked of students. Data indicate that students perceived the traditional pre-laboratory to be more effective in helping to integrate different topics in physiology.

Previous work by Songer and Mintzes [9], as well as Michael *et al.* [10], identified conceptual difficulties in understanding basic principles of cellular respiration. While these findings do not necessarily eliminate these difficulties, an approach grounded in educational research can serve to increase the likelihood of meaningful understanding of these concepts. These results are consistent with those found by Modell *et al.* [11], in that the addition of learner-centered, knowledge-centered, and community-centered elements led to positive student outcomes in comparison with traditional, "cookbook" laboratory approaches. Our data indicate that the experience of communication, with other students in particular, may have had the most powerful effect. In addition, this study helped to address some concerns raised by Silverthorn [4], in that innovative educational approaches grounded in education research were utilized to improve student experience and enhance their ability to apply core concepts in systems physiology.

One strength of this effort was its use of a quasi-experimental methodology for evaluation. While not a true experiment, care was taken to eliminate sources of selection bias such that this approach closely approximated the control conditions that are observed in true experiments. In addition, the use of a concurrent comparison group eliminates the need to use historical controls or compare performance across instructors. This effort demonstrated success in the face of common difficulties in evaluating pre-existing programs while preserving student choice and maintaining the integrity of curricular goals. Still, more work is needed. Future efforts need to address other aspects of such inquiry-based design, and if improvements to the design can result in perceptible changes among students in other domains.

We have charted several next steps in this work. First, we will complete the analysis of laboratory reports and other test items that may reveal differences in understanding and in transfer of problem-solving skills. Second, we will run a replicate of this experiment with the laboratory experience as a required, rather than optional part of the course and some technical improvements. Third, we will make the materials and detailed instructions available to a selected number of other institutions to test whether the results obtained here were instructor-specific.

The work described herein is one example of the research being performed by the Vanderbilt-Northwestern-Texas-Harvard/MIT (VaNTH) Engineering Research Center for Bioengineering Educational Technologies. VaNTH is now in its fourth year and is beginning its dissemination process. Links to current work can be found at www.vanth.org. Some of the learning science underpinnings of this work, and their application to bioengineering, have recently been reported.[13]

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