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Design of an Inquiry-Based Independent Experiment in a Heat Transfer Laboratory

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Abstract

Studies of various educational strategies aimed at improving student performance focus heavily on self-efficacy, with surveys using validated scales developed to measure students' confidence in their own skills and ability to perform tasks. Inquiry-based learning (IBL) is identified by some of the sources as a key approach to increasing student engagement and teamwork, especially in laboratory courses and activities requiring creative thinking, such as engineering design. Some studies highlight benefits of hands-on experience and engagement with real-world problems. Overall, IBL has shown enhancement of multiple skills, such as teamwork, problem solving, communication, and technical understanding.

In this work we present the development of an inquiry-based laboratory exercise for a required junior-level heat transfer laboratory in the Mechanical Engineering curriculum at a large midwestern university. This is a course where Design of Experiment is well-scaffolded through guided practice of DoE in a prerequisite fluid dynamics laboratory course, as well as three guided laboratory exercises in the Heat Transfer lab, followed by a novel four-week exercise where students design and conduct their own experiment. This pedagogy was created as a response to ABET Student Outcome 6: "An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions."

The laboratory course opens with a week of intensive instruction in Measurement Uncertainty Quantification (MUQ), which introduces many important aspects of designing an experiment. MUQ is taught using five online mini-lectures and quizzes and one in-lab group worksheet. The course then features three two-week long guided exercises in Thermal Measurement Techniques, Free and Forced Convection, and Heat Exchanger performance, which include pre-lab and post-lab worksheets designed to challenge the students to think about the DoE of the lab experiments. Following these exercises, the students work in teams to propose a heat transfer experiment of their own design, including a hypothesis to test, equipment to use, and data that they propose to collect. Graduate Teaching Assistants (TAs) and the laboratory manager review the proposals and either approve them or require further development. Once their proposal is approved, students use the remaining weeks to complete their study and write a full technical report, which they submit using an assigned pseudonym. The project finishes with each student conducting a single-blind Peer Review of a student's work from another lab section. Grading is based on the TA's assessment of the report and the Peer Evaluation.

Pre- and post-surveys of the students measure their self-efficacy, among other aspects of their experience with the course, to evaluate the effectiveness of this pedagogy. The pre-survey is conducted the week before the independent exercise begins and the post-survey is conducted after the Peer Review.

Literature review

Inquiry-based learning (IBL) is identified by some of the sources as a key approach to increasing student engagement and teamwork, especially in laboratory courses and activities requiring creative thinking, such as engineering design [1], [2], [3]. Some studies highlight the benefits of hands-on experience and engagement with real-world problems [4], [5]. Some of the studies also highlight the impact of different approaches to teaching a course, such as comparison of IBL implementation to a traditional teaching style, and comparison of setting different goals, such as mastery and performance [3], [4], [6]. It is suggested that IBL in laboratory courses can narrow the knowledge and skill gaps between students, and that differentiated instruction should better accommodate student needs [1]. IBL can also help increase student engagement in class activities, and students show a positive response to this approach [2]. Additionally, the IBL approach can be applied in STEM courses to enhance students' preparation for future educational challenges, tailored to their individual intellectual talent [3].

Self-efficacy is a description of how a person perceives their own ability to prepare for and perform courses of action to accomplish desired outcomes. Bandura [7] states that "Perceived self-efficacy refers to beliefs in one's capabilities to organize and execute the courses of action required to produce given attainments." He highlights the importance of self-efficacy and analyzes its' overall effects on individuals' performance, showing that increased self-efficacy can lead to an improvement of performance in various tasks. Self-efficacy plays a key role in an individual's learning and motivation, as noted by [8]. They also show that learners' self-efficacy is influenced by their previous experience with the material, and that self-efficacy beliefs play a more significant role in prediction of one's behavior than outcome expectations.

Many studies have sought to assess various educational strategies aimed at improving student performance by measuring self-efficacy. Validated self-efficacy surveys have been developed to measure students' confidence in their own skills and abilities to perform tasks [1], [6], [9], [10]. In one such study, General Self-Efficacy was found to be a significant factor in predicting academic performance [9]. Developing such scales can be a useful tool for assessing and improving laboratory education [10]. One such study focused specifically on applying a design-focused and project-based approach to an engineering course has shown a positive impact on student retention and success, as well as an improvement of students' confidence in engineering design and tinkering skills [4]. Studies also show that mastery-based goals have positive effects in the long-term, as students' interest in the subject is often increased when using this approach [6], and that use of IBL helps improve educational outcomes in engineering laboratories [5]. Overall, IBL has shown enhancement of multiple skills, such as teamwork, problem solving, communication, and technical understanding. Using IBL approach along with setting mastery-based goals can help students enhance multiple skills, as well as increase their interest in the field, and development of self-efficacy scales is an important tool used in analysis of this approach [1], [2], [6].

This paper seeks to assess the effects of the addition of an inquiry-based exercise in a heat transfer laboratory course upon student motivation to learn, experimental skills self-efficacy, and their conceptual understanding. Additionally, an assessment is made of the student perception of the course resources and the contribution to learning that the inquiry-based exercise provided.

Course structure

The ME 320: Heat Transfer course is a required four credit hour introductory heat transfer lecture with a laboratory taken by junior and senior students in the Mechanical Engineering major at the University of Illinois Urbana-Champaign. The lecture portion of the course meets three times per week for a total of 2.5 weekly contact hours, taught by a professor who typically assesses student performance based on a combination of homework and exam performance. Most semesters feature two different lecture sections, each taught by a different professor, and enrollment is usually between 50 and 75 students per section. The prerequisite course, ME 310: Fluid Dynamics, is an introductory fluid dynamics course that is also a four-credit hour lecture with a laboratory.

The heat transfer laboratory meets once weekly for 1.8 contact hours, led by a Graduate Teaching Assistant (TA). Lab sessions typically have eight students enrolled, who may work in teams of four. Each semester has historically consisted of six lab exercises, each lasting two weeks, with students required to complete set experiments and then write a technical report about the experiment. The laboratory operates independently of the lecture, so the six lab exercises are not scheduled to coincide with the content presented in the lecture portion of the course. The laboratory portion of the course is worth 25% of the course grade. All of the relevant background and theory is included in each laboratory manual, as well as requirements for the lab reports. Laboratory TAs are trained weekly by the laboratory manager about how to conduct each experiment, and they grade the lab reports based on a standard rubric for each exercise.

For many years prior to 2022, the typical semester schedule consisted of the following lab exercises shown in Table 1. Each lab exercise required two weeks to complete, after which the students were given one week to complete their technical report on the exercise. The reports were all completed individually, with the exception of the Lab 6 report, for which students prepared a group report.

During the 2012 academic year, the ABET self-assessment indicated that students in the curriculum were not satisfactorily learning Design of Experiment (DoE) in the laboratory of either this course or the prerequisite fluid dynamics course. Laboratory procedures were typically given to the students in a recipe format as part of their laboratory manual. Subsequently, a new pedagogy was introduced whereby the experimental procedures were removed from each laboratory manual, and students were required to prepare their own DoE for each exercise. In each lab section, the TA would review the theory to be tested in each exercise and the students would assess the capabilities of the given equipment and then work together for about 30 minutes to prepare their own DoE with experimental procedures to use. Students were required to identify the independent, dependent, and control variables and then write out a series of steps to follow to gather their data. After that time, the TAs would review their DoE to verify that the procedures were safe to use with the equipment, correcting them as necessary before allowing them to proceed with the hands-on exercises. The same approach was also adopted in the prerequisite course, whereby procedures were removed from the manuals and students were asked to prepare their own DoE.

Table 1. The semester lab schedule that was used prior to 2022

Weeks	Lab activity	Due
1–2	No lab	None
3–4	Lab 1: Temperature Measurement Investigation, using Hampden Engineering equipment	None
5–6	Lab 2: Cartesian and radial conduction investigation, using equipment from Armfield Engineering	Lab 1 report
7–8	Lab 3: Combined modes of heat transfer investigation, using equipment from Armfield Engineering	Lab 2 report
9–10	Lab 4: Free and forced convection heat transfer investigation, using equipment developed in-house	Lab 3 report
11–12	Lab 5: Heat exchanger investigation, using equipment from Hampden Engineering	Lab 4 report
13–14	Lab 6: Various group design projects over the years, including a paper-only heat exchanger optimization problem, and a forced convection energy dissipation competition, using nichrome wire and an air duct developed in-house	Lab 5 report
15	No lab	Lab 6 report (group)

In subsequent ABET assessments since 2012, this pedagogy led to satisfactory outcomes with respect to the ability of the students to design and conduct experiments, namely ABET Student Outcome 6 (SO6), which states "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions" [11]. However, it seemed redundant for both the fluid dynamics course and heat transfer course to use the same approach toward DoE. Since both courses were showing satisfactory outcomes for SO6, the opportunity presented itself to take their DoE experience further by giving the students even greater independence at designing and conducting an experiment.

New laboratory course structure featuring Independent Laboratory Exercise

Starting in the Fall of 2022, to give students a better opportunity to develop their DoE abilities, the laboratory portion of the course final five weeks of the semester were replaced by a single Independent Laboratory Exercise (ILE), whereby students were challenged to design and conduct their own experiments using equipment and measurement devices found in the laboratory facility. The students would first have to propose their experiment to their lab TA in the form of a document where they describe the experiment that they plan to conduct, identifying equipment to use, a hypothesis or theory to test, independent, dependent, and control variables, and proposed experimental procedures. Some budget was approved by the department for students to make small purchases for the course, if the lab manager found them to be reasonable, and students were allowed to use the department machine shop and 3D printing facilities to help them manufacture equipment as needed for their investigation. Common purchase requests include off-the-shelf heat sinks, cartridge heaters, heating pads, thermal pastes, and samples of materials to use in their investigations, such as cubes, cylinders, and spheres made of metals, plastics, and ceramics.

Table 2. The new laboratory schedule, with MUQ and Independent Laboratory Exercise

Week	Lab activity	Due
1	No lab	None
2	Online MUQ modules	Online MUQ modules
3	MUQ in-lab group worksheet	None
4	Lab 1: Temperature Measurement Investigation – Week 1	MUQ group worksheet, Pre-lab 1 worksheet
5	Lab 1: Temperature Measurement Investigation – Week 2	Post-lab 1 worksheet
6	Lab 2: Free and forced convection investigation – Week 1 (previously Lab 4)	Lab 1 report, Pre-lab 2 worksheet
7	Lab 2: Free and forced convection investigation – Week 2 (previously Lab 4)	Post-lab 2 worksheet
8	Lab 3: Heat exchanger investigation – Week 1 (previously Lab 5)	Lab 2 report, Pre-lab 3 worksheet
9	Lab 3: Heat exchanger investigation – Week 2 (previously Lab 5)	Post-lab 3 worksheet
10	Independent Laboratory Exercise – Week 1	Lab 3 report
11	Independent Laboratory Exercise – Week 2	Proposal
12	Independent Laboratory Exercise – Week 3	Proposal (if still needed)
13	Independent Laboratory Exercise – Week 4	Proposal (if still needed)
14	Overflow week (if needed)	Anonymized technical report (due 11:59 pm Friday for all)
15	No lab	Peer reviews

To prepare the students for this project, the semester schedule was modified to include new content related to Measurement Uncertainty Quantification (MUQ). The new semester schedule is shown in Table 2. The semester began with one week of students working through online modules about the statistics of the normal distribution for large and small sample records, bias and precision uncertainty, and the propagation of measurement uncertainty through calculated quantities. The MUQ content closely followed the framework presented by Coleman and Steele, [12] and ANSI/ASME PTC 19.1 [13]. Modules included five video presentations of the content, each followed by a Canvas quiz. They then did a one week in-lab group exercise related to estimating uncertainties of real-world experimental data, for which a worksheet was given for them to complete in the lab. They then spent two weeks each on Lab exercises 1, 4, and 5 from the previous schedule before getting started on the independent laboratory exercise for the final four weeks of the semester, with one week remaining for flexibility, in case a large number of students needed extra time to get good data. To supplement their understanding of DoE, students were given pre-lab worksheets that were designed to require critical thinking about why each of those experiments was designed as it was. Students completed these pre-lab worksheets during the first week of each of those three lab exercises. After completing their lab exercises in the second week of the lab, students were given a post-lab worksheet where they were required to reflect on their impact of measurement uncertainty on their lab results. Finally, students were required to submit their technical report one week after each of the labs, with the exception of the report for the ILE, which was due at the 11:59 pm on the Friday of Week 14 for all students. This deadline was set so that students could all have equal time to complete the peer review of an anonymous colleague's ILE Report.

Due to the protracted nature of the independent exercise project, all students were required to submit their report to learning management system (Canvas) of the course by 11:59 pm local time on Friday of Week 14 of the semester, regardless of the day and time of their lab section. Students were not allowed to include any indication of their identity, their lab mates' identities, and their TA's identity in their technical report for the independent exercise. They were each given a specific pseudonym to use on their lab report, which was assigned based on their university ID number. Finally, after turning in the technical report for their independent laboratory investigation using their pseudonym, the students were required to complete a single-blind peer evaluation of a student assigned to them from another TA's lab section. The built-in peer review tool in Canvas was used for matching each student to their assigned report for review. Students were given basic guidelines for completion of a satisfactory peer review.

Grading of the reports was based on a hierarchical checklist inspired by the Specifications Grading system, whereby certain satisfactory elements were all required for them to earn a D, C, B, or A on their report, including all lower-grade checklist items [14]. To earn a C, for example, a report had to satisfactorily achieve all items for both a D and a C, and so on for a student to earn an even higher grade. The ILE lab manual and grading checklists are given in Appendix A.

Assessment of effectiveness of ILE

This study seeks to assess how the introduction of the inquiry-based ILE affects the students' self-efficacy, motivation, and self-assessment of their conceptual understandings. The students were surveyed on items related to these categories using survey items drawn from validated surveys. The pre-exercise survey consisted of 24 Likert questions in three categories: Motivation (items 1–13), Experimental Skills Self-Efficacy (items 14–18), and Conceptual Understanding (items 19–24). All of these items were drawn from validated surveys [1], [6], [9], [10], respectively. Items that were asked only in the post-survey come from source [15] and are not validated. They relate to the usefulness of the resources provided, the contribution to learning, and the free-response items. The post-exercise survey consisted of 37 Likert questions in five categories, with first three being the same as pre-exercise survey, and two additional ones: Usefulness of Resources Provided (items 25–30) and Contribution to Learning (items 31–37), as well as four open-ended questions (items 38–41). The first 24 items were the same as in the pre-survey. The next thirteen items were related to the usefulness of the laboratory resources provided and how they felt that the Independent Laboratory Exercise contributed to their learning. To gain more detailed information about the students' perception of the Independent Lab Exercise, the post-survey was followed by four open-ended free response questions. The survey items and open-ended questions are all given in Appendix B. This study was approved by the Institutional Review Board as an exempt study due to minimal risk to the research participants, who consented to participate upon completion of each of the surveys. Grades were not associated with their participation, and all student data was anonymized and analyzed after the course grades were recorded.

Student participation

The study was conducted during the Fall 2024 semester, when approximately 150 students were enrolled in the course. During Week 10, before the students were allowed to begin work on their Independent Lab Exercise, they were given the pre-exercise survey. No overflow week was needed during the Fall 2024 semester. The students were given the post-exercise survey in Week 15 after the deadline for submitting their Peer Evaluations had passed.

Responses from 133 students were received during the pre-exercise survey. Out of those 133 students, 67 also responded to the post-exercise survey. There were three students who only responded to the post-exercise survey. For this paper, only responses from the $n = 67$ students who participated in both surveys are included in the presentation of quantitative data. During analysis of free-response questions, which were only included in the post-exercise survey, responses from three students who did not participate in the pre-exercise survey were also included.

Results and Discussion

Wilcoxon Signed-Rank tests were performed on the pre- and post-survey results to assess any significant effects of the ILE. These results are summarized for the Motivation, Experimental Skills Self-Efficacy, and Conceptual Understanding survey questions in Tables 3–5, respectively. Items for which the results are statistically significant ($p < 0.05$) are shown in boldface. Histograms of all of the survey items are included in Appendix C, but select figures are presented in the next five subsections, based on their statistical significance. In these histograms, series shown in blue (left bars) represent responses received during the pre-exercise survey, while series shown in orange (right bars) represent responses from the post-exercise survey. Some student quotes from the free-response survey items are also included to give some individual thoughts about various aspects of the ILE, where they seem relevant to the Likert-survey prompts presented in Figures 1–13.

Motivation

Wilcoxon Signed-Rank tests were performed on the pre- and post-survey data using SPSS. Table 3 shows the results for the Motivation section of the survey. Survey Items 1–13 comprise the Motivation group. Items 1 ($p < 0.012$), 9 ($p < 0.007$), and 11 ($p < 0.015$) are shown to be statistically significant based on the negative ranks. For example, Figure 1 shows the survey distributions for the Item 1 prompt “In a laboratory course like this, I prefer to do lab exercises that challenge me to explore my curiosities about heat transfer.” Students generally agreed with the statement before doing the ILE, but the trend shifts from Neutral, where a decrease from 14% to 7% is observed, to Strongly Agree after completion of the ILE (9% to 18%). Very few students disagreed with the statement either pre- or post-ILE.

Table 3. Summary of Wilcoxon Sign-Rank tests for the Motivation items in the pre- and post-surveys. Boldfaced survey items are statistically significant.

Pre-/Post-Survey Statement	*Z*	*p*
In a laboratory course like this, I prefer to do lab exercises that challenge me to explore my curiosities about heat transfer.	**-2.504[b]**	**0.012**
The most important thing for me in this lab is trying to understand the content as thoroughly as possible.	-.008[c]	0.994
Understanding heat transfer is important to me.	-.058[b]	0.954
I like it best when something I learn makes me want to find out more.	-1.703[b]	0.088
It is important for me to do well compared to others in this class.	-.970[c]	0.332
I want to do well in this class to show my ability to my family, friends, advisors, or others.	-.738[b]	0.460
Getting a good grade in this class is the most important thing for me right now.	-.177[b]	0.860
I think what we are learning in this class is interesting.	-.780[b]	0.436
I would recommend this class to others.	**-2.690[b]**	**0.007**
If this course was not a required course, I would still choose to take it.	-.534[c]	0.593
I think the material in this lab is useful for me to learn.	**-2.435[b]**	**0.015**
I would like to take more heat transfer classes after this one.	-.393[b]	0.694
I am more interested in doing experimental work because of my experience in this laboratory course.	-.378[b]	0.706

b. Based on negative ranks

c. Based on positive ranks.

Figure 2 shows results for the Item 9 prompt "I would recommend this class to others," and most of the movement is away from Disagree (pre- to post- decrease of 5%) toward Strongly Agree (pre- to post- increase of 7%), with other responses showing comparatively small change.

Figure 3 shows the results for the Item 11 prompt "I think the material in this lab is useful for me to learn." A shift toward Strongly Agree can be seen, with a 50% increase in Strongly Agree responses can be seen, as well as a slight increase in Agree responses.

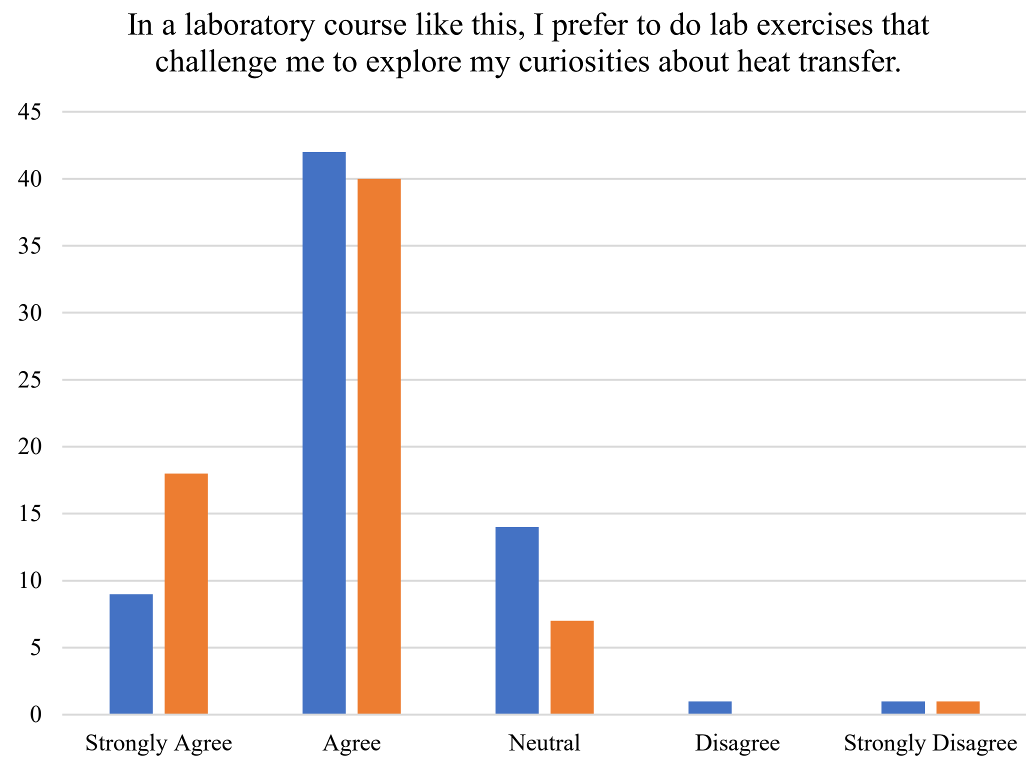

Figure 1. Response distribution for Item 1 (Motivation group). Pre-survey data is represented in blue and post-survey data is represented in orange.

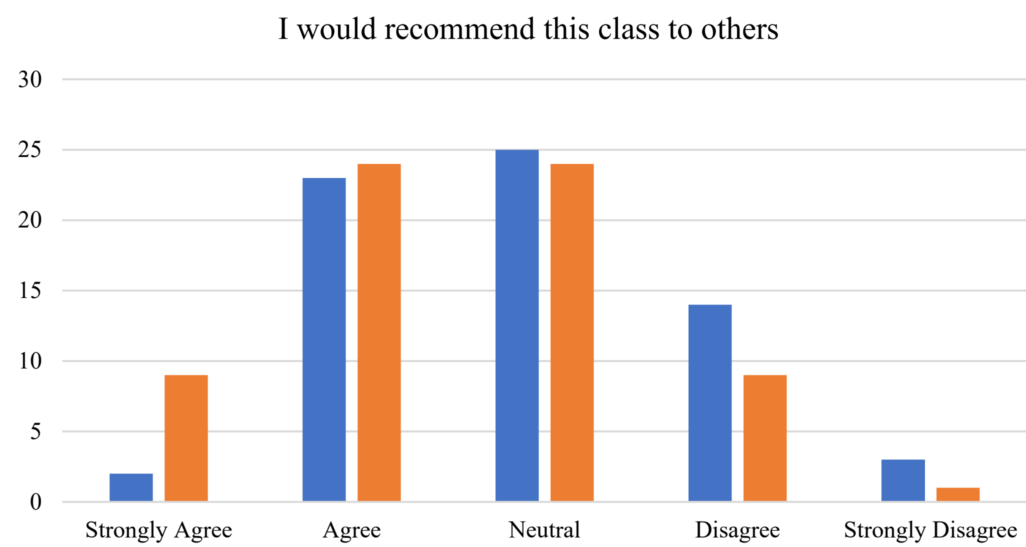

Figure 2. Response distribution for Item 9. Pre-survey data is represented in blue and post-survey data is represented in orange.

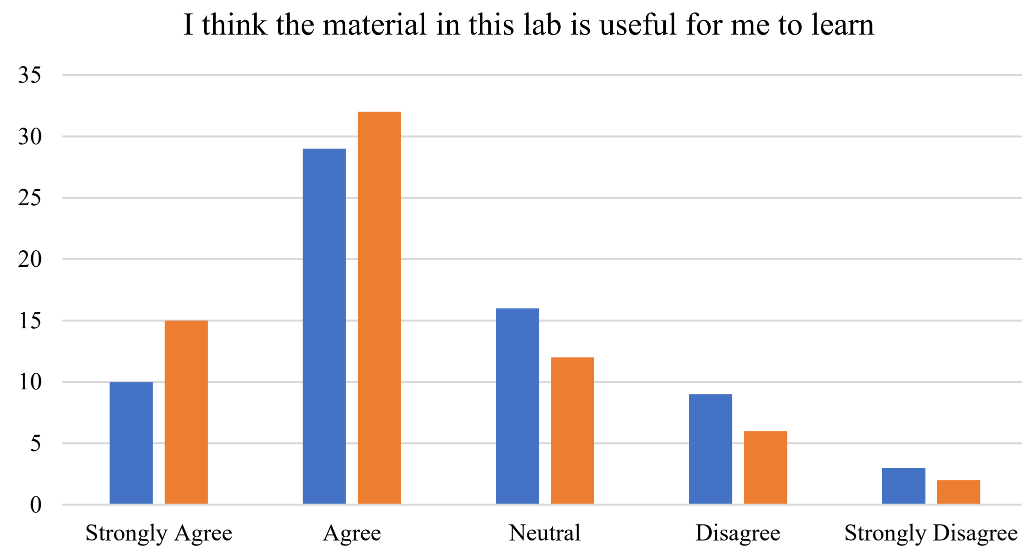

Figure 3. Response distribution for Item 11. Pre-survey data is represented in blue and post-survey data is represented in orange.

Experimental Skills Self-Efficacy

Table 4 shows the Wilcoxon Signed-Rank test results for the Experimental Skills Self-Efficacy section of the survey. Survey Items 14–18 comprise this group. Items 14–17 are shown to be statistically significant based on the negative ranks.

Figure 4 shows the response distribution for Item 14 with the prompt “I can design experiments independently.” The results shifted sharply towards Strongly Agree (pre- to post- change from 7% to 24%), along with a slight increase in Agree, and a significant decrease in Neutral (21% down to 8%) and Disagree (6% to 1%) responses.

Figure 5 shows the response distribution for the Item 15 prompt “I can perform experiments independently.” This item also reveals a trend moving towards Strongly Agree in the post-exercise survey (from 15% to 34%), as well as a small increase in Neutral responses. Very few students disagree with the statement before or after the ILE, so much of the movement comes from the Agree responses (decrease from 46% to 24%).

Figure 6 shows the response distribution for the Item 16 prompt “I can analyze data resulting from experiments.” Most of the movement is away from Agree (35% to 30%) and Neutral (8% to 4%), with no Disagree or Strongly Disagree responses in the post-exercise survey. Most of the movement is reflected in an increase from 23% to 32% at the Strongly Agree level.

Table 4. Summary of Wilcoxon Sign-Rank tests for the Experimental Skills Self-Efficacy items in the pre- and post-surveys. Boldfaced survey items are statistically significant.

Pre-/Post-Survey Statement	*Z*	*p*
I can design experiments independently.	**-4.841[b]**	**0.0000013**
I can perform experiments independently.	**-2.291[b]**	**0.022**
I can analyze data resulting from experiments.	**-2.233[b]**	**0.026**
I effectively present my experimental procedures, results, and conclusions through writing.	**-3.453[b]**	**0.00055**
I work well in teams of people with a variety of skills and backgrounds.	-1.054[b]	0.292

b. Based on negative ranks

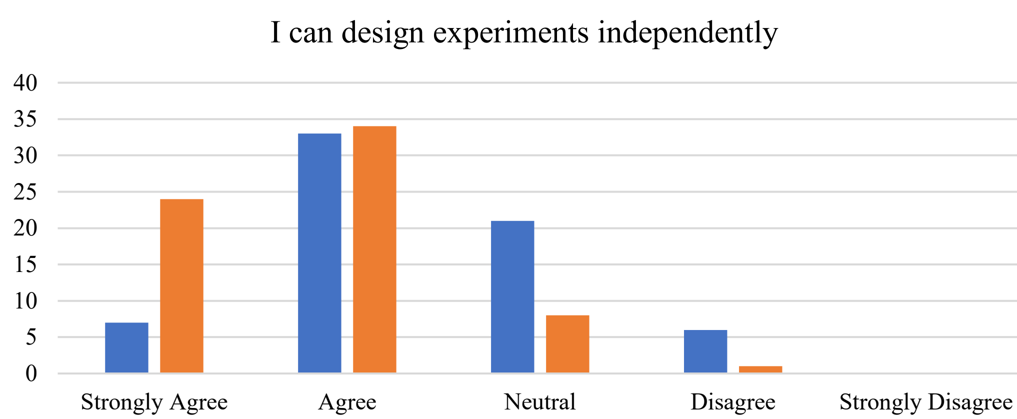

Figure 4. Response distribution for Item 14. Pre-survey data is represented in blue and post-survey data is represented in orange.

Figure 7 shows the response distribution for the Item 17 prompt "I effectively present my experimental procedures, results, and conclusions through writing." Changes from pre- to post- mostly shift from Agree responses (decreasing from 41% to 23%) towards Strongly Agree (increasing from 19% to 39%). No Disagree or Strongly Disagree responses were recorded in either the pre- or post-exercise surveys.

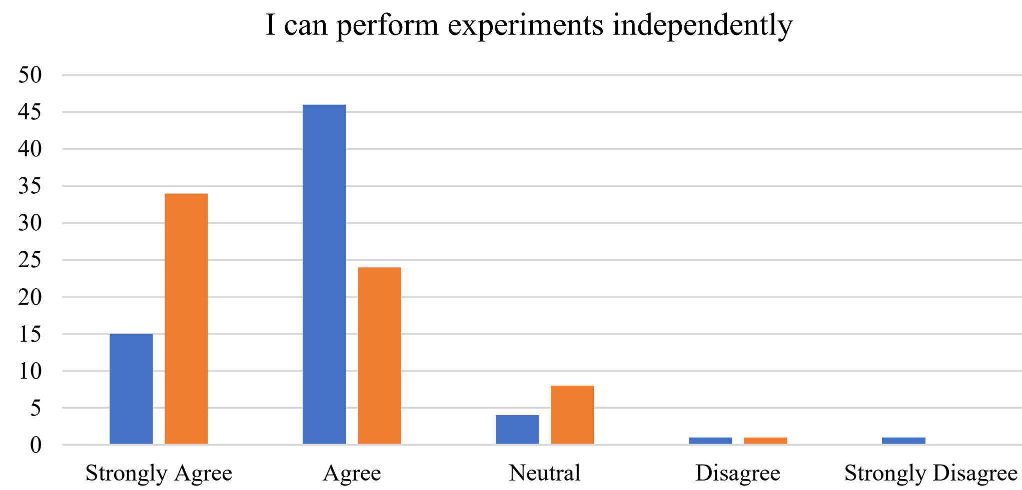

Figure 5. Response distribution for Item 15. Pre-survey data is represented in blue and post-survey data is represented in orange.

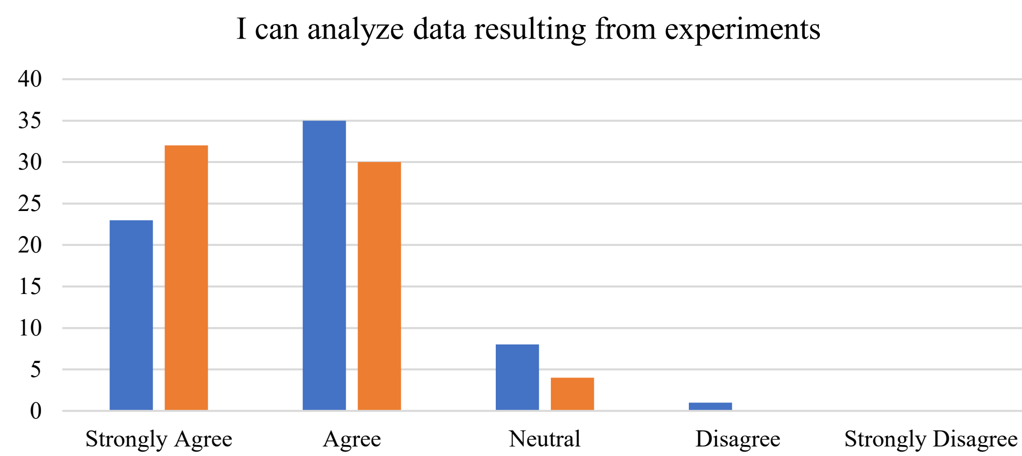

Figure 6. Response distribution for Item 16. Pre-survey data is represented in blue and post-survey data is represented in orange.

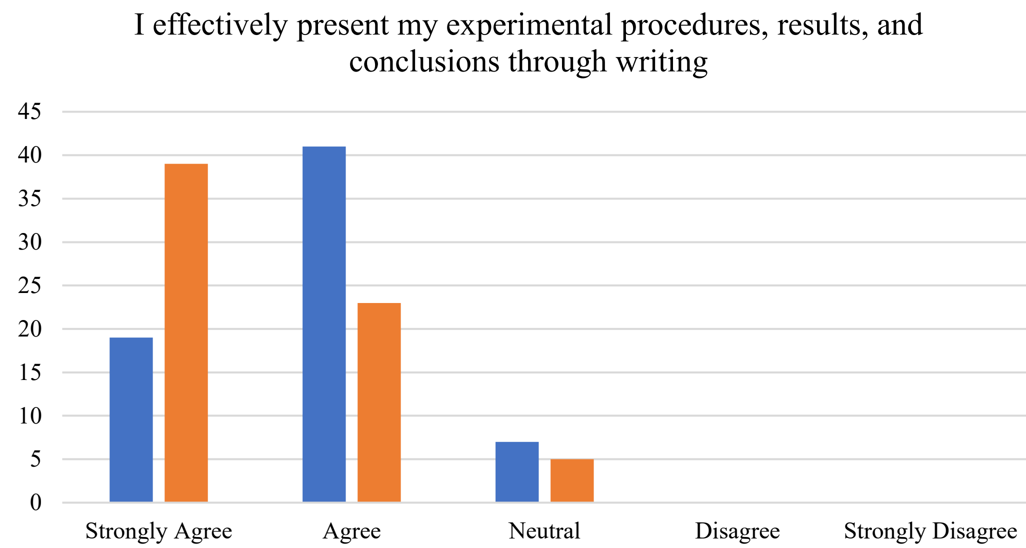

Figure 7. Response distribution for Item 17. Pre-survey data is represented in blue and post-survey data is represented in orange.

Conceptual Understanding

Survey Items 19–24 comprise the Conceptual Understanding group. Table 5 shows the Wilcoxon Signed-Rank test results for this section of the survey. All of these items are shown to be statistically significant based on the negative ranks. Overall, an improvement in conceptual understanding is observed from the survey results. One of the students specifically mentions that the Independent Lab Exercise made them explore the theoretical concepts further: "I enjoyed the process of coming up with your own investigation topic and defining how it would be performed, as typically we are just given an investigation and told to carry it out. This made me think deeper about what was needed for data collection, what were valid research questions, and how to formulate a valid hypothesis."

In Figure 8 shows the response distribution for the prompt "Scientific concepts become clearer to me as I perform an experiment." A near doubling of the Strongly Agree level can be seen, with a decrease in all other responses. No students recorded in the Strongly Disagree bin for either the pre- or post-survey.

Figure 9 shows the response distribution for the prompt "I am confident that I understand the underlying hear transfer phenomena in the experiment." A shift towards the Strongly Agree side can be seen, with a significant decrease in Neutral and Disagree responses.

Table 5. Summary of Wilcoxon Sign-Rank tests for the Conceptual Understanding items in the pre- and post-surveys. Boldfaced survey items are statistically significant.

Pre-/Post-Survey Statement	*Z*	*p*
I usually have a sound grasp of the theory behind laboratory experiments before performing experiments.	**-2.724[b]**	**0.006**
Scientific concepts become clearer to me as I perform an experiment.	**-2.677[b]**	**0.007**
I am confident that I understand the underlying heat transfer phenomena in the experiment.	**-2.235[b]**	**0.025**
After an experiment, I have no difficulty figuring out how my calculation procedures and measurement uncertainty affected my results.	**-3.200[b]**	**0.001**
When presented with laboratory results, I know how to interpret them and draw relevant conclusions from them.	**-2.297[b]**	**0.022**

b. Based on negative ranks

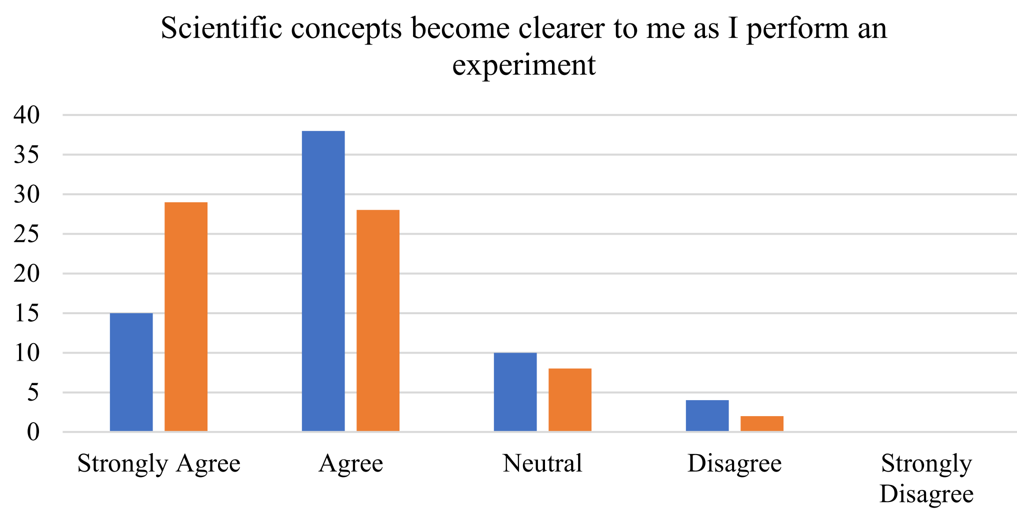

Figure 8. Response distribution for Item 20. Pre-survey data is represented in blue and post-survey data is represented in orange.

Figure 10 shows the results for the prompt "After an experiment, I have no difficulty figuring out how my calculation procedures and measurement uncertainty affected my results," and it can be observed that not all the responses show positive movement, with the exact same number of Strongly Disagree responses in both pre- and post- exercise surveys. However, there is still a very strong movement towards Agree, with a more than 100% increase, as well as a significant increase in Strongly Agree responses.

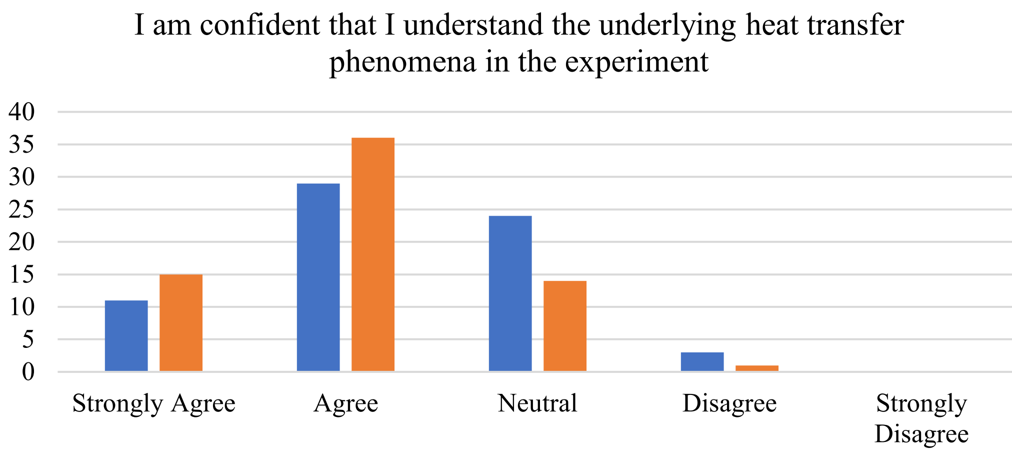

Figure 9. Response distribution for Item 21. Pre-survey data is represented in blue and post-survey data is represented in orange.

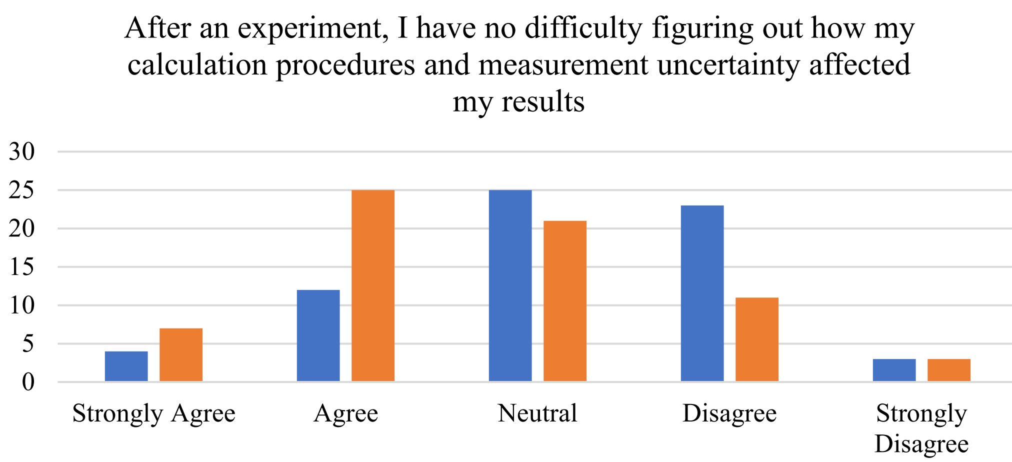

Figure 10. Response distribution for Item 22. Pre-survey data is represented in blue and post-survey data is represented in orange.

In Figure 11, survey results for the prompt “When presented with laboratory results, I know how to interpret them and draw relevant conclusions from them” are shown. There is a small decrease in Neutral responses, but a significant increase in Strongly Agree responses, as well as a significant decrease in Disagree responses.

Figure 12 shows the responses for the prompt “I think through the details of a hypothesis and carry it out to solve a science problem.” A significant increase in Strongly Agree responses is observed. No Disagree responses were recorded in the post-exercise survey.

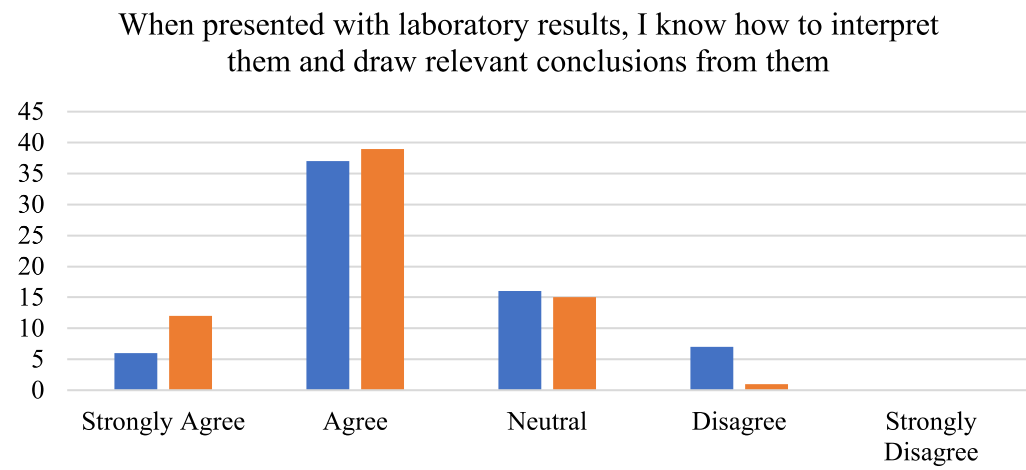

Figure 11. Response distribution for Item 23. Pre-survey data is represented in blue and post-survey data is represented in orange.

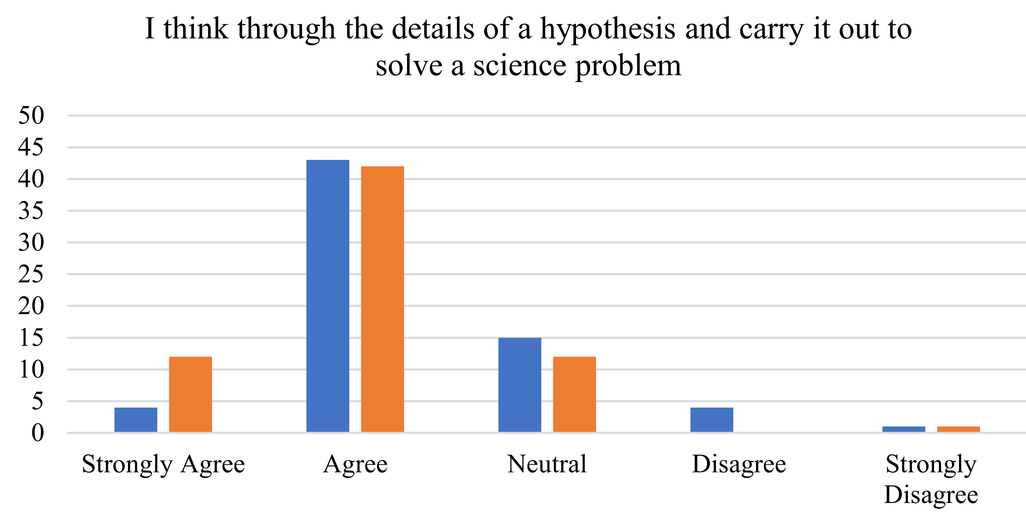

Figure 12. Response distribution for Item 24. Pre-survey data is represented in blue and post-survey data is represented in orange.

Usefulness of Resources Provided

The survey results for items 25–30 are shown in Figure 13. These items were only presented to the students in the post-ILE survey. Items in this section have identified some issues that students have encountered, such as accessing the equipment they hoped to use. In the open-ended questions, many students also mentioned issues with the equipment: “Often our equipment was completely broken or

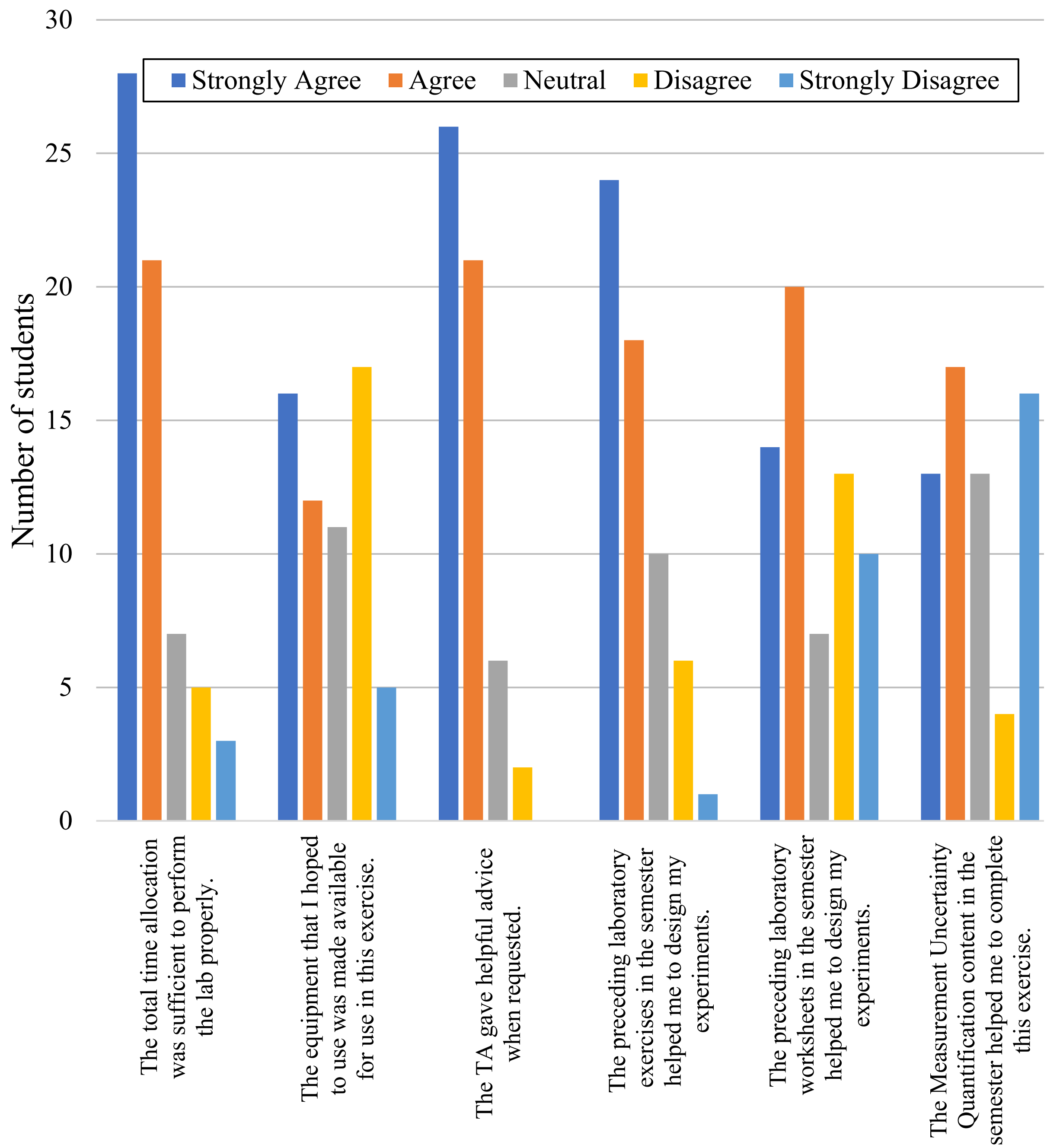

Figure 13. Response distribution for Items 25–30 about the Usefulness of Resources Provided

non-functional for a certain time frame, leading to more hurried experiments or longer waiting periods between experiments." Students had mixed opinions on the Measurement Uncertainty Quantification (MUQ) material, which is supported by the responses received in the open-ended section. One of the students mentions that "uncertainty could be better explained," indicating further interest in the topic and a recognition that they do not yet grasp the concepts well, while another student states that there was no connection between the uncertainty quantification material and the labs themselves. Students also found laboratory exercises more helpful compared to laboratory worksheets, but some students still mention that worksheets were useful in understanding the theoretical concepts.

Contribution to Learning

Figure 14 shows the survey results for items 31–37. These items also were only presented to the students in the post-ILE survey. The results showed that they found the ILE experience to be helpful for learning how to design an experiment. The results show that the students felt that they developed a better understanding of heat transfer over the period of the ILE, though it seems likely that a significant amount of that learning may be associated with the lecture portion of the course. In the free-response portion of the post-survey, one of the students specifically mentions "Learning to design experiments" as one of the most useful or valuable aspects of the lab in the open-ended section, which is particularly interesting given the extensive scaffolding of experimental design that was provided prior to the ILE in both this lab course and the pre-requisite course. Most of the students claimed that they were able to prove their hypothesis correct in the ILE, but there were also many students who claimed that they proved it wrong. The exercise made students more curious about heat transfer, which is mentioned by one of the students: "The independent lab forced us to think about potential concepts that we learnt in class that could be explored using the facilities in the lab. This was rather challenging and we managed to overcome this by discussing potential concepts that would be interesting to explore."

Conclusions

This study has shown some benefits of using the Inquiry-Based Laboratory approach in this laboratory course. These results seem to follow the claim by Harackiewicz [6] that mastery goals are generally focused on learning and developing skills, while performance goals are focused on demonstrating competence. With respect to motivation, students mostly entered the exercise with strong motivation, but the trend in motivation gains strength through the completion of the Independent Laboratory Exercise.

Strong shifts are observed in the Experimental Skills Self-Efficacy of the students, with a large portion of the students developing strong agreements with validated statements in this group of items. Given the claims in the literature of the value of self-efficacy, these results suggest that this independent laboratory exercise is a valuable learning opportunity in the curriculum. It is not clear what aspect or aspects of this exercise contribute most strongly to the increase in self-efficacy, which may warrant further investigation in the future. With respect to Conceptual Understanding, this

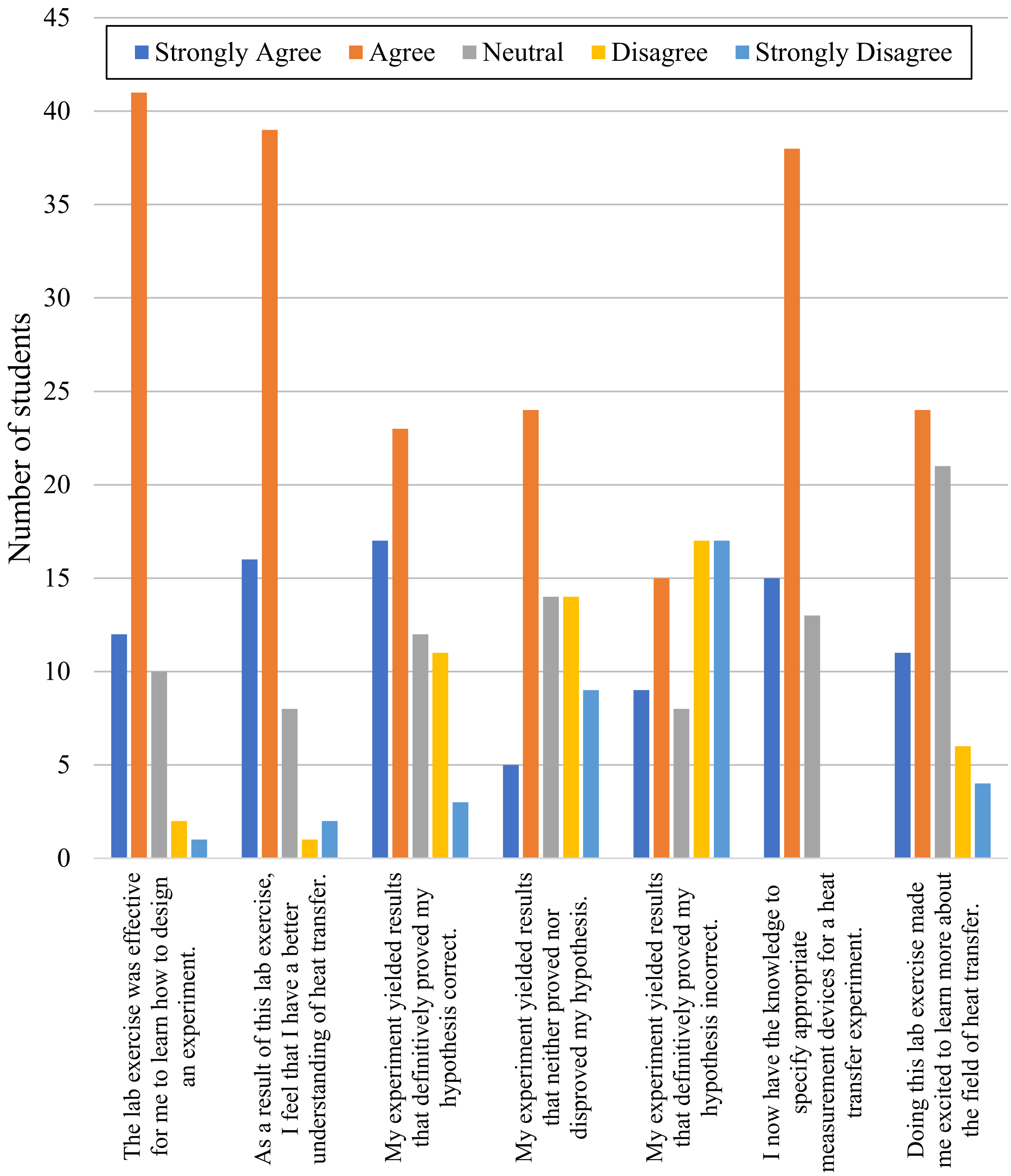

Figure 14. Response distribution for Items 31–37 about the Contribution to Learning

exercise seems to result in some general gains in the scientific concepts associated with the Independent Laboratory Exercise, as well as their confidence in being able to do related calculations and assess measurement uncertainty for the results of their experiments.

Finally, some potential areas for improvement of the lab can also be seen from the study, as some students encountered issues during the exercise, especially with the functionality of their equipment and the timeliness of repairs being made for them to have sufficient opportunity to perform their experiments without feeling terribly rushed. This result indicates that to administer an exercise of this nature requires a robust supply of equipment and a critical need to rapidly address such problems through good maintenance, timely repairs or replacement of equipment, and possession of redundant pieces of equipment.

Acknowledgements

The authors would like to thank the Mechanical Science and Engineering Department at the University of Illinois Urbana-Champaign for their support of this project.

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Appendix A-1: Independent Laboratory Exercise Proposal

In order to begin working on your independent laboratory experiment, you must propose your work to your TA. You may propose this experiment as a group of up to five students. The document should be submitted to Canvas, and you should also submit a hardcopy to your TA in your lab session. The proposal document must contain the following:

1. A statement of the heat transfer phenomenon to be investigated. Some example statements might be "An Investigation of the Thermal Conductivity of Various Materials" or "An Investigation of Combined Effects of Conduction and Convection of a Ceramic Material."
2. A list of what materials you would like to use for your investigation. You are welcome to use any of the equipment kept in the lab, including thermocouples, data acquisition devices, and materials stored in the cabinets. You are also allowed to use materials sourced from the Jackson Innovation Studio, including 3D-printed components. You may be able to request materials and equipment be purchased for your investigation in your proposal, but be aware of the lead times needed to acquire such materials. Some simple machining maybe requested from the MechSE Machine Shop.
3. A hypothesis that includes a mathematical model and/or empirical relation that will be used as the central focus of your investigation. You should cite literature, which may include the course textbook, in your explanation of the mathematical model(s). Based on your proposed equipment usage and mathematical model, classify independent, dependent, and control variables.
4. A list of experimental procedures to follow, including assessment of measurement uncertainty. Describe what experimental procedures you will use to complete your experiment, and how the raw data will be analyzed to test the hypothesis. Plan a way to assess the uncertainty of the measurements, such as comparing multiple measurement techniques or assessing the repeatability of the measurements that you make.

Once your TA reviews and approves your proposal, he or she will authorize your group to begin working with the physical materials in the lab to conduct your experiment. You are welcome to use any measurement devices or materials that are in the ME 320 lab, including items in the cabinets along the south wall. You should identify materials and measurement devices that you would like to use early in case any purchases need to be made to complete your experiment. Additionally, there are storage drawers in the bin cabinet on the south wall where your team may store their items for use in subsequent weeks. You may not access the storage bins of another group! Your primary deliverable is a full technical report about your findings. Your report may include no information from which you can be identified as its author. You will be assigned a pseudonym to use when you submit your report, and there should be no photographic information in the report that shows you or any of your teammates, etc. You will complete a single-blind peer review of another student's report, and another student will complete a review of your report. See Canvas for full report and peer review deadlines.

Appendix A-2: Grading Checklists

The independent lab report in the ME 320 lab should be written in the standard full engineering technical report genre and submitted to the Canvas site for the lab according to the stated deadline. The following grading scheme will be applied to the report. Individual checklist items must be completed at a high quality to be satisfied. To earn each grade level, the report must also satisfy all checklist items in all of the lower grade levels. For example, if a report satisfies all items but does not include a proper analysis of the experimental uncertainty, then it will not earn greater than a C. Any reports that fail to meet **<u>all</u>** of the minimum requirements for a "C" will be assessed as a "D" or "F" at the discretion of the TA.

To earn a "C," a student's lab report must clearly satisfy each of the following items:

- _____ Report must present a heat transfer research question and an experiment designed to answer that question
- _____ TA must have approved of the investigation that the student conducted
- _____ Report must include well-written introduction, experimental methods, results, discussion, and conclusions sections
- _____ Report may contain no misspelled words
- _____ Report must include original experimental data
- _____ Report must include an appendix where the student documents the time spent working on each portion of the laboratory exercise, including the writing process.

To earn a "B," a student's lab report must clearly satisfy each of the following items, in addition to the "C"-level checklist items:

- _____ Report must include a well-written, unambiguous explanation of the experimental procedures used in the investigation.
- _____ Report must include figures properly cited in the text, with appropriate numbering and captions.
- _____ Report must include a proper analysis of the experimental uncertainty.
- _____ Report must include a critical analysis of the experimental results.
- _____ Report must include thorough and proper citation of sources in IEEE format.

To earn an "A," a student's lab report must clearly satisfy each of the following items, in addition to the "B"-level and "C"-level checklist items:

- _____ Report must include clear and well-constructed diagrams of the experimental setup
- _____ Report must include properly-formatted and numbered equations. Equations should be included at minimum in a section that describes the theory under investigation, but may also appear in the Discussion of Results section.
- _____ Report must include well-reasoned recommendations for improvements to the experiment
- _____ Report must suggest ideas for further investigation based on the results of the experiment

Appendix B: Survey Items

Pre-exercise survey

Motivation (All items are from source [6], except item 10, which was written by the authors and is not a validated survey item)

1. In a laboratory course like this, I prefer to do lab exercises that challenge me to explore my curiosities about heat transfer.
2. The most important thing for me in this lab is trying to understand the content as thoroughly as possible.
3. Understanding heat transfer is important to me.
4. I like it best when something I learn makes me want to find out more.
5. It is important for me to do well compared to others in this class.
6. I want to do well in this class to show my ability to my family, friends, advisors, or others.
7. Getting a good grade in this class is the most important thing for me right now.
8. I think what we are learning in this class is interesting.
9. I would recommend this class to others.
10. If this course was not a required course, I would still choose to take it.
11. I think the material in this lab is useful for me to learn.
12. I would like to take more heat transfer classes after this one.
13. I am more interested in doing experimental work because of my experience in this laboratory course.

Experimental Skills Self-Efficacy

14. I can design experiments independently. [9] (modified slightly by authors)
15. I can perform experiments independently. [9]
16. I can analyze data resulting from experiments. [9]
17. I effectively present my experimental procedures, results, and conclusions through writing. [1]
18. I work well in teams of people with a variety of skills and backgrounds. [1]

Conceptual Understanding

19. I usually have a sound grasp of the theory behind laboratory experiments before I perform the experiments. [10] (modified slightly by authors)
20. Scientific concepts become clearer to me as I perform an experiment. [10] (modified slightly by authors)
21. I am confident that I understand the underlying heat transfer phenomena in the experiment. [10] (modified slightly by authors)
22. After an experiment, I have no difficulty figuring out how my calculation procedures and measurement uncertainty affected my results. [10]
23. When presented with laboratory results, I know how to interpret them and draw relevant conclusions from them. [10]
24. I think through the details of a hypothesis and carry it out to solve a science problem. [1]

Post-exercise survey only Additional Questions [15] (modified from source to match course content)

Usefulness of Resources Provided (POST ONLY)

25. The total time allocation (2 hours/week * 5 weeks = 10 hours in the lab) was sufficient to perform the lab properly.
26. The equipment that I hoped to use was made available for use in this exercise.
27. The TA gave helpful advice when requested.
28. The preceding laboratory exercises in the semester helped me to design my experiments.
29. The preceding laboratory worksheets in the semester helped me to design my experiments.
30. The Measurement Uncertainty Quantification content in the semester helped me to complete this exercise.

Contribution to Learning (POST ONLY)

31. The lab exercise was effective for me to learn how to design an experiment.
32. As a result of this lab exercise, I feel that I have a better understanding of heat transfer.
33. My experiment yielded results that definitively proved my hypothesis correct.
34. My experiment yielded results that neither proved nor disproved my hypothesis.
35. My experiment yielded results that definitively proved my hypothesis incorrect.
36. I now have the knowledge to specify appropriate measurement devices for a heat transfer experiment.
37. Doing this lab exercise made me excited to learn more about the field of heat transfer.

Free-response questions (POST ONLY)

38. What aspects of this lab were most useful or valuable?
39. What are some unexpected technical challenges (if any) that you faced while performing the lab exercise, and how did you overcome them?
40. How do you feel the administration of this lab could be improved?
41. If you could do this independent laboratory investigation over, what would you do differently? What would you do the same?

Appendix C: All survey results

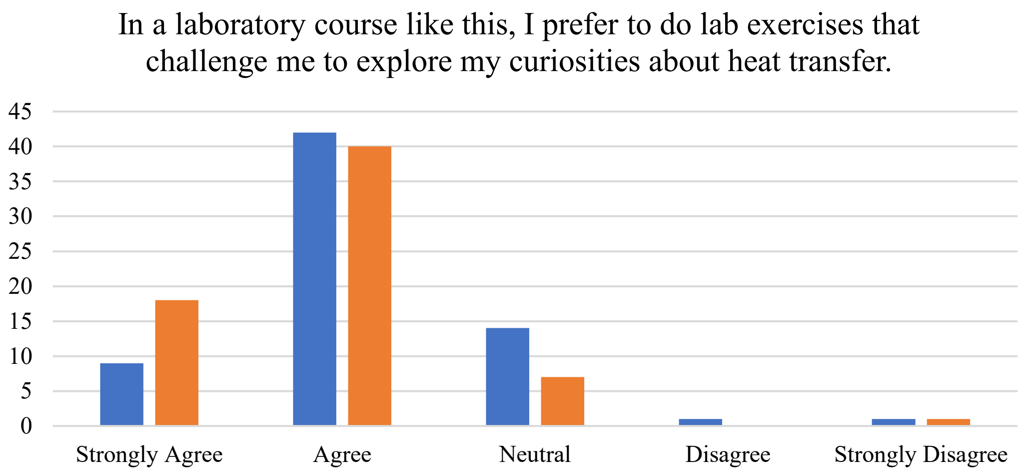

Figure A-1. Response distribution for Item 1. Pre-survey data is represented in blue and post-survey data is represented in orange.

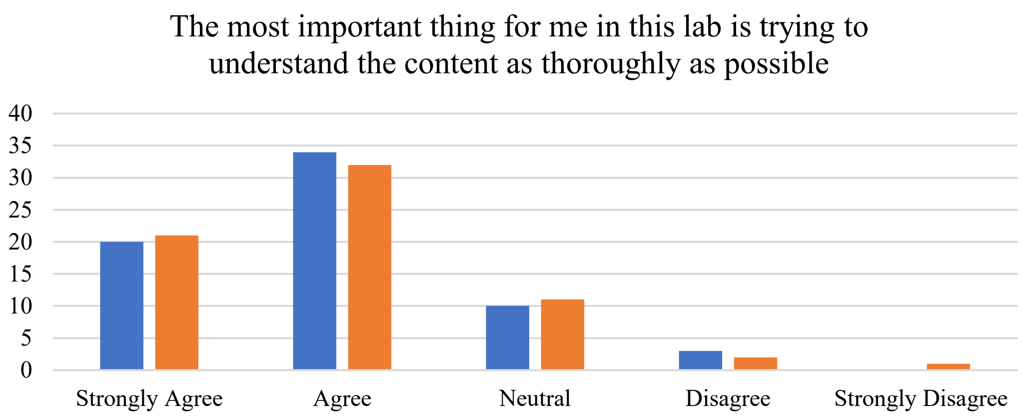

Figure A-2. Response distribution for Item 2. Pre-survey data is represented in blue and post-survey data is represented in orange.

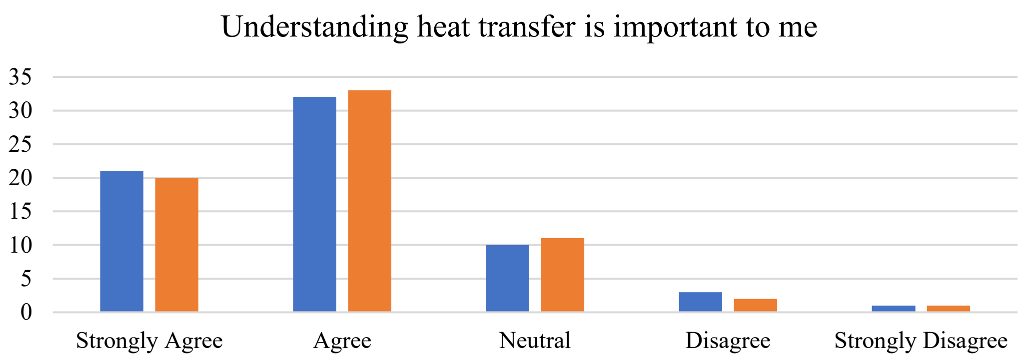

Figure A-3. Response distribution for Item 3. Pre-survey data is represented in blue and post-survey data is represented in orange.

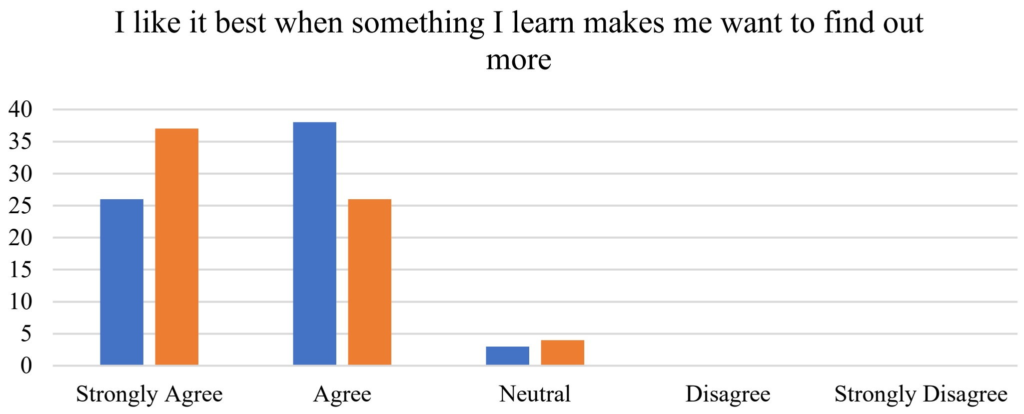

Figure A-4. Response distribution for Item 4. Pre-survey data is represented in blue and post-survey data is represented in orange.

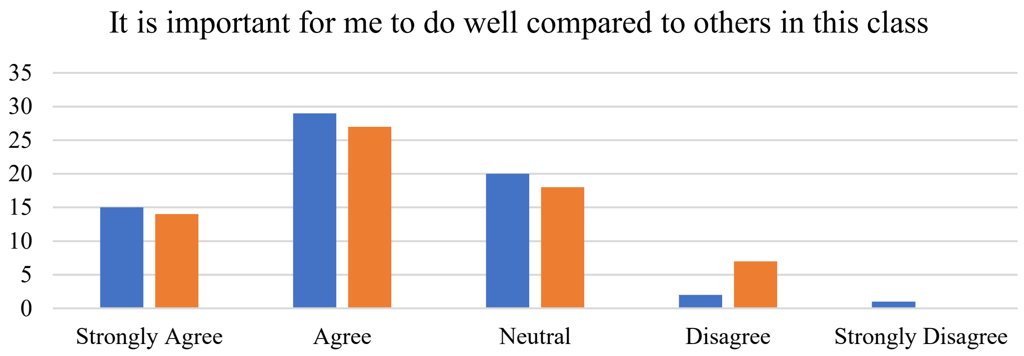

Figure A-5. Response distribution for Item 5. Pre-survey data is represented in blue and post-survey data is represented in orange.

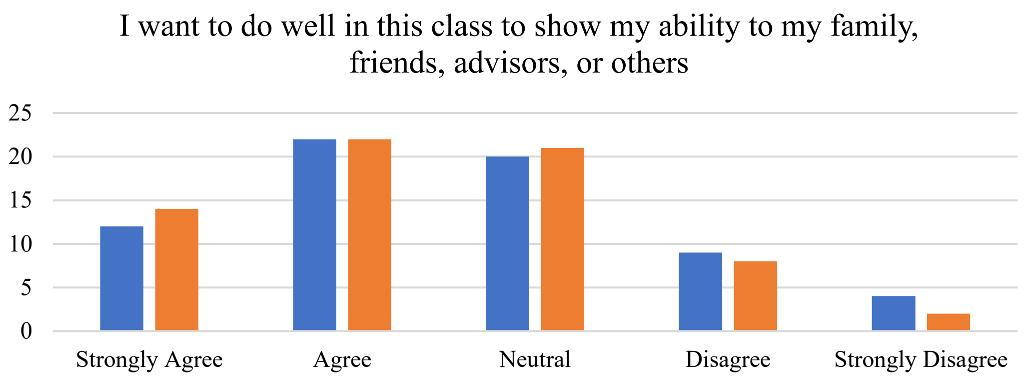

Figure A-6. Response distribution for Item 6. Pre-survey data is represented in blue and post-survey data is represented in orange.

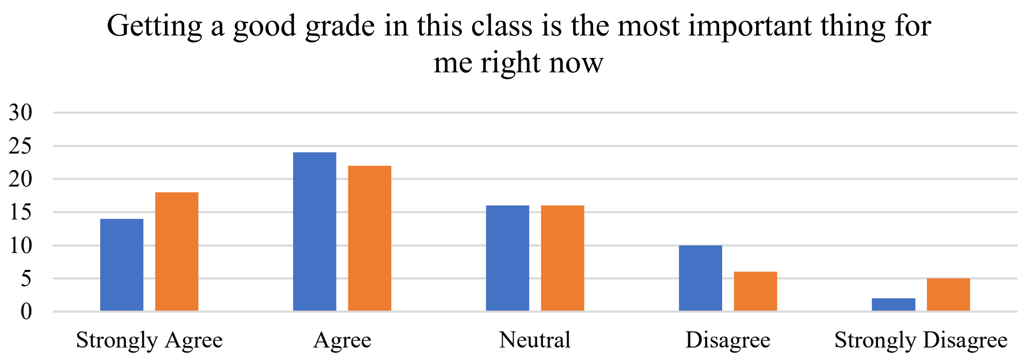

Figure A-7. Response distribution for Item 7. Pre-survey data is represented in blue and post-survey data is represented in orange.

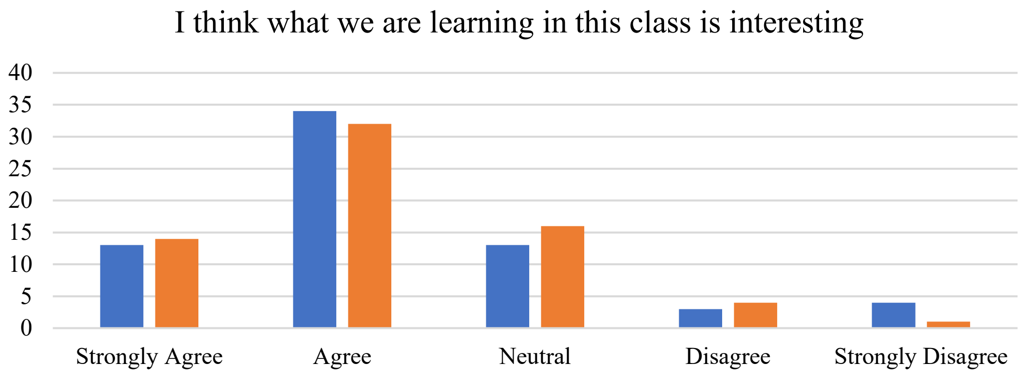

Figure A-8. Response distribution for Item 8. Pre-survey data is represented in blue and post-survey data is represented in orange.

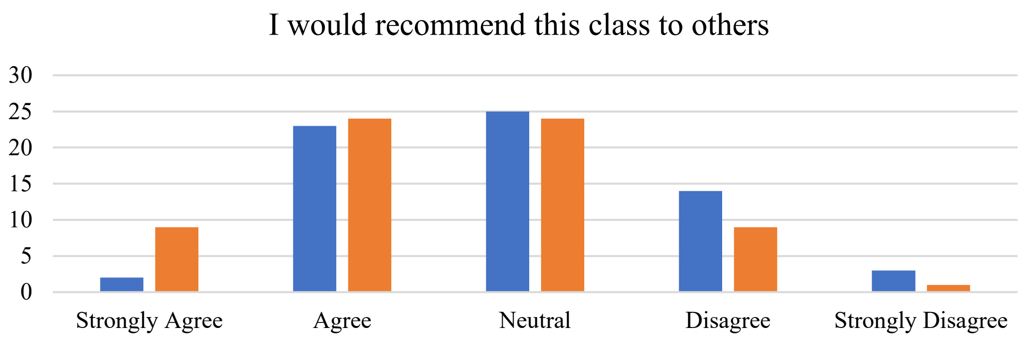

Figure A-9. Response distribution for Item 9. Pre-survey data is represented in blue and post-survey data is represented in orange.

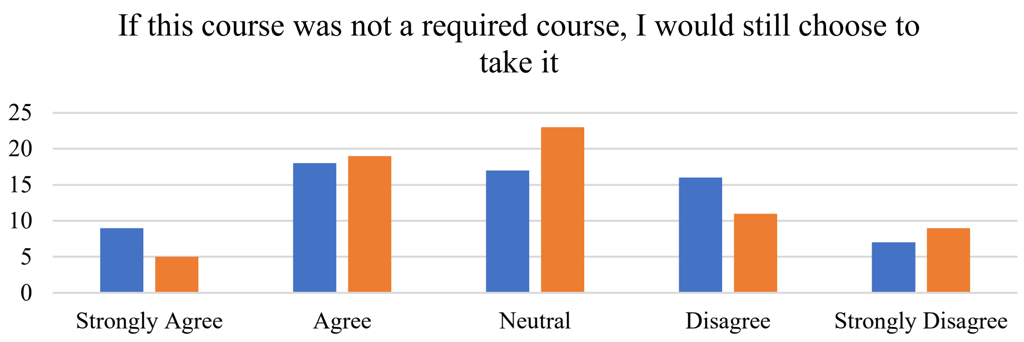

Figure A-10. Response distribution for Item 10. Pre-survey data is represented in blue and post-survey data is represented in orange.

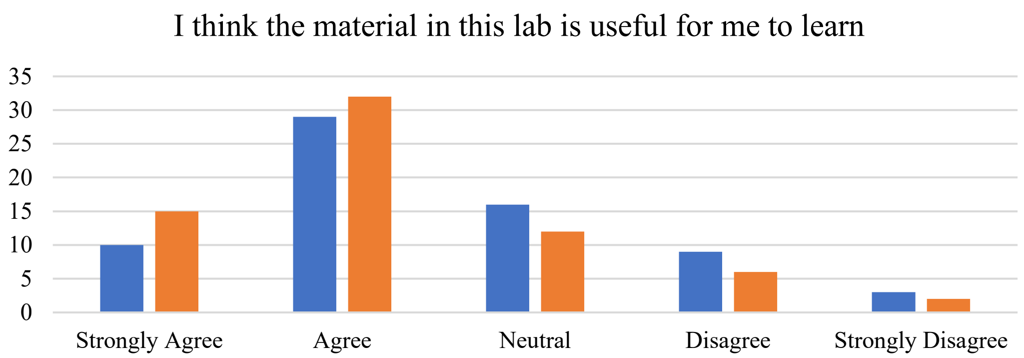

Figure A-11. Response distribution for Item 11. Pre-survey data is represented in blue and post-survey data is represented in orange.

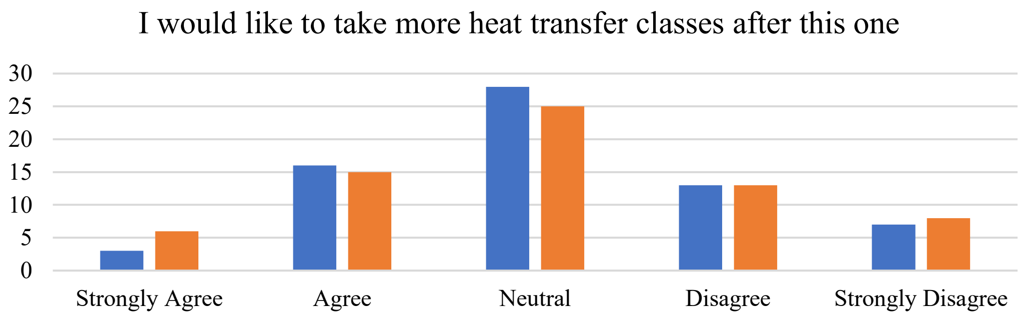

Figure A-12. Response distribution for Item 12. Pre-survey data is represented in blue and post-survey data is represented in orange.

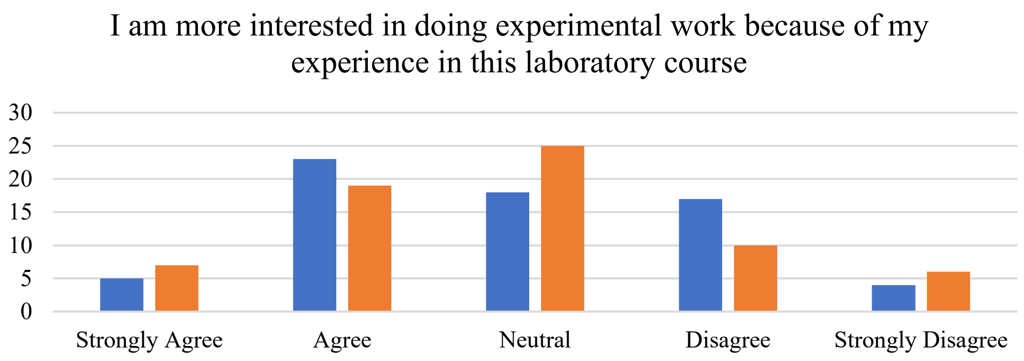

Figure A-13. Response distribution for Item 13. Pre-survey data is represented in blue and post-survey data is represented in orange.

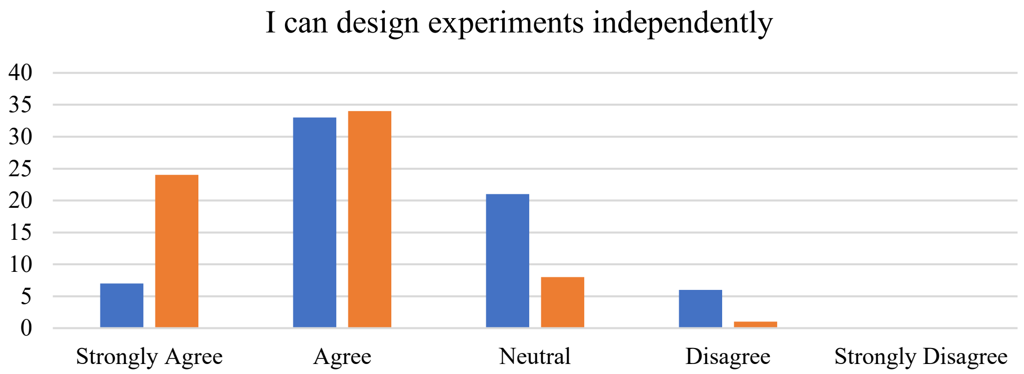

Figure A-14. Response distribution for Item 14. Pre-survey data is represented in blue and post-survey data is represented in orange.

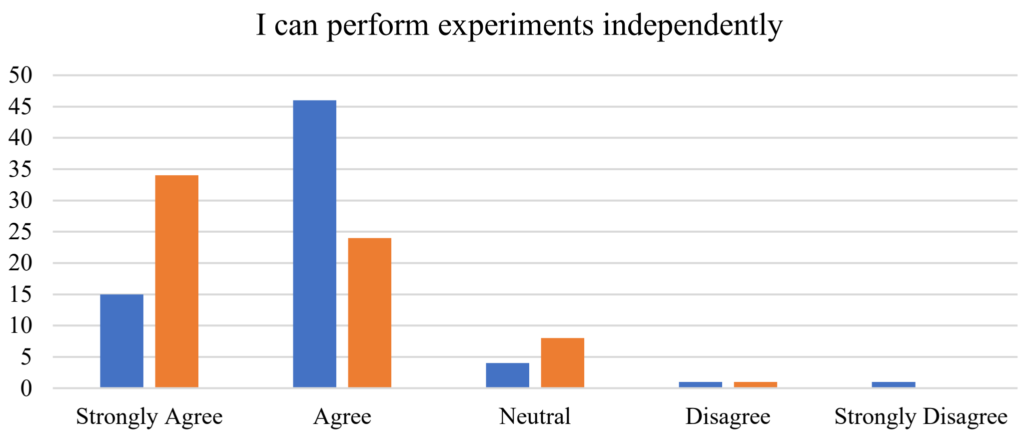

Figure A-15. Response distribution for Item 15. Pre-survey data is represented in blue and post-survey data is represented in orange.

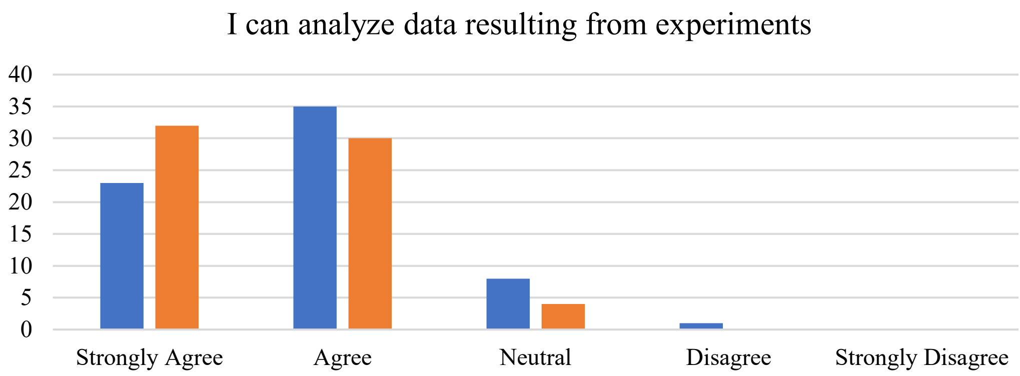

Figure A-16. Response distribution for Item 16. Pre-survey data is represented in blue and post-survey data is represented in orange.

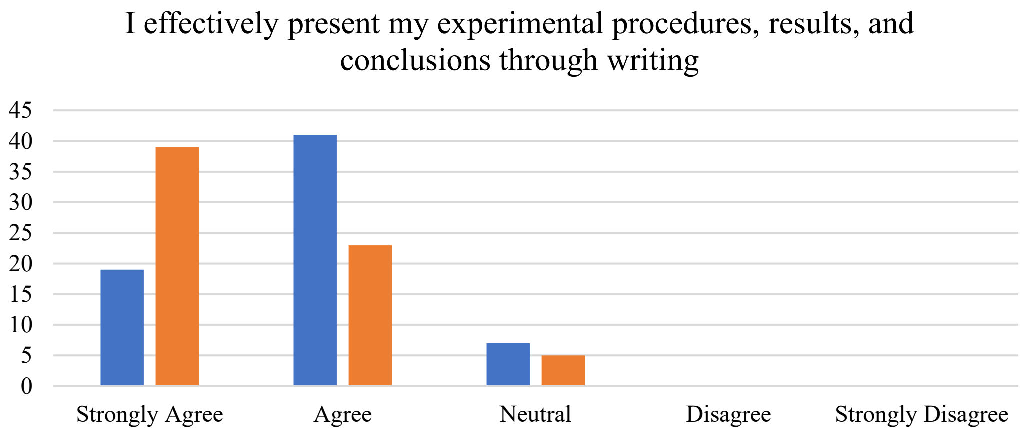

Figure A-17. Response distribution for Item 17. Pre-survey data is represented in blue and post-survey data is represented in orange.

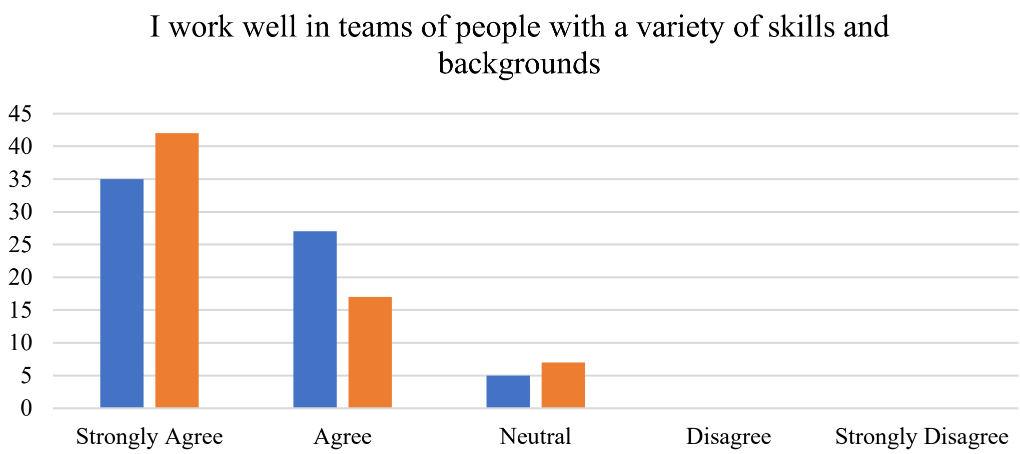

Figure A-18. Response distribution for Item 18. Pre-survey data is represented in blue and post-survey data is represented in orange.

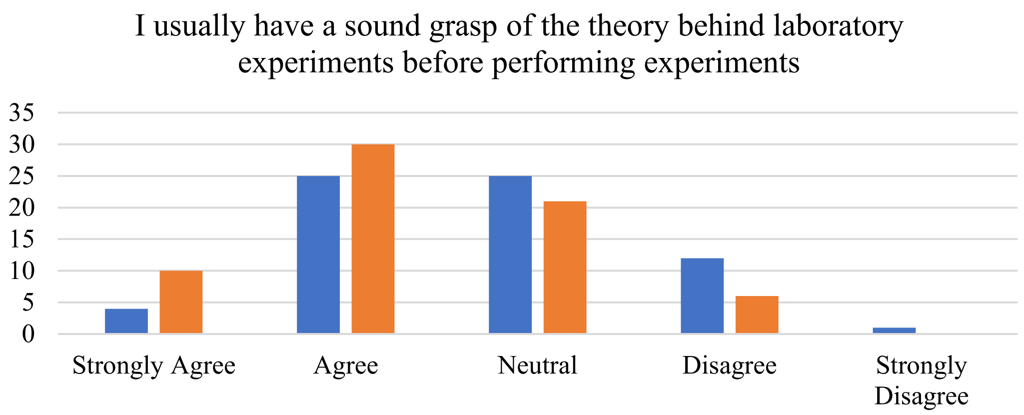

Figure A-19. Response distribution for Item 19. Pre-survey data is represented in blue and post-survey data is represented in orange.

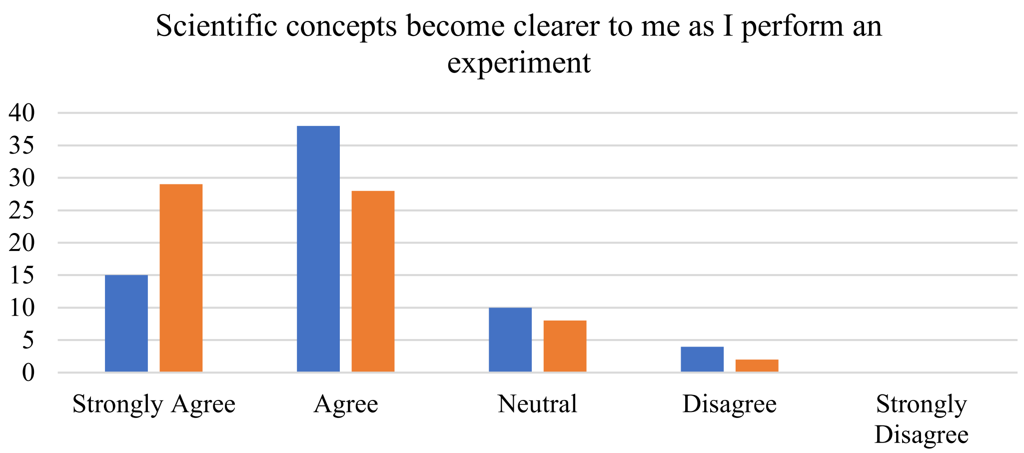

Figure A-20. Response distribution for Item 20. Pre-survey data is represented in blue and post-survey data is represented in orange.

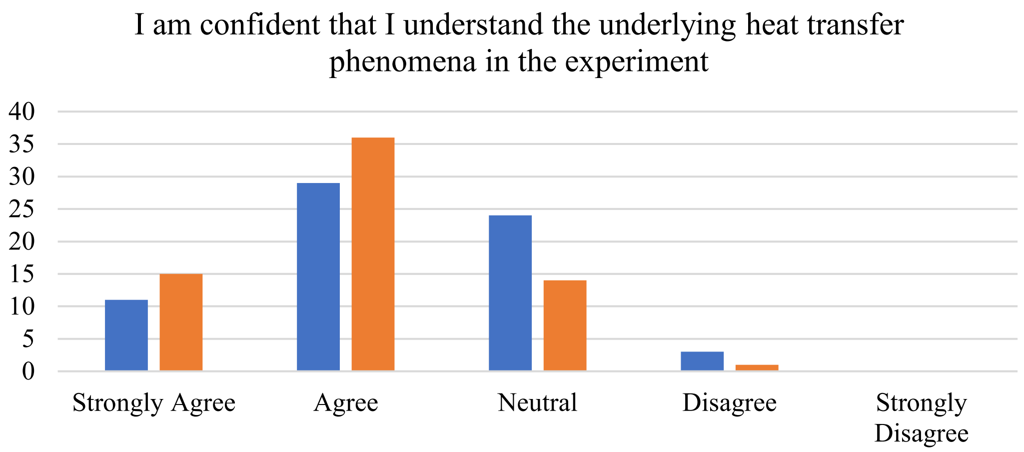

Figure A-21. Response distribution for Item 21. Pre-survey data is represented in blue and post-survey data is represented in orange.

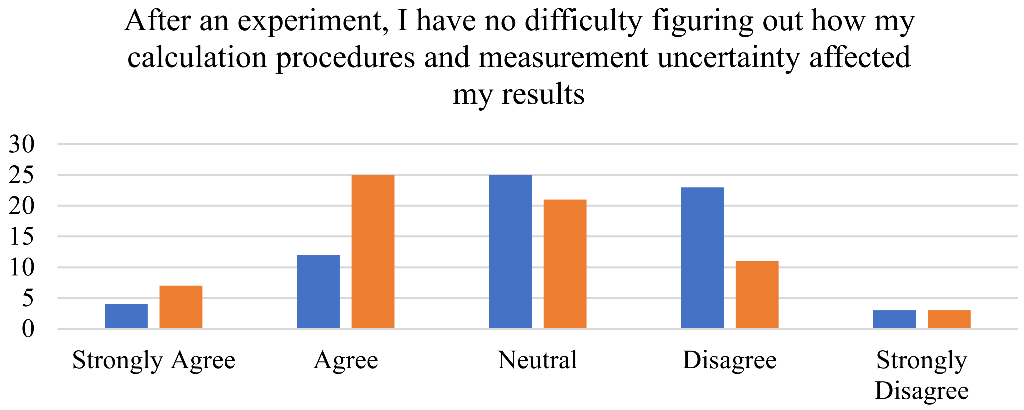

Figure A-22. Response distribution for Item 22. Pre-survey data is represented in blue and post-survey data is represented in orange.

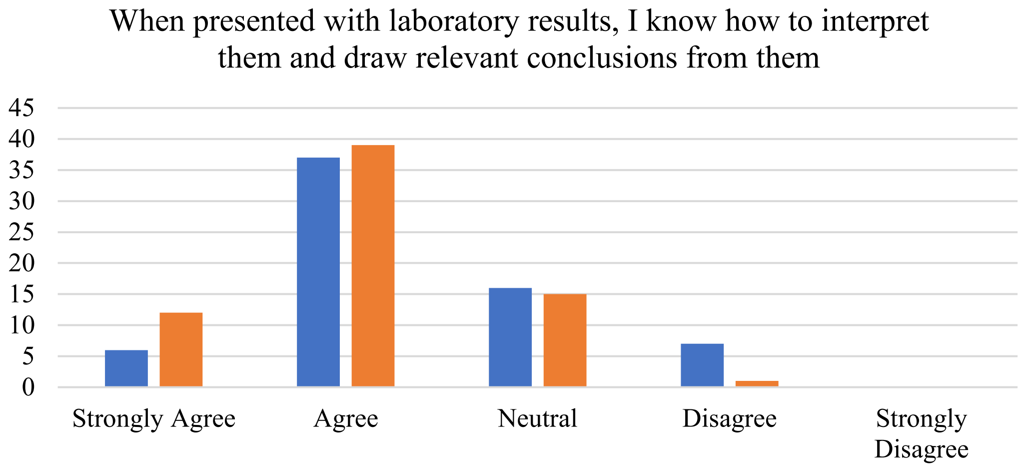

Figure A-23. Response distribution for Item 23. Pre-survey data is represented in blue and post-survey data is represented in orange.

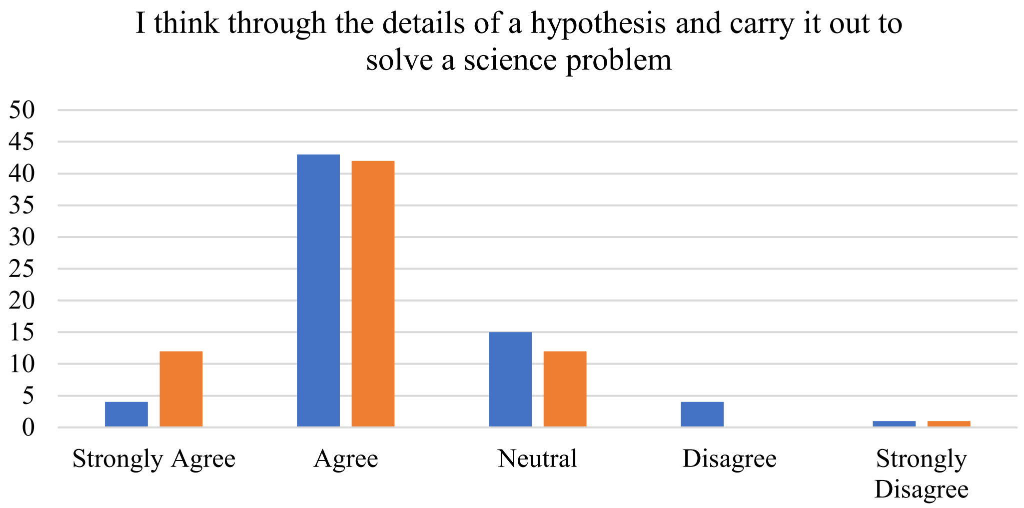

Figure A-24. Response distribution for Item 24. Pre-survey data is represented in blue and post-survey data is represented in orange.

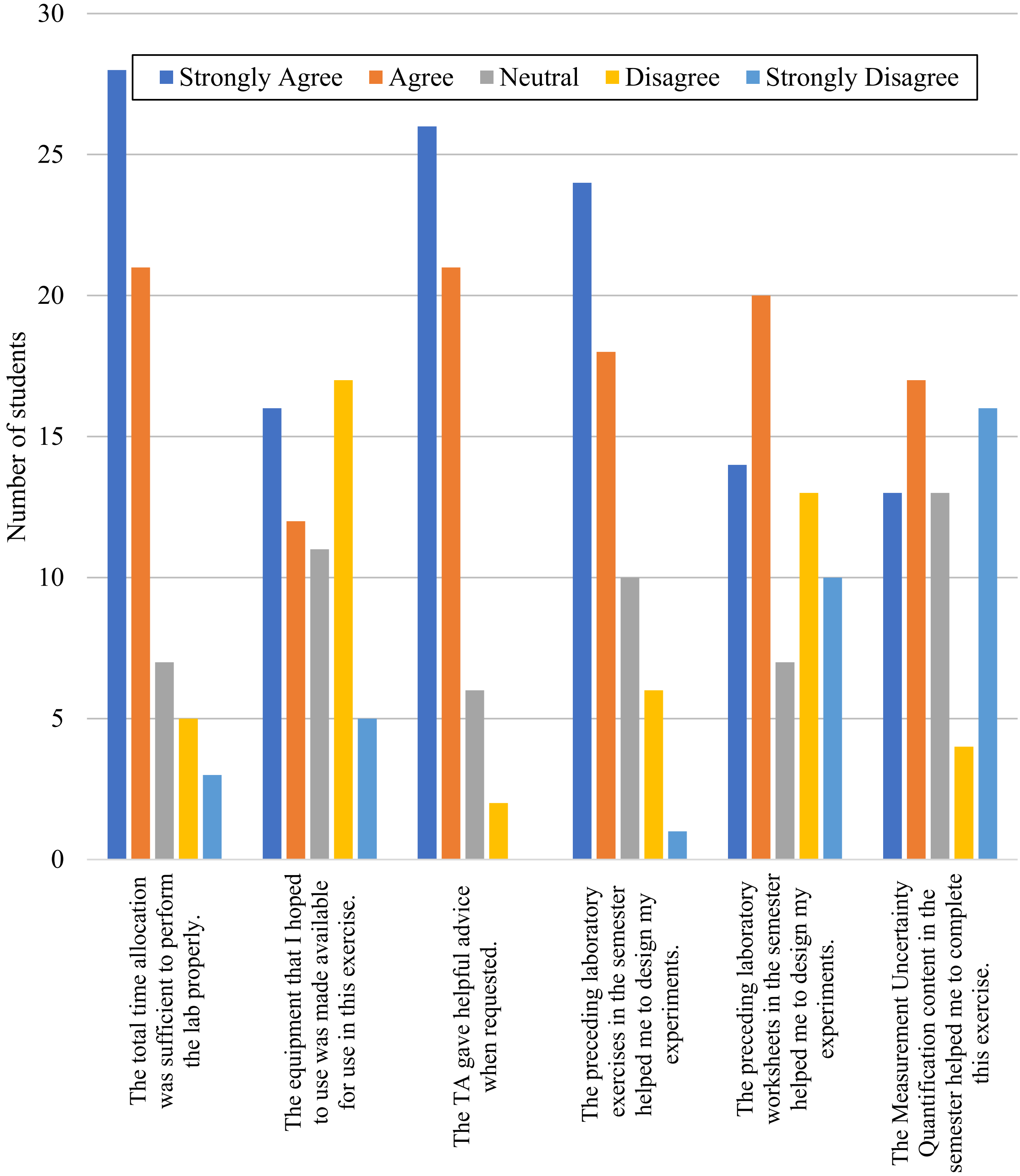

Figure A-25. Response distribution for Items 25–30

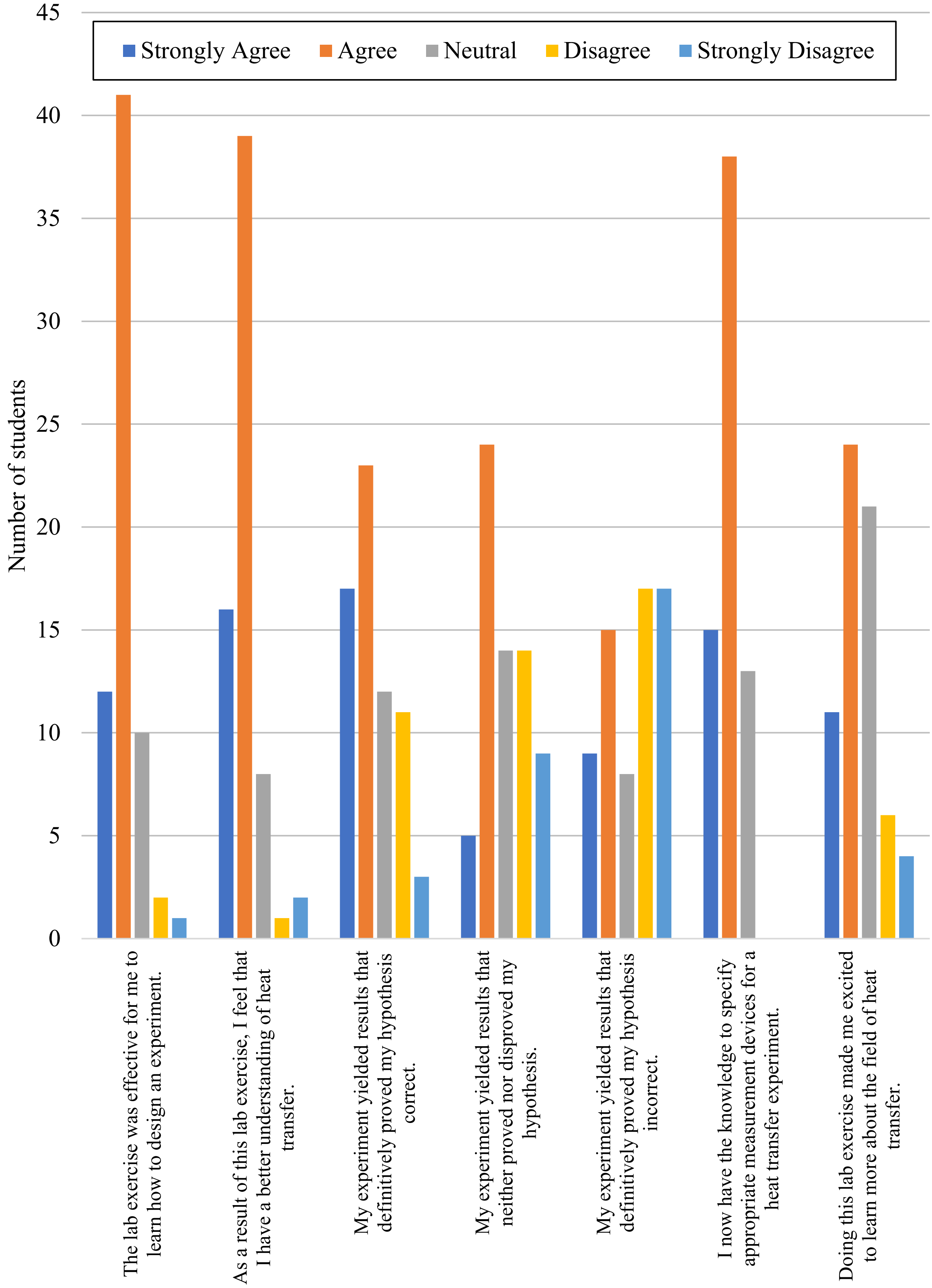

Figure A-26. Response distribution for Items 31–37