Relating Level of Inquiry in Laboratory Instructions to Student Learning Outcomes

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Abstract -- This research paper will describe the results of an experiment in which the level of inquiry in a laboratory manual is varied from guided inquiry to open inquiry by reducing the specificity of the instructions in the lab manual. The hypothesis is that less specific instructions will cause students to reflect on their actions in lab and, as a result, circle further around Kolb's experiential learning cycle during each step of the lab. This should result in improved recall and better integration of laboratory and classroom understanding. Student learning outcomes are assessed using an in-lab, direct assessment which evaluates both students' laboratory skills and their ability to relate experiences in the laboratory to classroom learning. Student attitudes are also assessed with surveys.

The in-lab assessment is the primary tool used to assess student learning outcomes, so it is discussed in detail. It is a series of questions which are designed to be answered at a laboratory bench. The questions ask the student to record data from an instrument using an oscilloscope, extract information from that data, and then use the extracted information to perform analysis.

The experiment had 195 participants: 106 in the specific-instruction, control group and 89 in the non-specific-instruction, treatment group. Results show that more treatment students than control students learned to scale a signal on an oscilloscope screen , while control students learned to use an oscilloscope's built-in save/recall feature more effectively. There is also weak evidence that shows greater affective gains in the treatment group. This shows that there is potential for increasing student learning by studying how best to write laboratory manuals, and that increasing reflection is a way to achieve that goal. However, it also shows that there are many ways to increase reflection, and further research is required to identify them thoroughly.

1 Introduction

Level of inquiry refers to the specificity of instructions and corresponding degree of student freedom in laboratory exercises. Rubrics have been developed which characterize the level of inquiry in a laboratory exercise [1], and it is possible to find examples of labs which fall into every possible level of inquiry. The relationship between these levels of inquiry and student learning outcomes are not well known [2], so this work describes an experiment in which two groups of students in a laboratory class used lab manuals with slightly different levels of inquiry. The control lab manual provided detailed instructions for procedures, which is strictly guided inquiry, and the treatment lab manual replaced detailed instructions with less specific prompts, which is closer to open inquiry.

The central hypothesis of this work, that a relationship between level of inquiry and learning outcomes exists, is supported by Kolb's experiential learning theory [3]. Kolb's theory suggests that students learn from experience by cycling between experiencing, reflectively observing, abstractly conceptualizing and actively experimenting with phenomena. Reducing the specificity of laboratory instructions should cause students to think more carefully about completing each step of their labs, increasing the chance they will reflect on and conceptualize their work before returning to experiments. This rapid cycling around Kolb's experiential learning cycle should improve learning. Evidence that Kolb's experiential learning theory can be used to improve learning in labs can be found in [4], which applies Kolb's learning theory to redesigning an entire prelab, in-lab and post-lab experience instead of individual exercises within the manual.

The focus on the manuals used by the students in this work fills a gap in previous literature. Though many works have reported on the implementation of specific laboratory exercises -- [5]–[8] are examples from electrical engineering -- few of these works focus on the supporting materials and instructions used with the laboratory apparatus [9]. [10]–[12] focus on relating instructions, supporting materials and staff training to student satisfaction, but not to learning.

This experiment was carried out in an introductory engineering course at Harvey Mudd College, a small liberal arts college that only offers STEM majors. The course takes an interdisciplinary approach to introducing fundamental mathematics used for engineering: students learn how to model electrical and mechanical systems, predict step and frequency responses, and use Laplace analysis and control theory. These lessons are reinforced by lab experiments where students observe dynamics of electrical and mechanical systems and the effect of control on dynamics.

Part of the midterm exam for the course takes place in lab, and this "practicum midterm" is a natural opportunity to directly assess students' laboratory skills. Student learning was assessed by coding practicum midterm submissions. Affective gains, including changes in confidence, reasoning, satisfaction and interest, were measured with a combination of numerical and open-response survey questions.

Section 2 discusses the details of the methods used to conduct the experiment. Section 3 discusses the data obtained in the experiment, the statistical analyses performed on it, and the implications of individual results. Section 4 concludes the paper and suggests future work.

2 Methods

This section discusses the implementation of the experiment in the context of the experiment's host class, the open response and survey questions, the differences between the control and treatment manuals, and the details of the in-lab assessment.

2.1 Implementation in Context of Class

The course hosting the experiment has two types of meetings. One type, called a tutorial, occurs in a flipped classroom, and during this meeting students work on problems, take quizzes and discuss engineering topics (in the style of [13]). The second type of meeting, called a practicum, takes place in a laboratory where students experiment with engineering systems to see concrete examples of the phenomena they are learning about in tutorial.

The first step of implementing this study was picking the learning goals to treat and assess. This was complicated by the experiment's focus on the effect of lab manuals on student learning. The lab manual was the treatment variable, so the study did not control the student's tutorial experience. That meant that concepts which were only taught in practicum were the best candidates for treatment and assessment because those skills would not be affected by the student's tutorial experience.

Handling of benchtop electronics, particularly oscilloscopes, was a particularly good candidate learning goal. The use of benchtop electronics was a subject taught only in practicum. Further, there was a precedent for testing students' use of benchtop electronics on the practicum midterm, so the practicum midterm was a natural avenue for assessing learning gains.

Students are trained to use oscilloscopes during two of the practicums in the course, which are referred to as practicums 2B and 2C. These practicums focus on oscilloscopes at different times in the lab, which affects how students responded to surveys and response questions. In practicum 2B students are introduced to oscilloscopes at the beginning of the practicum and then spend the last half of practicum using them to measure step responses to meet tutorial learning goals. In practicum 2C students assemble some electronics, then use oscilloscopes to test them and finally turn the oscilloscopes towards analyzing the frequency behavior of a motor. Students were more focused on oscilloscopes in practicum 2B, which led to richer data from open response questions, and the time students take to work with oscilloscopes was easier to measure in practicum 2B.

The opportunity to consent to participate in this study was offered in an early practicum, and students were told that they could participate in the study simply by doing their practicums. During practicums 2B and 2C, different manuals were distributed to the control and treatment groups. It was possible to distribute different manuals to the two groups because the labs for this course happen in two adjacent rooms. One professor supervises both rooms during a lab with the help of four student assistants, called proctors, who have already taken the course. One room received control manuals and the other room received treatment manuals.

The adjacent rooms also helped with splitting students into control and treatment groups. Students were assigned to the rooms based on their registration for the class, and it was assumed that students randomly dealt themselves into the two rooms because they appeared identical to students during registration. Observation of student registration practices suggests that coordinated efforts to enroll in the same room are rare.

This experiment was repeated with multiple instructors to ensure that the treatment was not instructor dependent. Eight sections of practicum were offered, and each section was evenly divided into control and treatment students in the two adjacent rooms. Four different professors each taught two of the eight practicum sections. Every section had a different subset of proctors, and proctors were given explicit training to respond to student questions in the same way regardless of the room in which they worked.

These sections served 218 students majoring in math, physical sciences, computer science and engineering; the course serves various majors because it is required of every student at the school. Students work on the practicums in pairs but complete the assessment individually. The sample population is discussed in greater detail in Section 3.1.

2.2 Surveys and Open Response Questions

Students fill out worksheets during each practicum and submit them at the end of the practicum session. Two open response questions -- "What was the main take away from this practicum?" and "What is one thing in this practicum that you still need to understand better?" -- were added to the worksheets after every practicum in the class. The responses to these questions on the practicum 2B and 2C worksheets were analyzed for this study. The worksheets in the practicum 2B and 2C weeks also asked students to report the times at which they finished certain parts of the lab: the oscilloscope training at the start of 2B and the electronics assembly at the start of practicum 2C. These results were compared to the start time of the lab to check whether if students required more time to complete control or treatment instructions.

In addition, pre-course and post-course surveys are common at the Harvey Mudd, so a few questions were added to the pre-course survey (abbreviated as "pre" in tables and figures) to support this study. A survey was also sent out after practicum 2B (abbreviated "2B") and a slightly modified survey sent after practicum 2C (abbreviated "2C"). The survey questions and the surveys on which they appear are in Table 1. All answers were on a five point Likert scale.

When Was it Asked	*Question: Rate your agreement with the following statements (on a 5 point Likert Scale of agreement)*
Pre, 2B, 2C	I can use an oscilloscope to measure an electrical signal
2B, 2C	Learning about the oscilloscope was intellectually engaging
2B, 2C	Practicum stimulated my interest in using oscilloscopes in the future
Pre, 2B, 2C	I can generate a waveform on a function generator
2C	Learning about the power supply was intellectually engaging
Pre, 2B, 2C	I can use a power supply to supply a voltage

Table 1: Questions asked in surveys. Other questions not used in the study omitted from the table

2.3 Treatment

The treatment group received a lab manual with less specific instructions than the control group. The control group received a manual that was similar to those used in previous years: it contained step-by-step instructions on the use of different features of the oscilloscope. The treatment manual instead contained exercises that gave students significant leeway to teach themselves how to use the oscilloscope.

The difference between these manuals is most clearly illustrated by an example. Figures 1a and 1b show exercises from each manual designed to teach the same concept: how to scale the oscilloscope display. It is clear that the control manual is much more detailed.

2.4 In-Lab Assessment

The practicum midterm asked students to interact with the apparatus pictured in Figure 2. Students were tasked with connecting a power supply to the 5V and 0V terminals of the device, connecting an oscilloscope to the signal and 0V terminals, adjusting the oscilloscope display so the oscilloscope captured the dynamics of the swinging pendulum, and saving and uploading their oscilloscope data. Data captured from the oscilloscope was required to answer the final few questions on the exam, which were related to the in-class topics of extracting parameters from step responses.

Students' oscilloscope data was analyzed as part of grading the midterm. A separate analysis of the midterm data was carried out for this study. A discussion of that analysis appears in Section 3.3 below, and examples of uploaded oscilloscope data can be found in Figure 3.

Students were allowed to ask instructors to set to set up parts of their hardware in exchange for a penalty on their final score. These requests were tracked as another means of assessing the competence of the treatment and control group.

Figure 4.7 Vertical scale adjustment knob (top) and vertical offset knob (bottom).

To manually adjust the vertical scaling, you will need to use the vertical scale adjustment knob, as shown in Figure 4.7. The vertical scale adjustment knob (the knob above the number button) changes the volts per division of the display, thus scaling the height of the waveform on the screen. Each channel has its own vertical adjustment knob, giving you the ability to scale and fit multiple inputs into the same window. The vertical offset knob (the knob below the number button) changes the location of the ground cursor on the screen, thus moving the waveform up and down.

Vary the vertical scale of Channel 1 by turning the knob, and observe how the vertical scaling of the square wave changes. Also note how the volts/div in the upper left corner is affected. Turning the knob one way should increase the volts/div, making the waveform appear smaller or shorter; and as expected, turning the knob the other way will decrease the volts/div, making the waveform appear larger or taller. Vary the vertical offset and observe how the position of the wave changes. Turning the knob one way should move the wave up, and turning the knob the other way should move the wave down.

(a) CONTROL

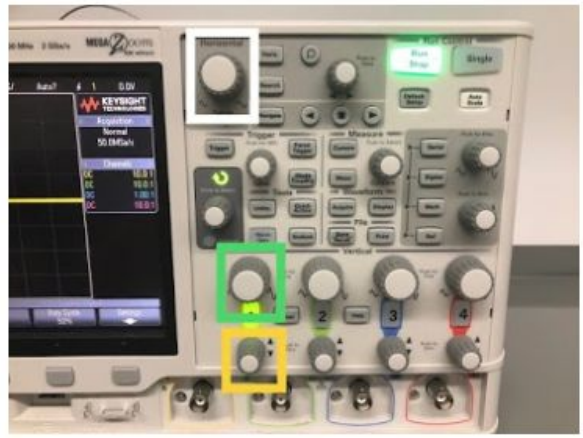


Figure 4.6 Horizontal scaling knob (white), vertical scaling knob (green), and vertical offset knob (yellow).

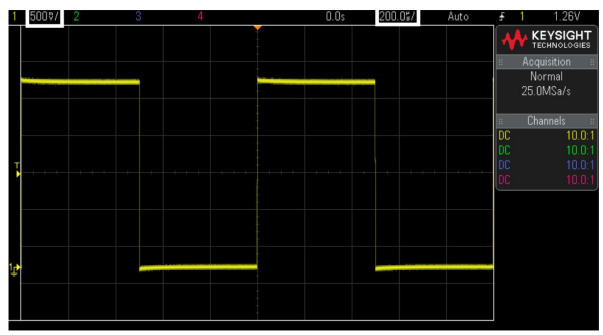


Figure 4.7 Nicely scaled Demo 2 signal with volts per division and time per division.

Turn the horizontal and vertical scaling knobs and the vertical offset knob (see Figure 4.6) to get an idea of their functions. Adjust these knobs to zoom in on the signal until the display looks as similar as possible to Figure 4.7.

(b) TREATMENT

Figure 1: Comparison of exercises in treatment and control lab manuals.

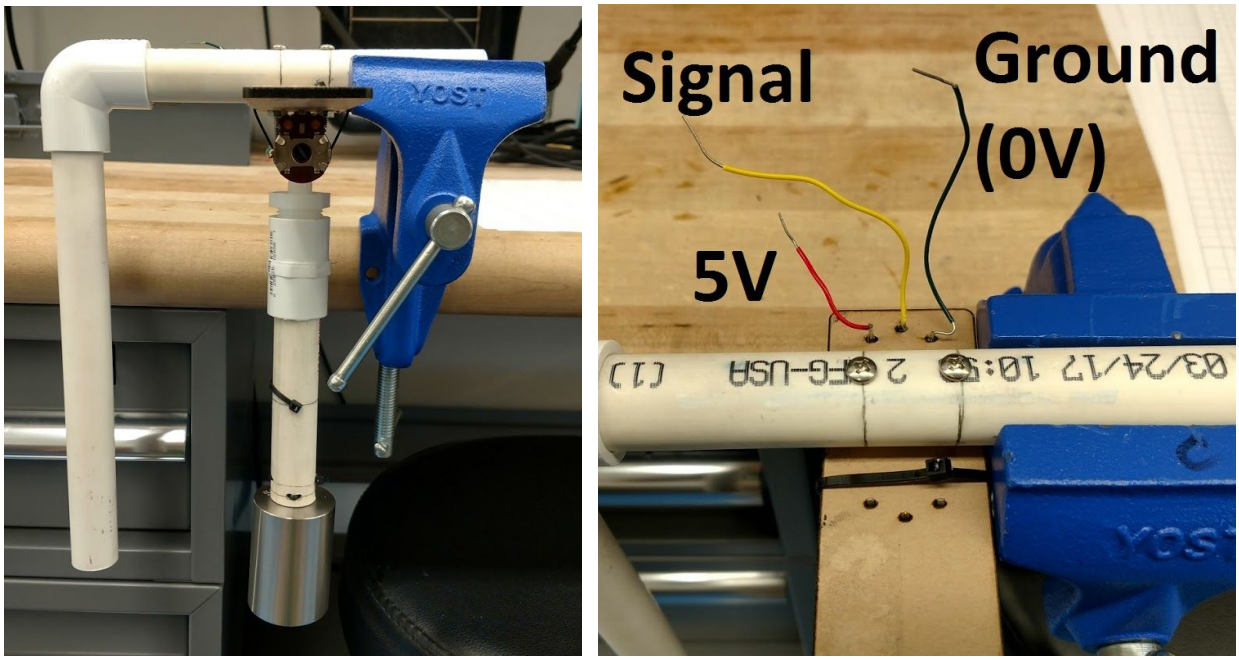


Figure 2: Experimental apparatus for in-lab assessment.

2.5 Summary

To summarize the experiment: students were divided into control and treatment groups quasi-randomly based on their class registration. They were tasked with completing laboratory exercises with manuals that had different levels of detail in their instructions. They were surveyed on their confidence and sentiment as they completed the labs, and they answered open-ended questions about their lab experiences on the worksheets that accompanied each lab. Student mastery of using oscilloscopes and power supplies was assessed on a midterm exam where students were required to interact with an instrumented pendulum by connecting it to an oscilloscope, adjusting an oscilloscope to capture data, and then saving and uploading that data.

This process provided the following data:

- Quantitative reports of the time it took to complete each type of lab
- Categorical data on student exam performance, including features that indicate the quality of students' oscilloscope images and whether students requested help from instructors
- Categorical data based on coding student the responses to the open response questions
- Quantitative survey data where students self-assessed their confidence and sentiment

3 Results and Analysis

This section discusses the sample population and the analysis of each of the data types described in the summary section 2.5: time to lab completion, performance on the exam, coding of open response questions, and survey responses.

3.1 Sample Population

The control and treatment groups were assumed to be representative samples of students at Harvey Mudd College. 218 students took the host course and 195 consented to participate in the experiment. Differences in registration and consent rates for the control and treatment rooms resulted in groups having slightly different sizes: 106 students were in the control group and 89 were in the treatment group. As a reminder: assignment to the control and treatment groups was quasi-random based on whether students registered for class sections in the control or treatment rooms.

The results of the Prelab survey were used to identify students who had prior experience with oscilloscopes. Students who rated themselves a 5 in the pre-survey question "I can use an oscilloscope to measure an electrical signal" were excluded from the study. Eight such students were excluded from the control group and two were excluded from the treatment group. After this exclusion, 98 students remained in the control group and 87 students remained in the treatment group.

3.2 Timing Data

The time required to complete different exercises was gathered for both practicums 2B and 2C. In practicum 2B the exercises that focused on the oscilloscope appeared at the beginning of the practicum, so the time spent on those exercises can be readily computed from the recorded times. The difference between completion times for the control and treatment groups was found to be 0 ± 2 minutes with 95% confidence. This is a tiny difference when compared to the 150 minute run time of a practicum, so there is clearly no significant difference in the completion times of control and treatment groups. Giving students leeway for inquiry in their exercises did not delay students significantly in this lab.

In practicum 2C, the exercises that focused the oscilloscope appeared at the end of the practicum, and practicum 2C was too long for students to finish in the allotted time. As a result, some students were still working on oscilloscopes at the end of the practicum, which meant that their reported completions times don't capture the total time they would have spent on oscilloscopes. In other words, some of the measurements of how long students worked on oscilloscopes in practicum 2C are right censored by the end of the practicum. As a result, the practicum 2C timing data was not analyzed because the censoring confounds the results.

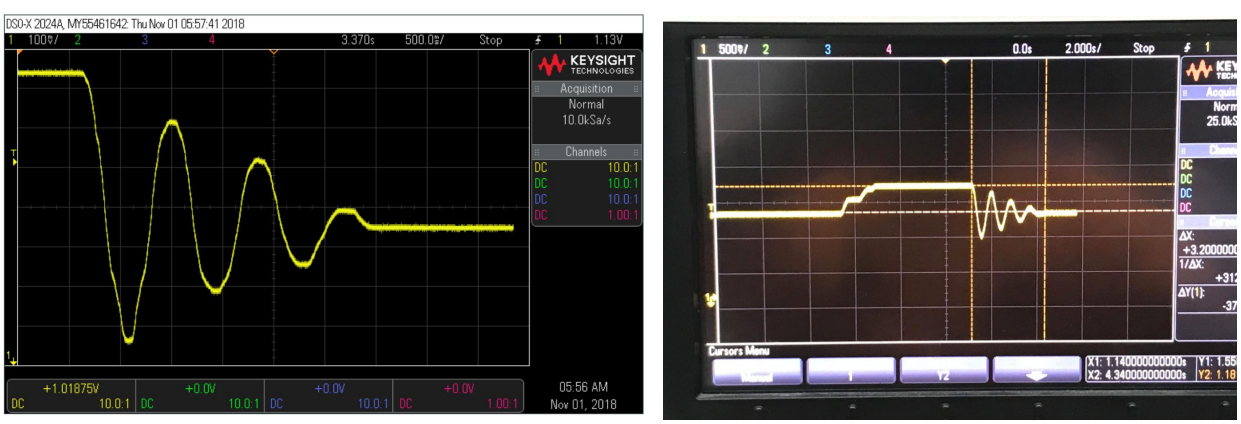
3.3 Practicum Midterm Performance

The oscilloscope data uploaded by students was analyzed to assess their mastery of various oscilloscope skills. There were an assortment of indicators which could be used to discern if students used oscilloscopes effectively. Many of these features can be understood by comparing Figures 3a and 3b, which are examples of using an oscilloscope to take the same data well and poorly. Figure 3a shows a well-scaled signal which is aligned with the left side of the screen (using a feature called horizontal delay) and saved directly to a USB drive using built-in features of the oscilloscope. Figure 3b shows a figure which is poorly scaled, not aligned with the left side of the screen, and saved by taking a cell phone picture.

With these features in mind, the oscilloscope images that students submitted during the lab were awarded the following codes:

- Was the oscilloscope trace scaled properly such that it spans four divisions both vertically and horizontally as requested in the exam manual?
- Was the horizontal delay used to align the signal to the left side of the screen? Using this feature represents an advanced understanding of the oscilloscope.
- Was the image recorded using the built-in save/recall feature of the oscilloscope? This is more desirable than taking a cell phone picture.
- Did the student request help from an instructor on their practicum midterm? This represents a lack of mastery of the oscilloscope or a failure of recall.

These codes were converted to proportions and the 95% confidence interval of the difference between the control and treatment proportions was calculated. The confidence intervals are displayed in Figure 4.



(a) (b)

Figure 3: A comparison of good and bad oscilloscope traces.

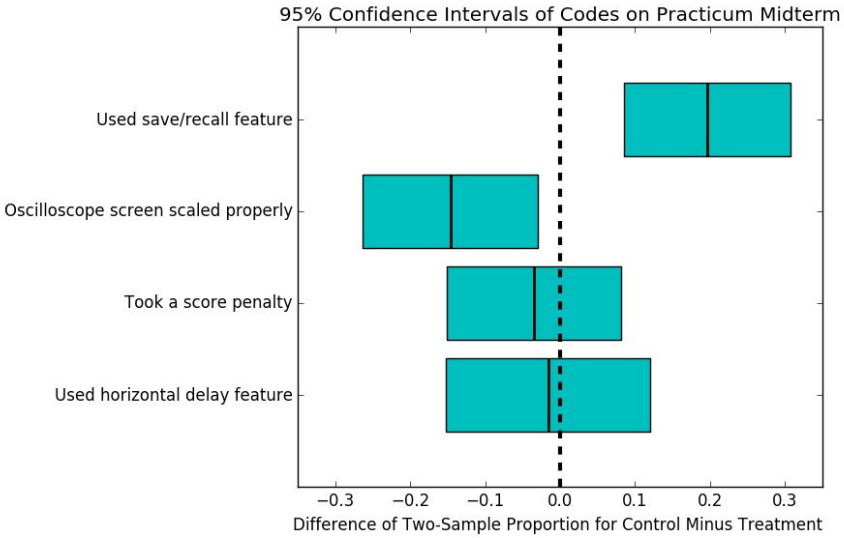


Figure 4: Confidence intervals of the difference of proportions of students receiving specific codes on practicum midterm.

Significantly more control students used the save/recall feature than treatment students, but significantly more treatment students scaled their oscilloscope trace properly. There was no significant difference between the populations in terms of the numbers of penalties taken or in the use of the horizontal delay.

The difference between the two groups suggests that increasing the openness of inquiry does not always increase the reflection necessary for entering experiential learning cycles. This study did not directly measure student reflection, so it is difficult to assess whether changing the laboratory instructions caused students to spend more time in reflection. However, one explanation for the difference in performance is that the exercise pictured in Figure 1 spurred more reflection in the treatment group on how to scale the oscilloscope, but the specific instructions about the save menu caused the control group to reflect more deeply on saving their figures.

3.4 Open Response Question Coding

Student answers from the treatment weeks were coded on features like “Positive Sentiment Towards Oscilloscopes” and “Wants Improved Understanding of Lab Equipment.” The codes were determined by starting with a base set of likely codes -- e.g.: positive and negative sentiment towards oscilloscopes -- coding the data, removing underused codes and then adding codes to capture significant uncoded features of the comments. Two raters coded the data independently and had an inter-rater reliability of 77%. The raters discussed with each other to resolve disagreements in their codes, and their resolved coding was used as the final data set.

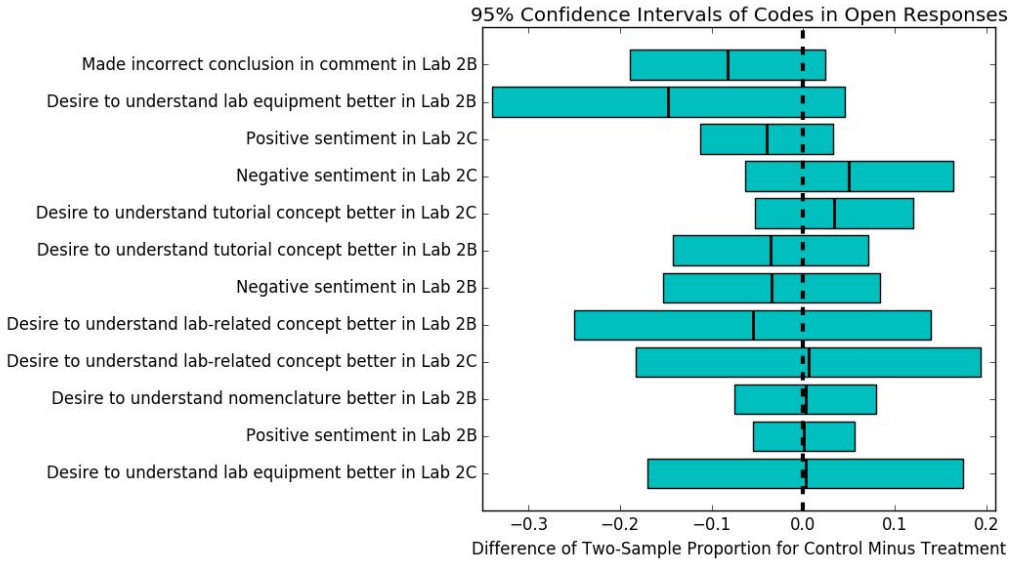


Figure 5: Confidence intervals for difference in proportion of comments receiving listed codes between control and treatment groups.

The number of observations in the control and treatment data sets for these comments is smaller than the number of observations for the practicum midterm: students work on practicum in pairs, so only one end-of-practicum worksheet is submitted for each pair of students.

These codes were converted to proportions and the 95% confidence interval of the difference between the control and treatment proportions was calculated. The confidence intervals are displayed in Figure 5.

None of the codes are significantly different at 95% confidence. However, two codes are significantly different in favor of the treatment at a 93% confidence level: in the lab 2B survey control students were more likely to make incorrect statements about the oscilloscope and more likely to ask about lab equipment instead of bigger picture concepts.

The 93% confidence bounds of these codes suggest, less confidently than the midterm data, that students' understanding of how and why oscilloscopes are used is affected by the treatment. Treatment students had fewer misconceptions about how oscilloscopes worked and they were more confident in their understanding of the oscilloscope. This suggests a stronger understanding of oscilloscope fundamentals than the control group and a greater confidence using the tool, which is consistent with moving further around an experiential learning cycle.

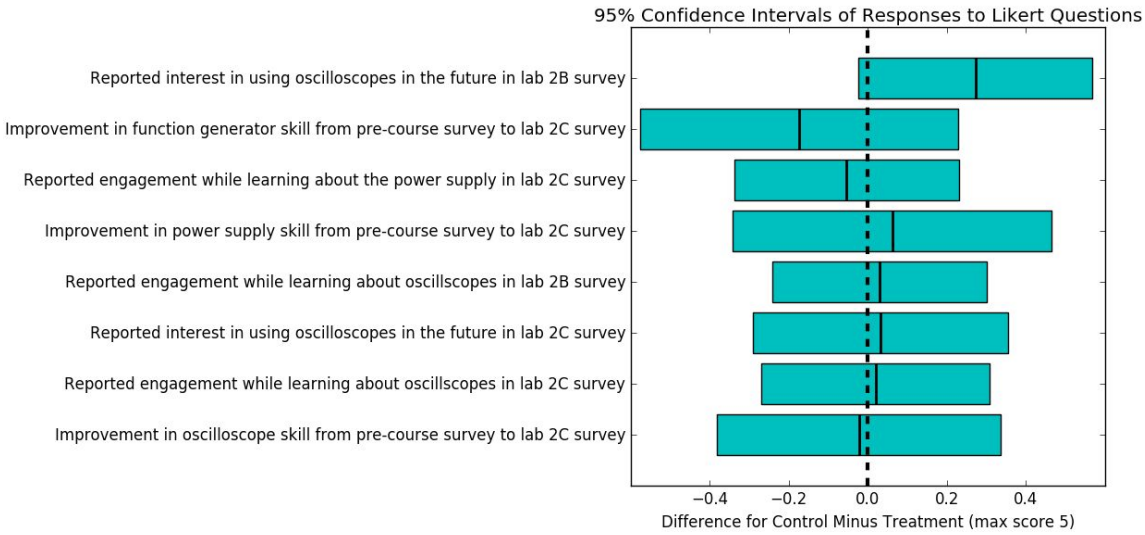


Figure 6: Confidence intervals of difference in responses to Likert scale survey questions between control and treatment groups.

3.5 Survey Responses

The difference between the control and treatment responses to the Likert questions shown in Table 1 were analyzed by calculating 95% confidence intervals of the difference. The confidence intervals are shown in Figure 6. The analysis revealed no significant difference between groups at the 95% confidence interval. The control group reported greater interest in using oscilloscopes in the future at the, rather weak, 91% confidence level.

3.6 Length of Manuals and Instructor Effort

As a final aside: it is worth noting that the treatment manual had a much lower word count than the control manual, but that it resulted in similar learning. It may be possible to reduce the amount of time instructors spend writing laboratory exercises by optimizing levels of inquiry.

4 Conclusion

In summary: the control lab manuals helped students acquire one specific skill more effectively while treatment lab manuals helped students learn a different one. Control students saved data more often while treatment students scaled their data correctly more often. The differences between the control and treatment open response questions also hinted, at a lower confidence level, that the treatment lab improved students' understanding of and confidence with the oscilloscope. Students using the control manual completed the laboratory exercises in the same amount of time as students using the treatment manual.

These individual results do not provide conclusive advice about the best way to write labs, but they do strongly suggest that the way that labs manuals are presented affects learning. Understanding what levels of inquiry are appropriate for different laboratory exercises could result in significant learning benefits. The lens of maximizing reflection in a laboratory exercise to usher students around Kolb's learning cycle seems useful, but the ways to maximize reflection are still unclear.

There is work to be done extending this work to other populations. The experiment should be replicated at other institutions, and it is worth noting that the web-based lab materials can help with the replication process.

A final extension of this work is examining whether the treatment and control conditions also affect student learning of classroom concepts. This study did not control the tutorial instruction that students received, so different tutorial instructors could have affected the exchange of knowledge between the classroom and laboratory. However, the techniques used in this study could be used to prompt reflection on in-class concepts that appear in a lab. This could be a great opportunity to improve student learning.

Acknowledgements

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