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Comparison of Student Learning in Challenge-based and Traditional Instruction in Biomedical Engineering

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Abstract—This paper presents the results of a study comparing student learning in an inquiry-based and a traditional course in biotransport. Collaborating learning scientists and biomedical engineers designed and implemented an inquiry-based method of instruction that followed learning principles presented in the National Research Council report "How People Learn" (HPL). In this study, the intervention group was taught a core biomedical engineering course in biotransport following the HPL method. The control group was taught by traditional didactic lecture methods. A primary objective of the study was to identify instructional methods that facilitate the early development of adaptive expertise (AE). AE requires a combination of two types of engineering skills: subject knowledge and the ability to think innovatively in new contexts. Therefore, student learning in biotransport was measured in two dimensions: A pre and posttest measured knowledge acquisition in the domain and development of innovative problem-solving abilities. HPL and traditional students' test scores were compared. Results show that HPL and traditional students made equivalent knowledge gains, but that HPL students demonstrated significantly greater improvement in innovative thinking abilities. We discuss these results in terms of their implications for improving undergraduate engineering education.

Keywords—Adaptive expertise, How people learn, Biotransport instruction, Challenge-based learning, Teaching methods, Student learning measurements.

INTRODUCTION

Future and current engineers' successful performance requires skills in both technical expertise and innovation.[4,11] This requirement is particularly relevant in biomedical engineering, which is a relatively young field for which the knowledge base and regulatory climate are changing rapidly. Biomedical engineers need a solid understanding of the fundamental principles and knowledge in their discipline, but they should also be able to adapt as opportunities and applications in this field evolve.

Achieving this type of practical adaptability is not trivial. Often, people can develop advanced technical expertise in a field independent of an ability to adapt and innovate when presented with a novel problem to solve. The concept of Adaptive Expertise (AE) can help describe this ability. Hatano distinguished between routine and adaptive expertise.[18] Routine experts are technically proficient in their established domains of knowledge and application. They apply their well-developed knowledge base appropriately and efficiently to solve core problems in the domain. However, when they face a novel problem they tend to misapply technical principles, analysis procedures, and outcome interpretations in their attempts to reach a solution.[7,18,19,26] In other words, they fail to adapt their expertise in a new context. Adaptive experts share the core technical proficiency of routine experts. Further, they are flexible in developing appropriate responses and solutions in novel situations. They tend to review multiple perspectives when considering the solutions to new problems, seek out challenges in their work, successfully gauge their own current knowledge state, and view their knowledge base as dynamic.[7,16,18,40]

All types of expertise require a significant investment of time and effort to develop.[10] Frequently AE is acquired only after many years of practical post-graduate industrial experience or of graduate and postdoctoral research study.[26] Therefore, undergraduate students in a course such as biotransport are unlikely to develop advanced AE in that field within a single semester of study. This realization leads to a consideration of how AE develops and how different educational methods may influence the AE developmental trajectory. Our research is based on a model for the development of AE adapted from Schwartz *et al.*[33]

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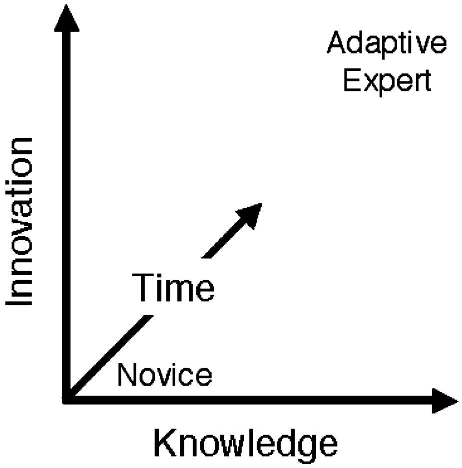

FIGURE 1. Developmental model for adaptive expertise. The figure shows how the aspects of knowledge and innovation develop together over time as learners progress from novices to adaptive experts (Adapted from Schwartz *et al.*[33]).

(see Fig. 1). This model proposes that there are two essential and complementary dimensions of AE: knowledge and innovation. Knowledge covers the taxonomic understanding of the field; innovation involves the ability to perform in novel situations. As people learn, both of these dimensions need to improve for AE to develop.

Our primary research question is to identify educational experiences that best promote both knowledge and innovation in the context of a semester-long formal course (for the present study this was an introductory biotransport course) in a biomedical engineering curriculum. This paper presents quantitative results of an experiment comparing the effects of traditional and inquiry approaches to teaching biotransport on the development of student knowledge and innovation.

BACKGROUND

Teaching Methods

Many alternative approaches to teaching courses that present fundamental and often difficult engineering content material for a subject domain exist. The most common approach is a didactic lecture format, which has numerous demonstrated benefits. Students receive a clear exposition of the information they need to learn, teachers can be sure they have covered the content if they follow well-organized materials that are readily available, and students tend to learn content well as measured by performance on tests that replicate the content and context under which the material was presented.[7,32]

However, there are drawbacks to the lecture approach as well. Students may learn the material in a disconnected fashion that makes it difficult for them to apply their knowledge out of context, and their long-term retention is often poor.[3,7] Further, students have difficulty in relating their accrued knowledge to problems in the ‘‘real world’’—in the workplace or graduate school.[7]

An alternate teaching approach is to apply one of the several methods that can be grouped together under the moniker of Inquiry Learning. Problem- and Project-based Learning, Authentic Inquiry, Challenge-based Learning, and Discovery Learning are all examples of this approach.[25] There are many substantial differences among these methods, although all engage students in developing solutions to real-world problems that revolve around key concepts in the discipline. These approaches increase student motivation and awareness of the connections between their in-class experiences and their future work, lead to positive attitudes about learning for both students and teachers, and, when structured well, lead to significant increases in knowledge.[2,12,13,15,36]

However, like traditional lecture, inquiry methods can have drawbacks as well. Without extensive training, teachers often have trouble selecting application problems that highlight the key principles in the discipline, opting rather for problems that merely seem engaging.[5] Students consequently often miss important concepts they need to learn.[2,15] Students may have trouble structuring their approach to these open-ended problems if they have not also learned the fundamental principles for the subject and how to apply them with an effective analysis strategy.[13] Thus, they may struggle with the processes needed such as hypothesis generation, defining appropriate systems for investigation, identifying the most relevant system variables and properties, and confining the breadth of their investigation to answer the question asked.[13] Finally, if these approaches are not structured well, students' knowledge gains are less than in traditional educational settings.[2,15,25]

In summary, traditional instructional methods can be effective at developing the knowledge dimension of AE, but often fail to improve students' innovation. In contrast, inquiry methods are frequently effective at developing the innovative dimension of AE, but if not structured correctly, can fail to help students improve on the knowledge dimension.

Structuring Learning Environments for Productive Inquiry

In order to develop both the knowledge and innovation dimensions of AE, it is important to structure inquiry learning environments wisely. Learning science research has shown that there are four key principles for designing learning environments that lead to effective learning. One is that the learning environment be knowledge centered.[6,7,13,15,25] This means that the core knowledge and skills that students should know and be able to use are the basis for designing the environment. Another principle is that the problems used should be realistic and fit with the community that students are being trained to join.[6,7,13,15,25] Further, the learning environment should be assessment centered. These assessments should include formative components that give students and teachers information about performance during the unit.[7,29] Assessments should also include summative components that occur at the end of the unit and demonstrate overall gains in student learning.[7] Finally, these environments should be learner centered, identifying and developing from students' level of prior knowledge.[6,7,13,15,25] These four principles are the building blocks of a quality inquiry learning environment.

Our work is based on a version of these principles as presented in the National Research Council report "How People Learn" (we will refer to them as HPL principles).[7] We implemented these four principles using a Challenge-Based inquiry cycle called the STAR.Legacy (SL) Cycle[34] (see Fig. 2). The SL Cycle helps students understand the elements and objectives of the learning process in which they are engaged, thereby establishing expectations for the class activity sequence and students' performance therein.

In the SL Cycle, students first receive a realistic, complex problem (The Challenge). They then generate ideas about what they already know and what they will need to learn to solve the challenge (Generate Ideas). Students often work in small teams during the class period to carry out this exercise. The instructor is available for consultation during and after this step. Then the students discover different views on important aspects of the challenge and key components of the knowledge taxonomy, including lectures from the instructor (Multiple Perspectives). The lecture may flow seamlessly from questions students pose during Generate Ideas. Next students revise their ideas, often via guided assignments outside of class (Research and Revise) and complete formative assessments with peers and/or the instructor (Test Your Mettle). Finally, students publicly present their solutions to the challenge (Go Public).

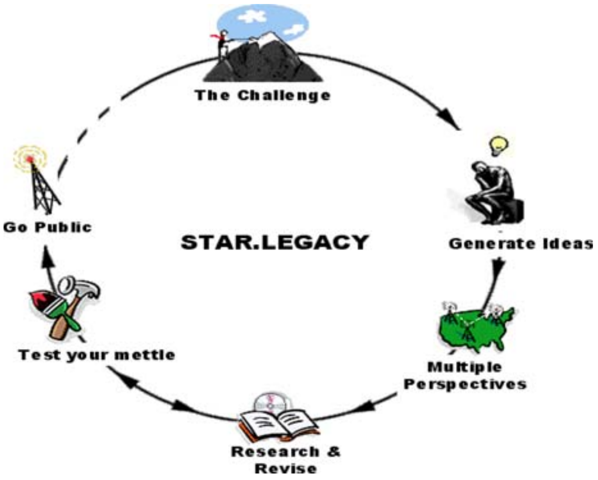

FIGURE 2. The STAR.Legacy (SL) Cycle. This model illustrates the sequence of learning activities used in the HPL classes. Permission was granted for use of this figure from VaNTH Engineering Research Center in Bioengineering Educational Technologies, http://www.vanth.org.

The SL Cycle helps instructors ensure that they have incorporated the HPL principles into their learning materials to improve both the knowledge and innovation dimensions of AE. The Multiple Perspectives, Research and Revise, and Test Your Mettle phases primarily develop the knowledge component. In each of these phases, students discover or receive important information for solving the challenge. The cyclical approach to addressing knowledge components used in these phases is beneficial because people learn more when they have a chance to revise.[37] In addition, in these phases students receive formative feedback, which helps teachers and students adjust their actions to improve learning.[13,28,37]

Students develop their innovative skills primarily in the Generate Ideas (GI) phase. Here, they attempt to address the novel and difficult challenge problem on their own prior to consulting resources that provide knowledge they need to solve the problem. This gives them practice with both the cognitive and affective aspects of confronting an unknown problem and helps them develop several of the characteristics of adaptive expertise.

On the cognitive side, GI develops several of the innovative characteristics of adaptive experts. First, it develops metacognition, or the ability to be aware of your own state of knowledge, because students consider and discuss what they know and need to discover.[38] Second, GI develops multiple perspectives because students work in groups and share ideas that they generated.[20] Third, GI helps students structure their work on the challenge problem. Grappling with problems independently prior to receiving resources and direct instruction improves students' subsequent learning.[32,35] In addition, it increases the likelihood they will generate questions that guide their inquiry productively.[33]

On the affective side, GI develops comfort with facing an unfamiliar problem that takes time to solve.

Many students in traditional engineering programs have not faced this type of problem and report feeling somewhat threatened by them early on.[22] However, as they practice generating ideas over time, they develop confidence in their ability to approach the problem. Though this is a classroom rather than a real world setting, it seems likely that students' persistence on tough problems could increase. Increased persistence in the face of obstacles could lead students to seek new learning challenges and become life-long learners, both key characteristics of adaptive experts.

In an HPL–SL Cycle module, knowledge and innovation develop in a mutually reinforcing manner.[21] The ideas of *transfer in* and *transfer out* can clarify this process.[33] The typical meaning of knowledge transfer is using knowledge learned in one situation to solve problems in another, or transfer out. For example, when students attend lectures and read about a topic for a few weeks and then take an exam, they transfer out their knowledge to solve the exam problems. Another important kind of transfer is transfer in. People transfer in their prior knowledge to interpret new situations and learn from them, whether intentionally or not. For example, a student's initial understanding of heat transport affects how they interpret lectures and readings on the topic. Sometimes the knowledge and procedures transferred in are useful and sometimes not. The key is to shape the educational experience to promote productive transfer in.

If learning experiences are structured to make transfer in support subsequent learning, they can improve transfer out as well.[35] The GI phase of the SL Cycle structures transfer in so that it prepares students to learn from subsequent phases of the cycle, which in turn can improve their transfer out.

Generate Ideas helps students transfer in useful prior knowledge because innovating first prepares students to learn from the next phases of the cycle.[8,32,35] This improved preparation improves students' learning from latter phases of the cycle such as Multiple Perspectives, Research and Revise, and Test Your Mettle. In turn, these phases help students improve their knowledge base to improve their transfer out. These phases help students answer the important questions they have identified for the challenge and hone and refine the knowledge they have developed in a contextualized setting so they can transfer it out to be able to solve problems in new settings. Finally, the cycle itself can become internalized as a way to solve problems as students complete multiple challenges over time. This helps students transfer in an approach to tackling novel problems when they receive a new challenge, again improving transfer out.[34,39]

Research on Adaptive Expertise in Biomedical Engineering

The VaNTH (Vanderbilt, Northwestern, University of Texas, and Harvard/MIT) National Science Foundation (NSF) Engineering Research Center (ERC) in Bioengineering Educational Technologies has conducted several studies examining the effects of HPL instruction. For this effort, the ERC created instructional materials and developed taxonomies of the core ideas in several areas of bioengineering including bioimaging, biomechanics, biotransport, biotechnology, physiology, bio-optics, bioengineering ethics, and design.[17]

We based our work on HPL principles implemented through the SL Cycle because research has shown that features of this learning environment are particularly effective at developing the knowledge and innovation components of AE.[6,15,25,35,37,38] To date, our research has demonstrated that the HPL–SL Cycle method can improve AE in biomedical engineering. Experimental studies compared student learning performance on subject material for biomechanics and bioengineering ethics covered by one or two HPL modules with performance on equivalent content in a traditional instruction format.[23,24] In both cases, students in the HPL group developed more adaptiveness along with equivalent levels of knowledge. In addition, developmental studies on an entire biotransport course implemented with the HPL method (designers mapped the core knowledge taxonomy to a set of SL Cycle challenges that covered all the core content) examined how knowledge and innovation change over time. The results show that over an entire course, students improve significantly in both the innovation and knowledge aspects of adaptive expertise.[21]

METHODS

Experiment

Our prior work demonstrated that HPL–SL Cycle instruction could be effective in increasing students' adaptive expertise in biomedical engineering.[21,23,24] However, these outcomes were obtained over short periods of time: 1–2 weeks.

Based on the foregoing studies, a more robust investigation of the relative outcomes of HPL and traditional instruction is needed. In this paper, we report on a study that compared the two methods over a longer time period: an entire course in biotransport. The course was taught at multiple institutions via HPL and traditional formats. Biotransport is a core course in biomedical engineering aimed at upper level students. It is important to test the effectiveness of innovative educational programs in courses that convey core bodies of knowledge for students. If these programs are effective, they will provide students with the key knowledge they need to progress in their fields as well as the added value aspects of innovative problem solving.

In this study, we administered a pretest and posttest to two traditional format classes and two HPL format classes. These tests had two components; one assessed knowledge, and the other assessed innovation. We tested knowledge with a set of multiple-choice questions that any general course in biotransport should have prepared students to answer. We tested innovation by examining students' performance on a novel problem that asked them to solve a real world challenge. This problem was more difficult than any of the students could be expected to answer correctly. The assessment focused primarily on how students developed an analysis strategy to solve this problem, but we also examined the correctness of details of their answers.

We anticipated that both groups would improve from pre to posttest on the knowledge problems, but that the HPL group would improve more on the innovation problem—both on their general approach and on their accuracy. Both groups covered the core knowledge content in biotransport well, so should be able to answer basic knowledge questions. However, only the HPL group practiced developing approaches to highly innovative problems and strategies for applying what they learned in the course to be inventive and accurate in these difficult challenges.

Participants

We solicited the participation of all members of the two HPL and two traditional classes. Each of the courses was taught at a Research I level university in the US with a long established record of excellence in engineering education. The two courses in each format were offered at different universities. We explained to each class the study design and the opportunity for students to participate. Students did not receive compensation. In total, 136 students participated in the study, of which 106 completed both the pre and posttests (54 in the HPL condition and 52 in the traditional condition). Most of these students were in their third year of undergraduate study (approximately 20–21 years old). The gender of the students was obtained with a demographic survey that was completed by 58 of the HPL students and 48 of the traditional students. The HPL group included 18 women and 40 men and the traditional group included 13 women and 35 men. The self-reported SAT math and verbal scores for the two groups were not significantly different (Math: HPL $M = 710$, $SD = 80$; Traditional $M = 702$, $SD = 112$. Verbal: HPL $M = 668$, $SD = 97$; Traditional $M = 656$, $SD = 73$).

Materials

HPL Instruction

The two HPL classes used a similar set of SL Cycle modules to organize the class. The instructors first developed a taxonomy of core biotransport concepts for an introductory course and then designed the suite of modules to address these concepts.[14] The two HPL faculty (at different institutions) shared the task of creating the modules and used subsets of the completed modules in instruction. Each module led the students through a complete SL Cycle experience.

The HPL courses each used 10–13 modules that addressed fluid, heat and mass transport processes in biological systems. The instructors ordered the modules with two goals in mind: (1) to ensure that students learned the targeted biotransport taxonomy, and (2) to lead the students through a learning sequence starting with core fundamentals and progressing to acquisition of specific analysis tools. The serial modules enable reinforcement of fundamentals while building a growing knowledge base.

An exemplar module starts with a challenge to quantify the "Danger of Hot Coffee Burns." Based on the infamous 1994 McDonald's coffee spill lawsuit, students solve in explicit quantitative terms the problem of how dangerous it is to spill a cup of hot coffee into your lap (see Appendix A). This challenge addresses several important taxonomic components such as types of systems on which to base an analysis, categories of system—environmental interactions, transient heat diffusion in a material of semi-infinite geometry, thermally driven kinetic processes, boundary conditions in a composite material system, and finite difference solution methods.

Though the two HPL instructors implemented the modules somewhat differently and even used some different modules in their courses, they followed the basic structure of the SL Cycle including the Challenge, Generate Ideas, Multiple Perspectives, Research and Revise, Test Your Mettle, and Go Public phases. However, they did not plan instruction together. Therefore, the presentation of the challenges, the lectures, and the tests, quizzes and homework assignments were entirely independent for the two classes. In addition, one HPL instructor taught a specific strategic process for addressing novel, open-ended problems while the other did not. The results section addresses whether this difference interacted with test performance.

Traditional Instruction

The two traditional classes followed a standard procedure focused around instructor lectures that followed the order of taxonomy of knowledge presented in a textbook specified for the course. Student activities included textbook readings, lectures, question and answer sessions, homework assignments, tests, and quizzes.

Assessments and Coding

All students completed a pre and a posttest with two sections (see Appendix B). The knowledge section measured students' understanding of fundamental principles of bioheat transfer. The innovation section measured how students' marshaled the tools of bioheat transfer to analyze a state-of-the-art research problem.

Knowledge Section

This section presented the knowledge questions in multiple-choice format. We did not attempt to cover the complete biotransport taxonomy. Instead, we sampled from it with a few questions that addressed core concepts. Any student who completed a general biotransport class would be likely to learn the material covered in these questions.

These questions all had a well-defined correct answer. Therefore, a student's knowledge score was the number of multiple-choice questions out of six answered correctly (range 0–6).

Innovation Section

This section presented the innovation question. This question is innovative because students need to go beyond their current capabilities and develop an approach to a novel problem that embeds technical issues with which they are unfamiliar. Although the problem is novel, it is not completely foreign. The governing principles, solution methods, and constitutive equations students learned in the class could, if applied adaptively, help them develop a viable approach to the question, even though it is unlikely they would completely solve the problem.

Our goal in using the SL Cycle is to accelerate the acquisition of adaptive problem solving. The SL Cycle makes the process of adaptive reasoning explicit, which should help students appropriate the process.[34] Therefore, we wanted our coding scheme to capture adaptive reasoning in novel situations, so we needed to define this type of reasoning. The research on expert problem solving in truly novel situations is not extensive, but we based our coding scheme on the available data.

The concepts of routine and adaptive expertise clarify how we operationalized adaptive reasoning to code students' solutions to the innovation problem. Routine experts employ useful engineering problem solving techniques in routine situations. However, when confronted with non-routine problems that call for new thinking, they transfer in inapplicable knowledge and procedures.[7] In contrast, adaptive experts transfer in useful and appropriate knowledge and procedures.[7,26,40] This facet of adaptive reasoning we refer to as efficiency. We operationalized efficiency by examining whether students applied appropriate governing principles and constitutive equations to model the process in the problem.

We refer to the other facet of adaptive reasoning included in our coding system as innovation. We based the operationalization of innovation on findings on expert problem solving. First, all experts tend to address problems initially from a global perspective to understand the primary issues of importance and then move toward developing specific equations or other solution methods.[9,10,31] In contrast, novices often skip the step of developing a deep understanding of the problem, and attempt to quickly apply equations or solution methods that match the problem on surface features.[10,30] In addition, adaptive experts tend to expand the problem space and consider multiple possibilities before they settle on a solution path.[7,40] Therefore, to code innovation, we examined whether students considered the problem globally and expanded the problem space by considering the system and its interactions with the environment.

A high score on innovation and efficiency indicates that a student is approaching the problem similarly to an adaptive expert in the area considering how to solve a novel problem. We had developed these coding schemes *a priori* and used them in earlier experiments.[22]

The specific coding scheme used a rubric with two categories with two elements in each category (see Table 1). The categories were: (1) innovation: a system definition (picture, diagram, or written definition) and identification of system interactions with the environment, and (2) efficiency: a statement of the governing conservation principles, and an application of transport constitutive equations.

We coded each element on a four point scale (0, 1, 2, or 3). A response received a 0 if the category was missing from the student solution. A response received a 1 if the students did some work that was in the coding category but was primarily incorrect or irrelevant to the problem they were given to solve. A score of 2 covers a wide range. A response received a 2 if it included some of the necessary information, but some incorrect information as well. A response received a 3

TABLE 1. Coding for innovation section.

	Innovation		Efficiency	
Code	System	Interactions	Governing principles	Constitutive equations
0	Absent	Absent	Absent	Absent
1	Picture or written description present but missing heat exchanger	Incorrect interactions	Incorrect governing principles	Incorrect constitutive equation(s)
2	Heat exchanger, fuel source, patient are all included in the system	One or more but not all (of 3) interactions: correct heat transfer to the blood, heat transfer from the fuel and heart as pump	Conservation of energy or momentum only	One or more but not all (of 4) correct: heat source from burner, convective exchange to blood, force of pumping, F > flow resistance
3	System is heat exchanger, that interacts with butane and person	All three correct	Both conservation of energy and momentum	All four correct

if all the information was present and correct. Since both the innovation and efficiency scores had two elements, the range for each score was 0–6.

The coding procedure for the innovation section was as follows. First, research staff who did not participate in the coding collected and blinded the completed tests as to time of test and condition of each participant. Next, a primary and a secondary coder trained on a subset of tests. Then, the primary and secondary coders checked reliability using new tests (30 tests—10% of the sample) drawn randomly from the pre and posttests. Inter-rater agreement was 92%. The primary coder subsequently scored all the innovation sections.

Procedure

Each instructor administered the pre and posttests in class. Students took the pretest on the first day of class prior to any instruction. They completed the posttest on the last regular class day.

Instructors did not answer any questions regarding the test and did not discuss it explicitly during the semester. They passed out the tests and read the instructions provided. Students had 10 min to complete the knowledge section and 15 min for the innovation section of the test. Instructors told students when to proceed to the second section. Students did not have access to any resources other than calculators during the tests.

Three of the classes received a small number of points toward their grade for completing the test (less than 1% of their overall grade). Students received these points regardless of the accuracy of their responses. One class did not receive points. The results section includes discussion of whether this difference interacted with test performance.

Study Design

The design for this study was a pre–post comparison with an experimental factor of HPL vs. traditional instruction. We examined both pre–post changes in and between group comparisons of student performance on three measures: the knowledge section and the two scores for the innovation section (the innovation score and the efficiency score).

RESULTS

Knowledge Section

To examine the scores on the knowledge section, we computed a total score, which was equal to the number of the multiple choice items students answered correctly (0–6). We analyzed these data using a 2×2 repeated measures analysis of variance (ANOVA) on the knowledge problem scores with time (pretest vs. posttest) as the within subjects factor and instructional treatment (HPL vs. traditional) as the between subjects factor.

All of the students improved on this multiple choice test over time (pretest $M = 3.08$, $SE = 0.11$; posttest $M = 3.53$, $SE = 0.10$), $F(1, 104) = 11.13$, $MSE = 0.93$, $p < 0.001$.

There were no other significant effects.

Innovation Section

As described in the coding section, we examined two facets of the students' performance on the innovation section of the test: innovation and efficiency.

Innovation

To examine the effects of instructional method on the development of innovation, we conducted a 2 × 2 repeated measures ANOVA on innovation score with time (pretest vs. posttest) as the within subjects factor and instructional treatment (HPL vs. traditional) as the between subjects factor.

The two groups developed innovation differently (see Fig. 3). We found that there was an interaction between time and instructional treatment, $F(1, 101) = 14.66$, $MSE = 1.75$, $p < .001$. *Post hoc* tests confirm what Fig. 3 demonstrates regarding the meaning of this interaction. The two groups' scores on the pretest were not different. However, the HPL group scored significantly higher than the traditional group on innovation score on the posttest ($p < 0.01$). The HPL group's scores significantly increased from pretest to posttest ($p < 0.05$) while the traditional group's scores decreased significantly ($p < 0.01$).

There were no other significant effects.

Efficiency

We conducted the same repeated measures ANOVA for the efficiency scores as for the innovation scores.

Efficiency scores improved over time (pretest $M = 0.84$, $SE = 0.10$; posttest $M = 1.47$, $SE = 0.14$), $F(1, 101) = 15.71$, $MSE = 1.32$, $p < 0.001$. The HPL group ($M = 1.60$, $SE = 0.12$) scored higher than the traditional group ($M = 0.70$, $SE = 0.13$) overall, $F(1, 101) = 25.46$, $MSE = 1.63$, $p < 0.001$.

Furthermore, the two groups performed differently on efficiency on the two tests (see Fig. 4). There was a significant interaction between time and instructional treatment, $F(1, 101) = 34.53$, $MSE = 1.32$, $p < 0.001$. *Post hoc* tests confirm the patterns Fig. 4 shows. While similar on the pretest, the HPL group scored significantly higher on efficiency on the posttest ($p < 0.001$). Moreover, the HPL group improved significantly from pretest to posttest ($p < 0.001$), while the traditional group did not change significantly. This effect also reveals that the main effect for improvement over time was likely due to the HPL group's improvement on efficiency, as the traditional group did not contribute to this improvement.

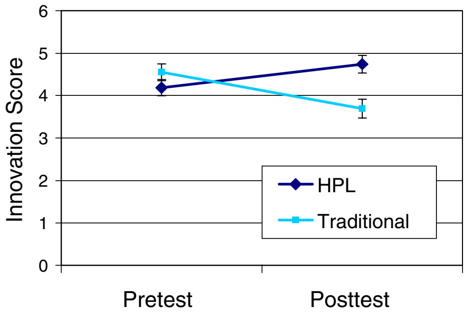

FIGURE 3. Innovation score on the innovation section. The highest possible score for innovation on the innovation section of the test was 6 points. The graph demonstrates that while HPL and traditional students performed similarly on this measure at pretest, the HPL students improved during the semester, while the traditional students' scores on this measure decreased.

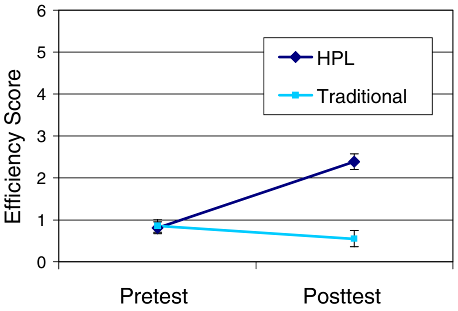

FIGURE 4. Efficiency scores on the innovation section. The highest possible score for efficiency on the innovation section of the test was 6 points. The graph demonstrates that while HPL and traditional students performed similarly on this measure at pretest, the HPL students improved during the semester, while the traditional students did not.

Additional Analyses

There are two differences in classroom practices that could affect the results that require presentation of additional analyses. One difference is that one of the HPL classes taught a specific method for addressing novel, open-ended problems while the other did not. The second is that one of the traditional instructors did not give points for completing the pre and posttests.

Effects of Differences in HPL Instructional Method

To address the first point, we conducted a 2 × 2 repeated measures ANOVA on the innovation scores of the two HPL teachers' classes with time (pretest vs. posttest) as the within subjects factor and teacher (HPL Teacher 1, HPL Teacher 2) as the between subjects factor. Both teachers' students improved in innovation over time (pretest $M = 4.19$, $SE = 0.22$; posttest $M = 4.74$, $SE = 0.15$), $F(1, 52) = 5.82$, $MSE = 1.4$, $p < 0.05$. However, there were no significant differences between the two HPL classes' scores. There was no main effect of teacher (HPL Teacher 1 $M = 4.46$, $SE = 0.22$; HPL Teacher 2 $M = 4.46$, $SE = 0.15$) or Time × Teacher interaction.

Effects of Completion Points

To address the second point, we re-ran all analyses excluding the class who did not receive completion points. There were no differences in any effects.

DISCUSSION

The HPL method of instruction promoted knowledge growth similar to traditional instruction, while showing significant added value in promoting students' innovation skills. Thus, the HPL framework of learning is more effective and better suited to undergraduate engineering students developing AE skills that will serve them well in future professional endeavors.

A result of interest to us was the significant decrease in innovation performance for the traditional students. While we would like to see this result replicated, we interpret it as an interesting comment on potential long-term effects of traditional instruction. Students in traditional instruction courses may become less willing to engage in challenging problems in adaptive ways. This result is consistent with a cross-sectional study we conducted comparing the development of innovative problem solving over the course of an HPL bioengineering ethics module for two groups: high school and first-year undergraduate students and upper-level undergraduate engineering students.[27] The upper level students were less likely to develop innovative problem solving, suggesting that there can be long-term detriments to students' ability to develop innovation in a short period of time if they learn by primarily traditional methods.

In light of current ABET guidelines for program outcomes and industry calls for more innovative engineers, our results are encouraging and significant.[1] We believe our work particularly addresses the following ABET outcomes: the ability to design a system, component, or process to meet desired needs within realistic constraints; the ability to identify, formulate, and solve engineering problems; and the recognition of the need for, and the ability to engage in life-long learning (p. 2).[1]

It is also important that these results were achieved in a regular class delivery setting. Our HPL classes had no additional teaching assistants, professor office hours, or graded assignments, and they were conducted in fixed seating lecture halls not adapted for convenient grouping of students to interact during the generate ideas exercise. In addition, the class sizes were in the average range for undergraduate biomedical engineering at the participating institutions.

We foresee that an important subsequent step from this research is to implement the HPL framework with instructors who have not been involved in the initial creation of the modules and methods. This step will provide an indication of the transportability and sustainability of the HPL framework in biomedical engineering curricula. Although the initial development of the HPL materials required a considerable investment of time and effort, the materials may now be used with a routine expenditure of instructor time and resources. Near term plans are to transfer the entire set of class materials to HPL-inexperienced faculty for use in teaching biotransport. Instructor effort and acceptance as well as student learning will be important to measure in this context. Based on our experience with teaching biotransport in the HPL framework, the authors have signed a contract with a publisher to write a text oriented around offering biotransport in the HPL framework. In the long-term, the success of this initiative will be one measure of the impact of this research.

Another important long-term outcome is the degree of persistence of the gains students make in HPL course. Our prior research showed gains from students using a few modules.[23,24] This experiment showed gains from using several modules over an entire course. We would like to know if these gains carry over to other courses and whether an HPL approach has effects even after students leave school. We are currently beginning two initiatives to attempt to answer these questions. First, we are comparing the adaptiveness of students in their capstone senior design course who participated in their third year biotransport course in HPL and traditional formats. Second, we have put in place ways to measure the performance of graduates educated in the HPL framework as they acquire and demonstrate AE in their professional careers as biomedical engineers.

We believe the results reported herein are generalizable to other educational venues that address significant core content in engineering, science, and mathematics. We are not aware of any prior attempts to implement the HPL framework in these disciplines on the scale of entire courses, and they represent a potentially ripe field of application for this educational method. Many of the courses conducted in these disciplines teach core knowledge topics, are conducted with large class sizes, and are not conducted in environments adapted for collaboration. These are the real challenges that college instructors face in implementing inquiry methods such as challenge-based instruction.

APPENDIX A: CHALLENGE EXAMPLE

Challenge 6. The Danger of Hot Coffee Burns

Every year in the US there are thousands of accidents at restaurants in which hot beverages are spilled onto customers causing scald burns that are severe enough to require hospitalization. In the most extreme cases, death results. A small fraction of these accidents result in law suits against various parties involved in the food service industry, the most publicized being the infamous McDonald's case in which a jury awarded an elderly New Mexico woman more than 2 million dollars in 1994. Part of the public outcry to this case was based on the concept that spilling a cup of coffee is such a trivial event that it could not be worth such a large legal settlement. **Thus, the focus of this challenge is to answer the question "How dangerous is it to spill a cup of hot coffee into your lap?"**

You may use the following information in your analysis. The Coffee Brewers Association recommends that coffee be held at a temperature of 185 °F for serving to customers, although a recent survey of the food service industry indicates the actual temperatures at fast food restaurants is somewhat lower. Many of the scald accidents occur while customers are seated in their vehicles at fast food drive-thru windows. A typical container contains 8 oz of liquid. The clothing worn by customers varies over a broad spectrum depending on geographic location and time of year, activity of the customer in conjunction with the visit to the drive-thru, and customer life style.

A consideration inherent to the issue of how dangerous is spilled coffee is how the level of danger can be modulated by altering the coffee temperature. For example, a recent scientific study demonstrated that the preferred drinking temperature of coffee is 140 °F. Thus, it is appropriate to ask how a progressive reduction in serving temperature would change the injury hazard associated with a spill.

Appendix B: Pre–Posttest

SECTION I. (10 min)

1. The flow of blood through microcirculatory blood vessels can have a large influence on heat transfer and temperature regulation in human tissues.

a. As the blood flows through the vasculature is the mechanism of heat exchange with the surrounding tissue most likely to be dominated by a process of

(i) Conduction
(ii) Convection
(iii) Radiation

b. Which vascular components will provide the most effective venue for heat exchange between blood flowing through them and the tissue in which they are embedded?

(i) Aorta
(ii) Arteries
(iii) Arterioles

c. Consider a comparison of the heat exchanges by the flowing blood and by the tissue in a very small volume of flesh. Is the magnitude of the heat exchange for the blood

(i) Smaller
(ii) The same
(iii) Larger

2. The alveoli of the lungs present a structure in which there is mass exchange between gas flow (air) and liquid flow (blood).

a. The fluid flow regimes of air and blood may be matched of different in the alveoli. Is the most likely combination

(i) Air: laminar and blood: turbulent
(ii) Air: laminar and blood: laminar
(iii) Air: turbulent and blood: laminar
(iv) Air: turbulent and blood: turbulent

b. During one complete respiratory cycle the air pressure in the alveoli when compared to the air pressure in the immediate environment is

(i) Always greater
(ii) The same
(iii) Always lesser
(iv) Fluctuates cyclically between being greater and lesser

c. During respiration the air flowing in the lungs at the center of a bronchial passageway has a velocity in comparison to air at the bronchial wall surface that is

(i) Always larger
(ii) Sometimes larger and sometimes smaller
(iii) Always smaller
(iv) Always the same

SECTION II. (15 min)

3. This is a very complex problem. A full solution would require extended attention and a number of iterations. However, one of the keys to success in extended problem solving is how you get started. Our goal is to access how you get started on a problem.

Your task in this problem is to begin designing the device described below.

In severe trauma patients hypothermia is a common occurrence and issues in a significant increase in mortality. This situation is particularly grave for wounded soldiers for whom it has been shown that mortality doubles when the body core temperature reaches a value of 34 °C or lower. Patients suffering from severe trauma tend to become hypothermic regardless of the environmental temperature, and in a war zone, such as the recent US involvement in Iraq and Afghanistan, casualties have suffered hypothermia at a rate in excess of 90%. Consequently, the prevention and treatment of hypothermia have been identified as being a major deficiency in American combat medical capability.

The Department of Defense is seeking solutions to solving the problem of preventing and treating hypothermia in war casualties. Owing to constraints imposed by the battlefield environment, there are a number of very specific limitations that must be enforced for any possible solution. Rapid evacuation to a Forward Surgical Hospital typically requires 5 h and a ride in a cold helicopter. To be effective a warming device must be able to transmit energy to the body core at a rate of 60 W over the 5-h period. It has been determined that the most effective method of delivering heat directly to the body core is via arteriovenous rewarming, being far more efficient than any surface warming technology. The device must be compact, light in weight, and robust (capable of being dropped from a helicopter at 150 feet onto a concrete surface). The device must contain its own power supply since there is generally not an external electrical service available on a battlefield and during critical phases of transport. Batteries are too heavy and are inefficient. Thus, the energy source of choice for heating is compressed butane, which can be used to fire a burner in a small heat exchanger through which a minor fraction of the patient's blood flows. A surgical group has proposed designing a unit capable of warming 300 mL of blood per minute. The pumping source to move blood through the heat exchanger is the patient's own heart. Access to the patient's arteriovenous system for this device will be the same as standard practice for a heart lung machine.

The proposed device holds tremendous potential for providing life-saving support for trauma patients in both the military and civilian populations. At the present time it is still in the concept and prototyping phase of development. Since the early studies have been accomplished via some ingenious but intuitive work by a team of surgeons, there is no basis for understanding and predicting performance based on a rational model of the device when attached to a patient.

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