Guided Inquiry-based Lab Activities Improve Students' Recall and Application of Material Properties Compared with Structured Inquiry

Dr. Sarah J. Christian, Carnegie Mellon University

Sarah Christian is an Assistant Teaching Professor in the Department of Civil & Environmental Engineering at Carnegie Mellon University. Sarah earned her BS in Civil Engineering at Carnegie Mellon University in 2003, MCE at Johns Hopkins University in 2004 and PhD in Civil and Environmental Engineering with a focus on Structural Engineering and Materials at Stanford University in 2009. Sarah has practiced as a structural engineer and building envelope engineer in Washington, D.C. and Pittsburgh. She previously served as a lecturer at the University of Edinburgh in Scotland. Sarah teaches courses in Structural Engineering, Materials, Soil Mechanics, and Design. Her current research focuses on course design to improve student engagement and agency as well as to prepare students to be innovative problem solvers and leaders in their field of engineering.

Dr. Chad Hershock, Carnegie Mellon University

Eberly Center for Teaching Excellence & Educational Innovation, Carnegie Mellon University

Dr. Michael Cameron Melville, Carnegie Mellon University

Michael Melville works as a Data Science Research Associate at Carnegie Mellon University's Eberly Center for Teaching Excellence and Educational Innovation, where he consults with faculty, graduate students, and post-docs to design, implement, and assess research projects that relate to teaching and learning in their classrooms. He also contributes to a variety of program-level assessment projects on the CMU campus. Mike's training includes an M.A. and Ph.D. in Social Psychology from the University of New Hampshire, as well as an M.Ed. in sport and performance psychology from Springfield College. His interests include the science of learning, research methodology, and data analysis. Prior to joining the Eberly Center in 2017, Mike worked as the Teaching and Learning Research Coordinator at the Center for Excellence and Innovation in Teaching and Learning at the University of New Hampshire.

Guided inquiry-based lab activities improve students' recall and application of material properties compared to structured inquiry

Abstract

Prior research suggests that lab courses taught by following traditional, recipe-based instructions may lead to suboptimal learning outcomes when compared to inquiry-based procedures where the students must think for themselves. However, the relative impacts of different forms of inquiry-based learning are unclear. In an attempt to extend the current research, we measured student learning in a materials lab course that taught labs in two different ways. Our main objective was to test whether implementing structured or guided inquiry-based learning methods, would lead to better learning outcomes.

Two inquiry-based learning methods were implemented in a junior-level, civil engineering materials lab course that featured three independent labs based on the materials of concrete, wood, and masonry. The concrete and wood labs were taught using a structured inquiry-based approach known as predict-observe-explain or POE. Students predicted the outcome of a lab exercise before following a standard, recipe-based lab protocol provided by the instructor. Afterwards, students evaluated their predictions by explaining observed data and underlying concepts of material properties. In contrast, the masonry lab was taught using a guided inquiry-based approach. Students were given an authentic engineering question: is the design of a masonry building for which they were given drawings feasible? To answer the question, they needed to decide which material properties were important and identify the experimental methods necessary to determine those properties. Because the activities related to guided inquiry were new to the students, the activities were broken into scaffolded tasks and questions. Students were assessed on all labs via a final exam at the end of the semester, allowing for a within-subjects comparison of student learning using both instructional approaches.

Analysis of the data showed a significant difference in student learning for the content related to the guided inquiry-based lab compared to the content from the two structured inquiry-based labs. Relative to content from the two structured inquiry-based labs, students exhibited an 11% gain, over a full letter grade, in learning on content related to the inquiry-based lab (Cohen's d = .86). This gain was consistent across recall- and application-based exam items.

Design for implementation of inquiry-based methods can take significant time and preparation. Student development of experimental methods appears to be an effective inquiry-based method in this case, but requires a significant amount of guidance and oversight to effectively implement. In addition to improved exam performance, application of results to solve real-world problems gives the students an understanding of how their experimental work relates to their other courses and the world in general, which provides context and may increase motivation. Given the workload, a best practice may be implementing these methods incrementally rather than implementing a wholesale change in a course.

The guided inquiry-based methods applied in this materials lab course can be applied in all types of classes, but methods are most easily transferable to laboratory, design, and problem-based project courses. For future iterations of this course, we are redesigning the two structured

inquiry-based labs using guided inquiry approaches and will be continuing to collect data to assess their effectiveness.

I. Introduction

Lab experiences are traditionally a major component of hands-on learning in engineering curricula and intended to impart a practical understanding of how science applies to the real-world [1]. Students in laboratory courses often conduct experiments or complete demonstrative tasks by following "cookbook"-style instructions [2], [3]. This passive process directs the students' focus towards completing prescribed steps (i.e., following a procedural recipe), but rarely challenges students to think critically about what they are doing and ought to be learning conceptually [3] - [5]. Although students may develop a practical understanding of process skills through tangible, hands-on lab experiences, the effectiveness of cookbook laboratory exercises to impart conceptual understanding through those means alone may be limited. For example, even when students complete pre-laboratory assignments to prepare for cookbook lab sessions, these lab exercises do not necessarily improve student learning in corresponding lecture-based courses [6], [7].

Numerous authors discuss the potential merits of inquiry-based learning (hereafter IBL) as an alternative to cookbook approaches to instructional laboratories, e.g. [2], [3], [8]. In a recent literature review, Pedaste and colleagues [8] identified and summarized the core features of IBL. In general, student experiences mirror one or more steps of the scientific method and/or disciplinary habits of mind of scientists or engineers: (1) articulating testable questions and hypotheses; (2), making predictions that can be verified with observations or empirical data; (3) designing empirical approaches to testing hypotheses or solving authentic problems; (4) collecting, analyzing, and/or interpreting data to test a hypothesis or evaluate a proposed solution to an authentic problem; and (5) communicating findings, evidence-based recommendations, and/or next steps to colleagues and/or a lay audience. Key features of an IBL student experience include active learning and cognitive engagement, rather than passive listening or following stepwise directions or procedures alone. And, as Pedaste et al. [8] highlight, "...what is new knowledge to [students] is not, in most cases, new knowledge to the world, even if the approach can be flexibly used by scientists in making their discoveries of new knowledge. In addition, it should be noted that an investigation does not always involve empirical testing." As an additional merit, because IBL is applicable to and can be adapted flexibly across disciplines and course formats, using these methods has the potential to greatly improve learning across all STEM fields.

Despite this potential, however, rigorous, empirical evidence is limited in the context of college-level laboratory courses in STEM, especially in engineering [9]. Although a number of papers specifically discuss the merits of IBL as compared to "cookbook" laboratory exercises, e.g. [2], [3] or survey students regarding their impression of the course or change in attitudes toward a subject following IBL and cookbook lab experiences, e.g. [10], [11], relatively few of these studies actually assess learning outcomes [2]. A meta-analysis of studies conducted on introductory-level science laboratories suggests that "inquiry-discovery" methods significantly improve conceptual learning and reasoning as compared to the traditional cookbook methods [12]. This meta-analysis does have some limitations, however. For example, the reported sample of studies that rigorously compare learning outcomes across cookbook and IBL lab experiences is relatively small. Additionally, conspicuous variability in the definition of and approaches toward applying IBL among studies makes it difficult to generalize results.

Indeed, due to its flexibility, IBL in lab contexts comes in many forms. IBL experiences can differ not only in the steps of the scientific or engineering process that students actually experience (see above), but also in the degree to which the IBL experience is scaffolded by the instructor. For example, Tafoya et. al [13] have classified IBL experiences along a continuum according to the amount of independent thought required from the students. This continuum consists of confirmation, structured inquiry, guided inquiry, and open inquiry. *Confirmation* is when the students have already been taught a concept and performing a highly scripted laboratory exercise, provided by the instructor, confirms the concept. Confirmation requires little independent thought from students, does not integrate disciplinary habits of mind for problem solving, and most closely resembles traditional, cookbook approaches to instructional labs. In *structured inquiry*, instructors provide a problem to solve, question to answer, or hypothesis to test as well as specific lab procedures for students to follow. Because students are not aware of the outcome in advance, the activity is often designed to challenge students to make predictions and/or draw conclusions from observations to achieve the instructor's learning goals. A common example of structured IBL is the Predict-Observe-Explain (POE) method [14]. In the POE method, instructors provide a problem and procedure to follow. Students are then asked to make a prediction regarding the outcome before conducting the provided lab procedure and use the observed lab results to evaluate their prediction and to explain the outcome in terms of its underlying concepts. In *guided inquiry*, instructors only provide the problem, question, or hypothesis to students. Students must develop their own study design, data sources, and laboratory methods through which they will collect, analyze, and interpret data to investigate and respond to the instructor's challenge. *Open inquiry* most closely represents the scientific method in its entirety. Instructors provide minimal guidance as students articulate their own research problem, develop and implement their own methods for investigating the problem, and draw their own conclusions. Here, instructors function primarily as mentors, providing advice and feedback.

Ultimately, the quality of the student learning in instructional labs likely varies depending on the type of inquiry that is used, and how well those methods align with particular learning objectives. Without knowing the relative benefits of different types of IBL in different contexts, it is difficult to extrapolate from empirical results to inform teaching decisions. As mentioned above, few studies experimentally compare learning outcomes between cookbook and IBL labs in general, but the relative benefits of the different forms of IBL compared to cookbook labs remain unclear [12]. A number of researchers found that guided or open IBL labs resulted in comparable or greater outcomes than "cookbook" labs for conceptual learning, measured via a number of assessment types, including pre- and post-lab quizzes, final project presentations and reports, lab reports and/or final exams [15] - [20]. These studies did not directly compare learning outcomes between guided to open IBL. An indirect comparison between guided and open IBL in these studies is difficult because implementation differed greatly among studies within each form of IBL, including, but not limited to the amount of pre-lab support provided by instructors, whether pre-lab learning was through lectures or readings provide by instructors, the extent to which student were held accountable for pre-lab learning, whether or not students were told what to measure, the types of formative and summative assessments used to support learning, and the amount of scaffolding provided by instructors as student developed their questions and methods. Because direct, experimental comparisons of learning outcomes across structured, guided, and/or open IBL lab designs are lacking, we believe it is important to continue to gather more empirical evidence comparing various forms of IBL.

The present work compares the impacts of structured and guided IBL approaches on student learning outcomes in an upper-level, undergraduate, engineering laboratory course. In both forms of IBL studied, students must think for themselves, but the nature of the independent thought required was varied. Structured IBL leveraged the POE method, primarily because it is one of the simplest ways an instructor can infuse IBL to supplement a cookbook (i.e., confirmation) lab exercise. In contrast, guided IBL did not use POE. Instead, the instructor provided an authentic engineering problem and students had to develop their own protocols during guided IBL rather than following lab protocols provided by the instructor in the structured IBL labs. The empirical data collected here and conclusions drawn can contribute to the growing literature on IBL in instructional laboratories in ways that address some of the aforementioned limitations. Furthermore, in the fields of Engineering, there is a dearth of studies on IBL [9], and this work will contribute to filling that gap. By providing more empirical data, other engineering instructors may be more likely to attempt applying IBL, which would likely be a step toward improving the state of engineering education. Ideally, faculty will be more likely to invest their time in adapting particular forms of IBL to their teaching contexts if there is available data to inform those decisions.

II. Methods

Participants

We conducted this study during the Spring 2017 semester at Carnegie Mellon University, a 4-year, highly-selective, research-intensive university. We implemented the study within a half-semester, 7-week, Civil & Environmental Engineering laboratory course (Materials Lab) examining the material properties and behavior of concrete, masonry and wood. The course is required for third-year undergraduates in Civil & Environmental Engineering to give students a practical sense of how the materials used in the field behave. Courses in Solid Mechanics and Introduction to Material Selection are pre- and co-requisites, respectively, in the undergraduate curriculum. Each week, students attended two 80-minute sessions that are either lecture, workshop, or laboratory format. Lecture sessions introduced disciplinary concepts and skills necessary for lab exercises, and included both active learning and didactic lectures. During workshops, the instructor provided guidance and support when students were working with their teams to solve problems related to the upcoming lab exercise, such as how to measure the strength of a material. Lab exercises provided experiential, hands-on experiences with different construction materials and the measurement of their properties. The course organization contained three units of study, each pertaining to one of the aforementioned construction materials. Each unit contained a lab exercise spanning multiple class sessions. Students attend lab in small, permanent teams of 6-8 students each. Students worked collaboratively to both complete the lab activity and submit a lab report. Additionally, students individually complete either preparatory or review assignments. The instructor was present and provided mentorship during all lab sessions.

Study participants included all students who enrolled in the course. Data analyses included all 28 students completing the course (39% male, 61% female; self-reported race/ethnicity: Asian 36%, Black 7%, Hispanic 18%, White 36%, Unreported 4%). Mean student age was 22 years. Twenty-five students were third-year students, two students were fourth-year students and one student was a second-year student.

Study Design & Procedures

We conducted a within-subjects design, with one of two conditions, structured IBL or guided IBL design, applied to each of the course's three laboratory exercises. We implemented the first and third lab exercises (concrete and wood) using a structured IBL formats, but redesigned the second lab exercise (masonry) as a guided IBL experience (see below). Consequently, each student experienced all conditions, alternating between structured and guided IBL lab conditions. In such within-subjects designs, each student functions as his/her own experimental control. The masonry lab was selected as the target for the intervention because it was perceived to be the least engaging for students (i.e., most resembled a "cookbook, recipe-following" procedural experience).

For the guided IBL experience (masonry), students were asked to review slides providing basic information on masonry prior to the lecture/workshop meeting. The first 15 minutes of the lecture/workshop session were used to review the slides in lecture-fashion with a focus on important material properties. Then students were given an authentic engineering question to answer with their lab group: is the design of a masonry building (a single-car, detached garage) feasible? Students received drawings of the proposed design and samples of the masonry building units specified in the design. To answer the question, students needed to decide which material properties were important, identify the experimental methods necessary to determine those properties, and conduct those experiments on the masonry blocks provided by the instructor. After receiving the question, students gathered with their lab groups and collaboratively worked through a series of worksheets with questions that guided them through the problem solving process. Students were instructed not to use the internet to find an answer. The instructor monitored the progress, answered questions, and provided hints when necessary to help the teams to answer the questions. The first series of questions revolved around what properties needed to be found to solve the problem. The students worked through these questions for about 20 minutes, then the instructor gathered the class together to develop a class list of potential properties so that every team would then be focusing on the same properties. The next set of worksheets guided the students through the design of experimental methods to find each of the properties. The worksheet was generic enough that it could be used for all properties. It asked questions such as, "what data do you need to collect to find this property?" and "what equipment or tools do you need to conduct the test and measure the required data?" and asked the students to provide the steps for the experiment. Students then submitted these documents for review and the instructor provided feedback. Lab teams then submitted draft versions of their methods and data sheets. After the instructor reviewed these submissions and provided feedback, lab teams revised their methods and re-submitted to receive one last round of feedback prior to their testing. Requested equipment and materials were ready for the students so that they could begin testing at the beginning of their lab session. The instructor was present during the lab session, but told the students they were responsible for doing the lab without instruction. Following the lab session, lab teams composed a report designed to be directed to a client that did not include the methods section, but focused on the results and discussion, with particular focus on the relevance of the result for the client. Finally, students individually completed a post-lab assignment that asked them to compare the class's results to the standard requirements for the material.

In contrast, for the structured IBL labs (wood and concrete), the unit begins with a lecture providing general background on the material. Then, prior to the lab, students are required to complete a pre-laboratory exercise that asks the students to predict the outcomes of the experimental testing. For the lab exercise, the instructor meets with each of the small groups independently, does not provide the students with written step-by-step instructions, but guides the students through the exercise. Students are not given pre-prepared data sheets, but the instructor tells the students what information should be recorded. Through the course of the exercise, the instructor answers the students' questions, poses questions to the students, and shares other relevant information about the material's behavior and use. Following the lab, students compose a laboratory report with their team explaining what they observed relative to their prediction, and must explain their result in terms of the underlying material properties. To complete their report, they are given a rubric that includes the content that should be provided in each section.

Measures

We measured student performance via the lone exam in the course, administered in the final week (week 7), after the completion of the three lab exercises and their associated lab reports and assignments. Students had 80 minutes to complete the exam's 20 short-answer questions (for example questions, see Figure 1). Each question was scored by the instructor on a five-point scale. Rubric criteria varied across questions.

Analysis

We coded the content of the twenty exam questions as pertaining to material properties of concrete, masonry, wood, or a combination of thereof. Questions that were classified as concrete or wood were coded as structured IBL (control) condition questions, while questions that were classified as masonry were coded as guided IBL (treatment) questions. We combined the concrete and wood questions into one control condition because, in addition to the fact that they were both delivered using structured IBL, the mean scores on the corresponding exam questions for each material were virtually identical (see Table 1 under 'Total'). Three questions were classified as representing more than one of the materials, and were excluded from the analyses. Consequently, 5-7 exam questions represented each material type in our analysis. To test our primary hypothesis, we compared student performance on exam questions (in terms of percent correct) across structured and guided IBL conditions via a paired-samples t-test.

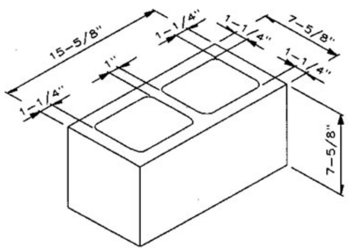
III. Results

A paired-samples *t*-test was conducted to compare the mean performance on exam content corresponding to the guided IBL lab to mean performance on exam content from the structured IBL labs. A significant difference in performance was found between the guided IBL (M= 80.71, SD= 13.56) and the structured IBL (M= 69.82, SD= 9.75) content, $t(27) = 5.406$, $p < .001$, 95% CI [15.02, 6.76], Cohen's d= .86, (see Figure 2). These results suggest that student performance on exam content benefited significantly from the guided IBL lab intervention, scoring more than

10 percentage points better, on average, on the content related to the guided IBL lab compared to content from other labs (i.e., wood or concrete). Our Cohen's *d* value for effect size can be interpreted as an increase in exam score of almost a one full (.86) standard deviation.

Recall questions:

1. What is the typical range of compressive strengths for concrete? Given the range you have stated, estimate the typical range for tensile strengths for concrete and explain how you've made your estimate.
2. Dimensions for the standard concrete masonry unit are shown below. What are the net and gross areas? Show all of your work.



Application questions:

3. The 28-day compressive strength for concrete cast as the slab-on-grade for the hospital you are working was an average of 3000 psi, but strength required by the specifications was 4000 psi. Table A presents the proportions by weight of each component added to the concrete mix. You've done some calculations and have found that the slab must be stronger than 3000 psi. The slab must be removed and replaced. (a) In general, how would you change the mix design to achieve a strength of 4000 psi or greater? (b) If the weight of water in the mix remains the same, what weight of cement will you add to the new mix? You may refer to the provided excerpt from ACI 211.1 Specifications to provide an estimate for cement in the new mix design. Assume that the concrete is non-air-entrained.

   Table A. Insufficient Concrete Mix Design

Constituent	**Weight (lb)**
Water	300
Portland Cement	480
Coarse Aggregate	1863
Fine Aggregate	1230

4. A sample of five bricks from a large shipment were tested and the average gross compressive strength was 4500 psi with a standard deviation of 750 psi. What would you recommend to be used as the design strength for these bricks and why?

Figure 1. Sample exam questions testing recall and application of materials properties.

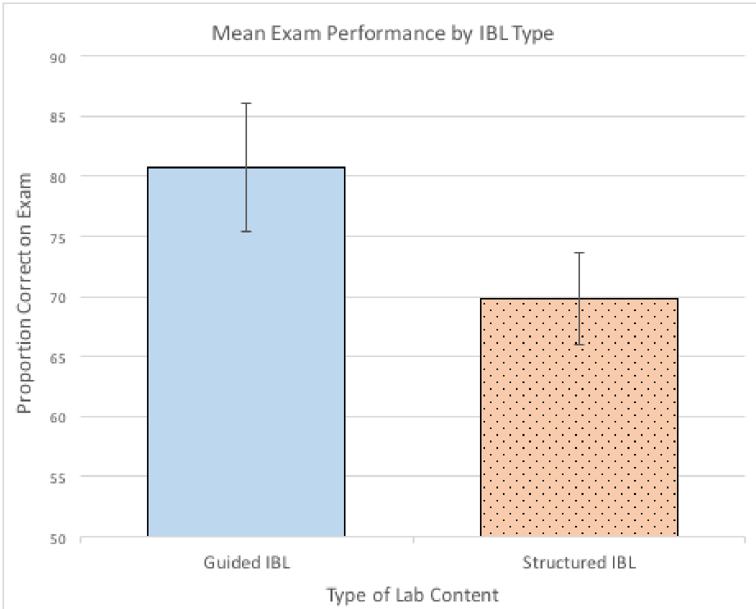


Figure 2. Mean student performance on exam questions pertaining to materials properties learned through guided inquiry-based (masonry) and structured inquiry-based lab exercises (concrete and wood). Error bars are the 95% confidence intervals for the means.

Further analyses

In addition to classifying the exam questions based on material type, we also coded each question by cognitive level required, classifying each as either "recall" or "application" (see Figure 1 for examples). Recall questions required students to demonstrate comprehension of fundamental concepts. Application questions presented students with unfamiliar scenarios and required students to extrapolate from fundamental concepts. Examination of the difference in performance between guided and structured IBL exam items broken down by cognitive level showed the same pattern of results as our primary analysis. That is, students performed better, on average, on both recall and application questions from the guided IBL lab, relative to content from the structured IBL labs. Further examination of the individual test questions also confirmed the uniformity of the effect; similar learning benefits were observed across all questions, excluding the notion that our results may be driven by exceptionally strong performance on only a small portion of the content. Table 1 summarizes student performance by material and question type.

Table 1. Mean percentage correct and standard deviation on exam questions by material type and cognitive-level required to answer questions.

Material	# of questions	Recall M (SD)	Application M (SD)	Total M (SD)
Concrete	7	77.86 (21.32)	66.43 (11.33)	69.69 (11.20)
Wood	5	69.46 (12.04)	72.14 (24.55)	70.00 (12.29)
Masonry	5	80.95 (19.85)	80.36 (14.01)	80.71(13.56)

IV. Discussion/Conclusions

The goal of this study was to determine if guided IBL increased student learning relative to structured IBL (i.e., Predict-Observe-Explain, where the observe phase followed confirmation laboratory methods). Students learned more when laboratories were taught using guided IBL format compared to the structured IBL format. Our study is consistent with the bulk of the research on guided IBL in laboratories by showing that student learning improves when a mostly scripted laboratory exercise is replaced by a student-generated method to solve a problem [15] - [20]. Others studying open and/or guided IBL have found various impacts on the type of learning that is achieved: for some recall increased [15] - [18], for others application increased [19], [20]. Guided IBL, as applied in this study, improved both recall and application.

The design of this study does not allow us to fully isolate the underlying mechanisms causing the observed learning gain in this particular implementation of guided IBL. However, several mechanisms are plausible contributors, including enhancement to students' organization of knowledge, the generation effect and/or student motivation. Compared to the structured IBL labs, the guided IBL methods used in this study engaged students in solving an authentic engineering problem, induced more critical thinking, required repetition of thought about the content, and required students to apply the content in a variety of contexts and from different perspectives. In combination, this greater level of individual thought required by guided IBL may lead to a better understanding of the relationships among materials properties, outcomes, and practical applications, as measured by our assessments, compared to the POE method. It is possible that a deeper understanding of these relationships among materials properties and how to measure and apply them provided students with a better way to organize new knowledge: new knowledge can be more efficiently encoded, which makes retrieval and application easier [19], [21]. Additionally, both structured and guided IBL seek to leverage the generation effect [22] by requiring students to think for themselves, rather than simply passively following a script. As implemented in our study, it is also possible that the generation effect was stronger in guided than structured IBL. In other words, generating ideas about what to measure and how to solve an authentic problem may lead to greater encoding of learning than making a prediction and explaining results obtained from a more scripted lab protocol. Another potential explanation for our observed differences is greater student motivation in the guided IBL condition: students may have been more interested and engaged because they were solving a real-world engineering problem.

Whereas many previous studies focused on introductory-level STEM laboratory courses [7], [12], [15] - [18], this study in an upper-level engineering course suggests that guided IBL can also be effective for more advanced students. Furthermore, guided IBL is a promising teaching method for the engineering community because it can be adapted for not only lab courses, but also design courses and traditional lecture courses. For example, in a senior-level capstone design course in Civil & Environmental Engineering, the first author gave students an engineering problem (e.g., design a sustainable dog house [23]) and a list of questions that guided them through the conceptual design. Similarly, to enhance a traditional lecture on experimental design, the same instructor designed a worksheet that students completed throughout the lecture so that students could design their experiment incrementally as the different components of a study design were discussed. In both cases, she leveraged elements of the guided inquiry approach to support students thinking independently in the context of an open-ended, authentic, engineering problem.

Advice for Instructors

While teaching laboratories through guided IBL requires significant initial planning, this decreases with subsequent deliveries, and guided IBL is more enjoyable and engaging for everyone than standard labs. It is truly exciting to see students thinking for themselves and engaging. To make the time investment more manageable, consider redesigning only one lab per delivery of the course rather than all of the labs at once.

To provide the proper support for students who are not used to IBL, instructors should think through the process from the student's perspective, considering their knowledge base and discomfort with a method that does not allow passive learning. This will help instructors to design an appropriate level of scaffolding into the exercises and to be prepared with supplemental support for struggling teams. Students may also need encouragement to overcome their resistance to a more challenging experience. They may be more receptive to the guided IBL method if you share that struggling with the problem is expected and an effective mode of learning. In this study, students worked on worksheets with questions that guided them through the process. Instructors in other studies have prepared the students by discussing a process for inquiry [15]. Others have found that students are more receptive when the initial level of guidance for laboratories is high and then gradually reduced through the semester [24]. If guided IBL is used throughout the curriculum, students will be more comfortable with the process and need less support. For example, the first author has added scaled-back elements of guided IBL to a preceding laboratory course to help the students to get comfortable with the process used in the course in this study: students identified the parameters controlled for a series of trials and the data that needed to be collected to answer an authentic question, but the instructor provided the testing procedure.

We also found it helpful to design a class session during which students develop their methods, so that they have time to think through the authentic problem with their teams, but also for whole class discussions to ensure that everyone is headed in the right direction. By having students work during class, the instructor can monitor their progress and provide additional support when needed. This method can also be used to ensure that students do not using the internet to find an answer.

To ensure that students are prepared to complete their lab, it is helpful to have them submit a proposal of their methods and data sheets. If students have never designed their own experiments, then they often overlook basic steps. A simple example is that students will say that the cross-sectional area of a specimen should be measured, when, in fact, the dimensions of the cross-section must be measured so that the area can be calculated. This process can be tedious. While students received feedback on multiple revisions of a written document in this study, it may be more effective to meet the teams face-to-face to discuss their proposals [5].

Careful design of the initial, pre-lab phase of the inquiry can minimize the impact of the higher time investment required from students completing guided IBL labs. By replacing a lecture with thoughtful, scaffolded, guided-inquiry activities like those used in this study, increased student engagement and critical thought can lead to improved learning and application of key concepts.

It may also be possible to reduce the content covered in the course by re-evaluating the course learning objectives. If students do not retain all of the content that is covered when taught by cookbook methods, reducing the coverage and teaching by guided IBL may actually result in a net gain in students' overall understanding of the subject.

Limitations and Directions for Future Research

Our results have several possible limitations. First, it is possible that students performed better on the questions related to the guided IBL content because that topic (masonry) may be easier to understand than the topics taught via structured IBL (concrete and wood) or because the related exam questions were easier. For this reason, we would recommend future research efforts target topics of varying difficulty. Alternatively, various elements of the implementation of guided IBL lab resulted may have resulted in greater student time on task compared to either structured IBL lab. Ideally, future studies comparing forms of IBL would control for students' time on task with course content. Furthermore, we implemented our guided IBL intervention mid-way through the semester. It's possible that the effects of our intervention could be stronger or weaker, depending on how its placement in the semester interacts with students' development of expertise. Earlier in the semester, students may need more scaffolding to produce the same learning gain, while later in the semester, students may need less scaffolding. Yet another potential limitation is the small sample size in this study. Although this course enrolled fewer than 30 students, approximately 30 subjects for a repeated measures design with moderate to large effect size is more than adequate [25-26]. As is the case with any single study, however, replication with broader sampling is certainly needed to strengthen the validity of the findings.

There are many different types of IBL, and it is likely that there are optimal strategies for particular contexts. Future work can aim to do more theorizing and testing regarding which strategies may work best and why, in addition to examining a broader sample of IBL strategies and evaluating their effectiveness. Our study of IBL laboratory methods has continued into subsequent semesters to collect data to assess the impact of different forms of IBL on learning.

V. References

[1] L. D. Feisel and A. J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," *J. Eng. Educ.*, no. January, pp. 2644–2652, 2014.

[2] N. C. Waters, "The Advantages of Inquiry-Based Laboratory Exercises within the Life Sciences," pp. 1–8, 2012.

[3] J. Handelsman et al., "Scientific Teaching," Science (80-.)., vol. 304, no. 5670, pp. 521–522, 2004.

[4] A. Hilosky, "Profile of instructional practices in beginning college level chemistry laboratory experiences," Ed.D. dissertation, Dept. Educ., Temple Univ., Philadelphia, PA, 1995.

[5] N. J. Buch and T. F. Wolff, "Classroom Teaching through Inquiry," *J. Prof. Issues Eng. Educ. Pract.*, vol. 126, no. 3, pp. 105–109, 2000.

[6] N. G. Holmes, J. Olsen, J. L. Thomas, and C. E. Wieman, "Value added or misattributed? A multi-institution study on the educational benefit of labs for reinforcing physics content," *Phys. Rev. Phys. Educ. Res.*, vol. 13, no. 1, pp. 1–12, 2017.

[7] C. Wieman and N. G. Holmes, "Measuring the impact of an instructional laboratory on the learning of introductory physics," *Am. J. Phys.*, 2015.

[8] M. Pedaste *et al.*, “Phases of inquiry-based learning: Definitions and the inquiry cycle,” *Educational Research Review*. 2015.
[9] T. A. Litzinger *et al.*, “Engineering education and the development of expertise,” *J. Eng. Educ.*, vol. 100, no. 1, pp. 123–150, 2011.
[10] S. E. Brownell, M. J. Kloser, T. Fukami, and R. Shavelson, “Journal Article Undergraduate Biology Lab Courses: Comparing the Impact of Traditionally Based ‘Cookbook’ and Authentic Research-Based Courses on Student Lab Experiences,” J. Coll. Sci. Teach., vol. 41, no. 4, pp. 36–45, 2012.
[11] J.R.V. Flora and A.T. Cooper, “Incorporating inquiry-based laboratory experiment in undergraduate environmental engineering laboratory,” Journal of Professional Issues in Engineering Education and Practice, vol. 131, no. 1,pp. 19–25, 2005.
[12] S. Rubin, “Evaluation and Meta-analysis of Selected Research Related to the Laboratory Component of Beginning College Level Science Instruction,” Ed.D. dissertation, Dept. Educ., Temple Univ., Philadelphia, PA, 1996.
[13] E. Tafoya, D. W. Sunal, and P. Knecht, “Assessing Inquiry Potential: A Tool For Curriculum Decision Makers,” Sch. Sci. Math., vol. 80, no. 1, pp. 43–48, 1980.
[14] R. White and R. Gunstone, *Probing Understanding*, 1st ed. London: Routledge, 1992.
[15] T. Lord and T. Orkwiszewski, “Moving from Didactic to Inquiry-Based Instruction in a Science Laboratory,” Am. Biol. Teach., vol. 68, no. 6, pp. 342–345, 2006.
[16] D. B. Luckie, “Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of ‘Teams and Streams,’” AJP Adv. Physiol. Educ., vol. 28, no. 4, pp. 199–209, 2004.
[17] W. H. Leonard, “An experimental study of a BSCS-style laboratory approach for university general biology,” J. Res. Sci. Teach., vol. 20, no. 9, pp. 807–813, 1983.
[18] S. W. Rissing and J. G. Cogan, “Can an inquiry approach improve college student learning in a teaching laboratory?,” CBE Life Sci. Educ., 2009.
[19] W. C. Newstetter, E. Behravesh, N. J. Nersessian, and B. B. Fasse, “Design Principles for problem-driven learning laboratories in biomedical engineering education,” Ann. Biomed. Eng., vol. 38, no. 10, pp. 3257–3267, 2010.
[20] R. A. Linsenmeier, D. E. Kanter, H. D. Smith, K. A. Linsenmeier, and A. F. Mckenna, “Evaluation of a challenge-based human metabolism laboratory for undergraduates,” J. Eng. Educ., vol. 97, no. 2, pp. 213–222, 2008.
[21] D. L. Schwartz, J. D. Bransford, S. Cognition, D. L. Schwartz, and J. D. Bransford, “A Time for Telling Linked references are available on JSTOR for this article : A Time for Telling,” vol. 16, no. 4, pp. 475–522, 2017.
[22] S. Bertsch, B. J. Pesta, R. Wiscott, and M. A. McDaniel, “The generation effect: A meta-analytic review,” *Mem. Cogn.*, vol. 35, no. 2, pp. 201–210, 2007.
[23] “Sustainable Dog House Challenge,” *Department of Civil, Architectural, and Environmental Engineering (The University of Texas at Austin)*, 2016. [Online]. Available: http://caee.utexas.edu/news/761-doghouse. [Accessed: 04-Feb-2019].
[24] F. W. Kolkhorst, C. L. Mason, D. M. Dipasquale, P. Patterson, and M. J. Buono, “Model for an Exercise,” vol. 25, no. 2, pp. 45–50, 2001.
[25] M. Lipsey, *Design Sensitivity: Statistical Power for Experimental Research*. Thousand Oaks, CA: Sage Publlications, 1990.
[26] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. Hillsdale, NJ: Lawrence Earlbaum Associates, 1988.