The Impact of Collaborative Learning on Theoretical Understanding in Electrical Engineering Laboratories: A Quasi-Experimental Study

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***Abstract*—This Research Full Paper presents findings from a quasi-experimental study on the effectiveness of collaborative learning in improving theoretical understanding within a large electrical engineering laboratory course. While there are several studies that report positive student responses and performance gains with collaborative learning in higher education STEM laboratories, as far as we know few studies include control groups and prepost-test to ascertain the impact of such approaches on students' perception and performance gains.**

142 students were surveyed on their perceived theoretical understanding under three experimental settings: an experimental group involving 90 students in a magnetic fields laboratory with collaborative learning (E), a control group involving the same students in an electric fields laboratory (C1) and a second control group involving a different group of 52 students who went through the same laboratory as E without collaborative learning (C2). The study found that students' perceived theoretical understanding in E improved significantly before and after collaborative learning (d=1.05). Significant difference in perceived theoretical understanding between E and C1 was found but this result needs to be interpreted with caution as students perceived C1 to be significantly more difficult. Nevertheless, students in C1 also feedback that collaborative learning would have aided their theoretical understanding. Furthermore, students' perceived theoretical understanding in E was significantly higher than those in C2 when laboratory sequence was taken into account (d=0.394), suggesting that collaborative learning was helpful for theoretical development. The scores achieved by a subset of these students in the E (n=69) and C2 (n=20) setting were also compared. A non-significant increase in performance were found with E, suggesting that short-term performance gains might be limited.

The qualitative feedback from students suggest that knowing the responses of their peer enabled them to understand the concepts from many perspectives and identify their mistakes. Furthermore, peer discussion provided affirmative feedback to some students which helped them gain confidence in their understanding. Hence, it is prudent for the study to conclude that including collaborative learning in engineering laboratory has provided students with a sense of much needed support with no negative consequence on theoretical knowledge gain.

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***Index Terms*—Collaborative learning, Laboratory, Student perception, Knowledge gain, Experimental research**

I. Introduction

In line with accreditation requirement, our university sought to provide every student with authentic laboratory experiences to enhance their understanding and application of engineering concepts. One such effort was a first-year course comprising six laboratory sessions that are taken by more than 677 students across three engineering schools.

However, many of these sessions need to be staggered due to a lack of physical equipment and spaces for large cohorts. The timetabling would require different groups of students to take the laboratory sessions in a different sequence. One consequence is the risk of the sharing laboratory answers by students in earlier laboratory sessions to their peers in later ones. We have been mitigating this problem by releasing the answers only after all laboratory sessions have been completed. However, this prevents students from receiving timely feedback that has been established to be most effective for learning [1]–[3]. Many students also reflected in the course feedback that they had forgotten much of the laboratory experiences given their packed curriculum.

II. Literature Review

A. Collaborative Learning

Vygotsky's cognitive development theory [4] suggests that learning is a social activity. Our ideas of truth are affirmed or changed when we get to compare our own views with that of our culturally significant others such as tutors and peers. Previous studies showed that collaborative learning (or getting two or more people to learn something together) was as predicted an effective source of timely feedback for learning [5]–[7]. For example, studies on peer instruction had shown that getting students to respond to a quiz question individually and then discuss with peers resulted in significant knowledge gains compared to traditional lectures [8], [9]. Similarly, Team-Based Learning demonstrated that students on the average perform better on a set of quiz questions after they had the chance to discuss the same set of question as a team [10], [11]. These results were reportedly valid even when the students are working as a team for the first time [12]–[15].

Meta-analyses on collaborative learning further suggested medium to large effect sizes in relation to affective and performance measures when compared to other approaches such as individual and competitive learning [16], [17]. In particular, a 2013 meta-analysis found that collaborative learning has a significantly greater impact for STEM subjects and non-western students, and is equally effective for primary and tertiary students [18]. An earlier meta-analysis further suggested that collaborative learning results in better outcomes when the group size is small, the team assignment is heterogeneous or random, and when the task structure is closed-ended [19]. These classroom-based studies suggest that collaborative learning may be a relevant approach for tertiary-level introductory engineering laboratory classes which tend to be conducted in small classes regardless of the cohort size and which has more closed-ended than open-ended tasks.

B. Collaborative Learning in Engineering Laboratory Classes

There are several existing studies around collaborative learning in tertiary level engineering classes. In general, they found favorable students' satisfaction ratings and learning gains [20]–[22]. For example, Cámara-Zapata and Morales [23] compared the persistence, performance and characteristics of two student cohorts in a 150 hours engineering physics course that include 60 hours of classroom teaching and 10 hours of laboratory work. They found that even though the two cohorts were demographically similar, the control cohort (n=78) who engaged in mostly individual learning fared worse than the experimental cohort (n=75) who worked collaboratively throughout the course in terms the proportion of students taking the final examination and the final examination results. The results were however not statistically significant. A problem with this study is that in both cohorts, the students worked in groups of three for the laboratory component of the course. Hence, this study was not able to inform the impact of collaborative learning in engineering laboratory sessions.

Jaksic [22] reported that students perceived their learning gains to be much higher when they work in pairs than when in larger groups in a digital logic circuit design laboratory. He also compared achievement gains with previous cohorts who only have opportunities to work in larger groups. The mean score and standard deviation for the final examination were higher and smaller respectively with the cohort of 22 students. However, the study did not contain a control group with no peer learning. Furthermore, he neither reported the statistical significance nor the effect size of achievement gains.

By contrast, Korkmaz [24] included a control group of 20 students and found that these students who worked individually fared significantly worse than an experimental group of 22 students who worked in teams of four in terms of intermediate electronics skills and their perception of collaborative learning within the Turkish culture. However, the two groups were not found to be significantly different in terms of basic electronic skills. Furthermore, their study did not include within group pre- and post-intervention comparisons. Hence, we do not know if the differences could have been a result of differences in students' prior knowledge and experiences.

In recent years, there has also been several publications of collaborative peer learning in remote or web-based laboratory settings. These studies however tended to be descriptive and anecdotal in their claims of improved learning [25]–[29]. In summary, as far as we know, while many authors reported success with collaborative learning in engineering laboratory classes, they either did not provide empirical evidence to support their claim or that their results appear to be statistically insignificant or mixed. This is contrary to the classroom-based findings such as those from peer instruction and team-based learning where collaborative learning appeared to result in significant achievement gains even within a single session of collaborative learning [12]–[15].

C. The Current Study

Our study intends to improve on the previous studies by adopting a quasi-experimental approach involving within and between groups comparisons of individual learning and collaborative learning in a physical engineering laboratory session. We argue that studies on physical laboratory remain pertinent as the literature is thus far equivocal about the impact of collaborative learning under these settings. Furthermore, physical laboratory is expected to play a significant role in engineering education in a post Covid-world [30], [31].

Our implementation also attempts to avoid some of the identified pitfalls of collaborative learning such as free riding [1], [16] by including an individual component before the team component in the laboratory report. This setup has previously shown to improve accountability [32], encourage more meaningful discussions [33] and significantly better performance gains [8], [11] in non-laboratory classes and is in line with pedagogical recommendations for collaborative learning in laboratory and project work [34]. Furthermore, the group size was kept small between 2 to 4 members as recommended for effective team discussion and learning [19], [35]. Importantly, such assessment design would allow the study to conduct within-group comparison to ascertain the extent to which peer collaboration improves students' learning.

In addition, though the intention of our laboratory sessions is to improve both theoretical understanding and laboratory skills, we would be assessing the impact of theoretical understanding in this study. This focus would complement Korkmaz's [24] finding on laboratory skills while at the same time enable comparisons with results from classroom-based collaborative learning which tended to be more focused on theoretical understanding.

Finally, we would investigate both the perception and performance in understanding as these are the two major ways of assessing learning gains in literature. There are good reasons for including both. Firstly, several authors have pointed out the illusion of objectivity in the assessment of knowledge. The questions for an assessment task are subjectively decided by a group of content experts [36], [37] whose grading are often affected by their own values even with standardized rubrics [38], [39]. Though the team had taken steps to enhance the validity of questions and the reliability of grading, performance gains should be considered as proxy for actual learning gains with any study. At the same time, subjective students' perception are no less important than time bound "objective" assessment of learning. Several studies have suggested that higher self-perceived level of understanding leads to more persistence in self regulated learning, mastery and/or performance approach goal orientation and less learning anxiety [40]–[42]. Hence, the research questions of the study are:

RQ1. To what extent do students' theoretical understanding change pre- and post- collaborative learning?

RQ2. To what extent do students' theoretical understanding differ between laboratory sessions with and without collaboration learning?

III. Methods

The study involved two out of the six laboratory sessions. The two sessions were chosen because they fall under two closely coupled themes, electricity and magnetism. These topics are commonly taught in University level foundation physics courses under the broad category of electromagnetism. Both laboratory sessions were three hours long and were taken by first year engineering students in the fall of 2021.

The experimental condition (E) occurred in the magnetic field laboratory session. The design of the laboratory session was inspired by peer instruction and Team-Based Learning. Students were assigned to discuss three theoretical questions in groups of two to four, after they had individually completed the experiment and submitted their response to four questions. Typically, the individual work takes around two hours while team discussion happened in the last hour of the session. The group formation was random as students were assigned a laboratory bench and made to work with their immediate neighbours. The electric field laboratory class was the first control (C1) where students conducted the experiment and answered all questions individually. Due to safe distancing measures in response to COVID-19 mid-semester, the study was able to include one further control group (C2) where students completed the same laboratory as E but individually without collaboration, like in C1.

An online survey was administered at the end of each laboratory session where students were required to complete within 24 hours to receive a $10 food voucher. It is plausible that students were motivated by this incentive to participate. Nevertheless, offering vouchers is a common practice within the university. At the same time, students were briefed to share their genuine feedback and assured that their feedback would be confidential and had no bearing to their score by the researcher before they complete the survey. Hence, we expect the majority of the students to take the survey seriously and honestly. In addition, no responses were removed during the data cleaning process as all students were found to vary their responses according to the questions[1].

The survey asked students to rate the level of difficulty of the laboratories on a scale of 0 to 10. For the experimental setting (E), the students were further asked to rate (on the same ten-point scale) their level of understanding of related theories before and after the collaborative learning part of the laboratory. For the control settings (C1 and C2), students were similarly asked to rate their level of understanding of related theories but only after the laboratory session. They were also asked to feedback if they thought their understanding would have improved had there been collaborative learning on a 7-point likert-scale ranging from strongly agree to strongly disagree. Finally, students in all three settings were asked to elaborate their ratings through an open-ended question.

142 first year engineering undergraduates (or 18.3% of the course cohort) who attended both the electric fields and magnetic fields laboratory classes consented to the study and completed both surveys. The breakdown of these students into the three settings (E, C1 and C2) are included in Table I.

TABLE I
Number of students under each experimental setting.

	Electric Field	Magnetic Field
No Collaborative Learning	C1:142	C2: 52
Has Collaborative Learning	-	E: 90

Next, to understand if there was a significant difference in performance gains between students who had gone through collaborative learning (E) and those who had not (C2), the magnetic fields laboratory reports from 89 students (69 from E and 20 from C2) were scored by an expert[2]. The questions in the laboratory report is divided into two sets. The first set comprised four baseline questions attempted individually by students in both E and C2 settings. The second set comprised three questions which were attempted by students as a team in E and as individuals in C2. An individual and a team question are included in Figure 2 as examples. Each question was anonymized and randomly ordered for marking. This ensured that the marker did not know if the response to each question come from C2 or E settings. The rubrics used by the marker is included in Table II. A diagrammatic representation of the various student groups in this study is included in Figure 1.

All quantitative analysis were conducted using SPSS Version 27. Descriptive, means comparisons and ANOVA analyses were employed to address the two research questions by testing four hypotheses, namely:

H1.1: Students' perceived theoretical understanding is higher after collaborative learning.

[1]The survey included several other questions in relation to the laboratory session such as the quality of teamwork but for brevity, we are only reporting those relevant to this manuscript.

[2]We were not able to include all students because only some faculty members were willing to release the students scripts to the research team. Furthermore, all these students had the magnetic fields laboratory as the second laboratory.

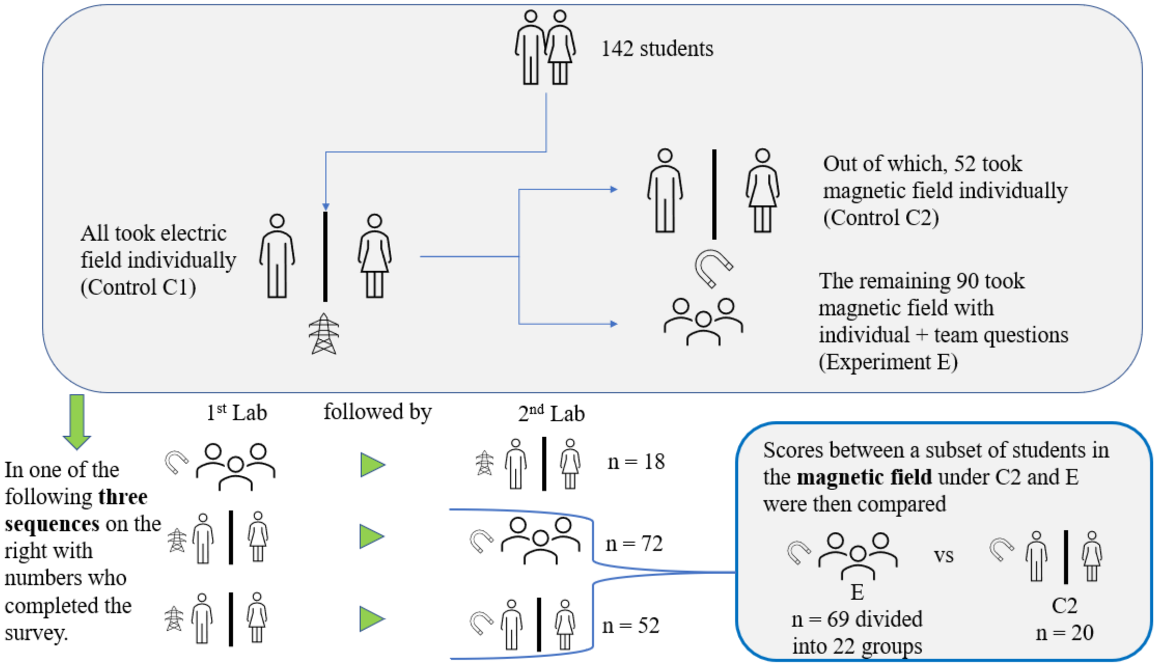
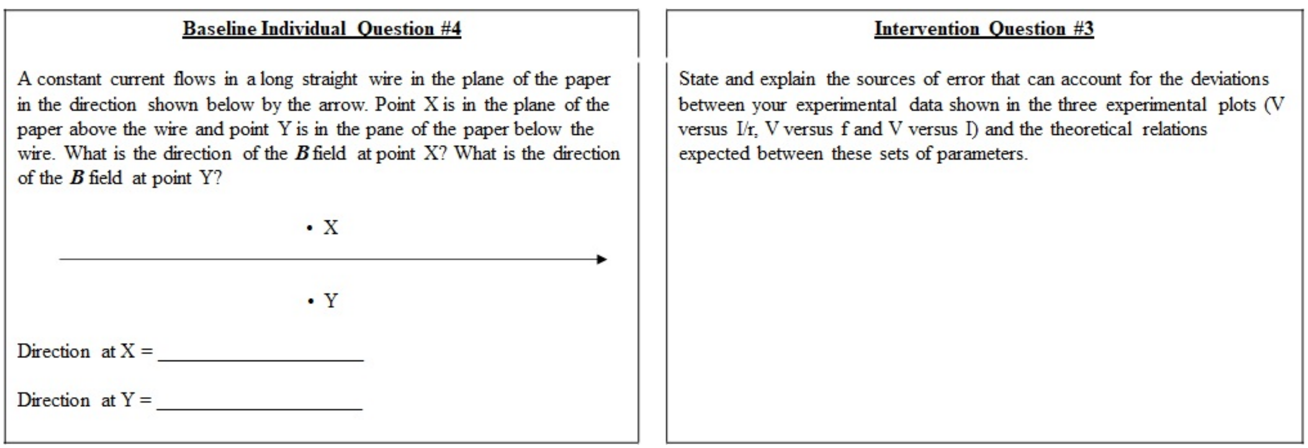


Fig. 1. Diagrammatic representation of the various student groupings in the study.



Baseline Individual Question #4

A constant current flows in a long straight wire in the plane of the paper in the direction shown below by the arrow. Point X is in the plane of the paper above the wire and point Y is in the pane of the paper below the wire. What is the direction of the ***B*** field at point X? What is the direction of the ***B*** field at point Y?

• X

• Y

Direction at X = ____________________

Direction at Y = ____________________

Intervention Question #3

State and explain the sources of error that can account for the deviations between your experimental data shown in the three experimental plots (V versus I/r, V versus f and V versus I) and the theoretical relations expected between these sets of parameters.

Fig. 2. Example baseline and intervention questions.

- **H1.2:** Students' scores on theoretical understanding are higher after collaborative learning.
- **H2.1.** Students' perceived theoretical]understanding is higher for the laboratory session with a collaborative learning component.
- **H2.2.** Students' scores on theoretical understanding are higher for the laboratory session with a collaborative learning component.

As students took the two laboratories in different sequences (see Table III), the study had to consider if there was order effect. Specifically, additional ANOVA analyses with laboratory sequence as the control variable were conducted for hypotheses H1.1 and 2.1. As there was no laboratory sequence where students attended C2 before C1, the analyses of these hypotheses were based only on students who attended C1 before E or C2. Finally, the qualitative analysis of students' open-ended responses were used to formulate possible explanations of the quantitative results.

IV. Results

To improve readability, we would first present the hypotheses H1.1 and H2.1 which involved comparisons of ratings on perceived theoretical understanding followed by the presentation of the results on H1.2 and H2.2 which involve comparisons of performance scores achieved by students under the different settings.

A. H1.1: Students' perceived theoretical understanding is higher after collaborative learning.

The testing of H1.1 involved the perceived theoretical understanding of students under the experimental setting E

TABLE II
RUBRICS FOR THE QUESTIONS

Grade	Score	Description
A	4	(a) precise presentation and understanding of relevant theoretical basis, (b) correct, accurate and complete data analysis, (c) critical discussion of assumptions, errors and inaccuracy, (d) in-depth interpretation of results and analysis, and (e) drawing of important conclusions
B	3	(a) proper presentation of the underlying theories, (b) correct and complete data analysis, (c) relevant discussion of experimental errors and inaccuracy, (d) careful interpretation of results, and (e) drawing of relevant conclusions.
C	2	(a) the theoretical basis of the experiments is merely reproduced and is not fully understood, (b) the data analysis is presented, but is either incomplete or part of it is erroneous, (c) cursory discussion of experimental errors, (d) results are mostly interpreted correctly but may contain some errors, and (e) conclusions are drawn, but lack emphasis or miss the most important ones.
D	1	(a) the theory presented is irrelevant or incorrectly applied, (b) largely incorrect data analysis, (c) possible experimental errors are not discussed, (d) inaccurate or faulty interpretation of results, and (e) conclusions drawn are unimportant or not relevant to the objectives.

TABLE III
NUMBER OF STUDENTS FOR EACH LABORATORY SEQUENCE AND EXPERIMENTAL SETTING.

1st Lab	2nd Lab	Sameple Size
E (Magnetic Field)	C1 (Electric Field)	18
C1 (Electric Field)	E (Magnetic Field)	72
C1 (Electric Field)	C2 (Magnetic Field)	52

pre- and post- collaborative learning. Firstly, pair-wise t-test suggested that collaborative learning resulted in significantly higher perceived level of related understanding (t(89) = 9.961, p <0.001, d = 1.050). The result was similar regardless of the laboratory sequence, suggesting that collaborative learning had a positive and large effect [43] on theoretical understanding (see Table IV). However, the rating after collaborative learning was significantly lower when E was the first laboratory session for the student (t(88)=-2.159, p<0.05) suggesting that there might be order effect (see Figure 3).

To determine the interaction between the laboratory sequence and collaborative learning, we conducted a two-way mixed ANOVA analysis. The analysis showed a significant main effect of ratings for the perceived understanding of the related theories before and after collaborative learning (F(1,88)=57.258, p<0.001, ηp^2=0.394), but not for the main effects of the laboratory sequence (F(1,88)=3.395, p=n.s.). Furthermore, the interaction effect between laboratory sequence and responses before and after the collaborative learning were not significant (F(1,88)=0.390, p=n.s.). Taken together, this

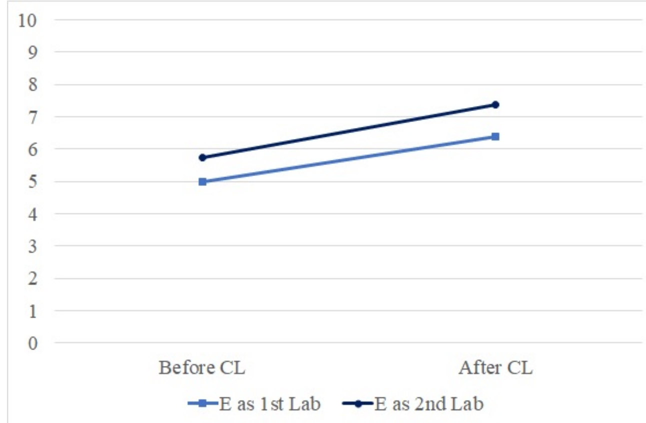


Fig. 3. Student Ratings on theoretical Understanding under Experimental Setting E. The rating for E was significantly lower when it was the first laboratory session.

implies that regardless of the sequence of the laboratory, participants perceived a greater understanding of the theories related to the laboratory after collaborative learning, hence supporting H1.1 fully.

The qualitative comments lent further support to this statistical result. A recurring theme that emerged from the coding had been the availability of different perspectives through collaborative work. As highlighted by the example quotes from two students who had E as the first and second laboratory respectively below, collaborative learning appears to lead to a positive improvement in theoretical understanding regardless of the laboratory sequence.

> "Having discussions with my team helped me understand their perspective and then combined our knowledge to better understand the theories and the experiment." - Student who had E as first laboratory.

> "We could discuss our results and use the results that made the most sense to answer our questions." - Student who had E as second laboratory.

B. H2.1: Students' perceived theoretical understanding is higher for the laboratory session with a collaborative learning component.

The testing of H2.1 involved comparisons of perceived theoretical understanding of students at the end of the laboratory sessions E, C1 and C2. As shown on Table V, When compared with the control settings C1 and C2, significant difference was only detected between the magnetic field laboratory with collaborative learning (E) and electric field laboratory (C1), t(89)=3.928, p<0.001, d=0.414). At the same time, there was no differences between C1 and C2 which comprised student responses from the magnetic field laboratory where there were no collaborative learning. These appear to support the hypothesis that theoretical understanding would be improved

TABLE IV
PERCEIVED THEORETICAL UNDERSTANDING BEFORE AND AFTER COLLABORATIVE LEARNING (CL) IN EXPERIMENTAL SETTING E

		Before CL - Individual		After CL - Team		Significance Test		Effect Size (Cohen's d)	
Perceived Understanding of Related Theories	**N**	**Mean**	**SD**	**Mean**	**SD**	**t**	**df**	**Standardizer**	**Point Est**
E as 1st lab	18	5.000	2.169	6.389	2.004	3.298^{***}	17	1.787	0.777
E as 2nd lab	72	5.722	2.057	7.361	1.630	9.612^{***}	71	1.447	1.133
Total for E	90	5.578	2.088	7.167	1.743	9.961^{***}	89	1.513	1.050

*** $p < 0.001$

when there was collaborative learning. Indeed, students also reflected on a scale of 1 to 7, that they believed their theoretical understanding would improved if they have a chance to discuss with their peers (n=142, M=5.866, SD=1.105). This was furthered supported by the qualitative comments from students from the C1 survey as one of main themes was around the desire for the opportunity to collaborate with their peers. Two comments are highlighted below as examples.

> "I might have missed out some points, it would be better if I can work with my friends where they can point out my mistakes."

> "While we could ask the instructors/ professors/ teaching staff, active discussion with peers would have been quite nice to better clarify our doubts because peers can explain in simpler terms sometimes."

However, the higher perceived theoretical understanding for E when compared to C1 was no longer significant when the laboratory sequence or order effect is taken into account (see Table V). It should be further noted that the magnetic field laboratory (both E and C2) was perceived by students as significantly less difficult than the electric field laboratory (C1) (n = 142, M_D=-0.972, SD=2.235, $p<0.001$). This result was the same even when we compared E and C2 separately against C1, and when we took the order effect or laboratory sequence into account. Hence, it appears that perceived theoretical gains between the two laboratories were not directly comparable.

Nevertheless, Table V also showed that after accounting for order effect, students who had collaborative learning for the magnetic field laboratory (E) rated their perceived understanding significantly higher ($t(122)=2.163$, $p<0.05$, d=0.394) than those who did not have collaborative learning for the same laboratory (C2). The effect size of 0.394 would indicate collaborative learning had a small to medium effect on theoretical understanding [43]. Furthermore, there was no significant difference in perceived difficulty between E and C2 ($t(122) = -0.967$, p=n.s) even though the former was surprisingly higher ($M_E(72) = 4.523$ vs $M_{C2}(52) = 4.154$). This result validates the comparison of findings around the collaborative learning E and the non-collaborative learning C2 setting within the magnetic field laboratory sessions.

To further investigate the interaction between the laboratory sequence and the three groups in terms of perceived theoretical understanding, we conduct a two-way mixed ANOVA analysis. The analyses showed a significant interaction effect of collaborative learning only when laboratory sequence was controlled ($F(1,122)=5.261$, $p<0.05$, $\eta p^2=0.041$). A significant main effect of laboratory difference was also observed regardless of whether laboratory sequence was controlled ($F(1,140)=13.409$, $p<0.001$, $\eta p^2=0.087$) or not ($F(1,122)=22.301$, $p<0.001$, $\eta p^2=0.155$). However, the main effect of collaborative learning was not significant regardless of whether laboratory sequence had been controlled ($F(1,140)=0.772$, p=n.s.) or not ($F(1,122)=0.694$, p=n.s.). Taken together, these results suggested that while perceived understanding of related theories were significantly higher among students in E who engaged in collaborative learning for the magnetic fields laboratory, this effect was affected by whether or not the magnetic fields laboratory was the second laboratory. Thus, H2.1 is only partially supported.

The qualitative comments provided some insights on this phenomenon. Some students who had the magnetic fields as their first laboratory reflected that they were rushing through their individual parts due to a lack of practice.

> "We did not really have the time to comprehend the underlying theory as we were just trying to get the answers out. It did not help that most of the guys had not touched laboratory work for quite a long time."

In Singapore, male citizens needed to serve mandatory conscription for two years before enrolling into university. They might need more time and practice to reacquaint themselves with laboratory work and to recall physics concepts learnt in high school. Next, we would present the results for the hypotheses H1.2 and H2.2 which were centered around actual students performance in relation to the two research questions.

C. H1.2: Students' scores on theoretical understanding are higher after collaborative learning.

To address H1.2, we compared the average score for the sets of individual baseline (n=4) and intervention team questions (n=3) under E setting. The pair-wise t-test suggested that students scored significantly lower ($t(68)=-2.882$, $p<0.01$) on questions they attempted as a team (M=3.140, SD=0.516) than questions they attempted individually (M=3.326, SD=0.412). Thus, this hypothesis was not supported by the study.

TABLE V
PERCEIVED THEORETICAL UNDERSTANDING BETWEEN EXPERIMENTAL SETTING E AND CONTROL SETTINGS C1 AND C2

	1st Group			2nd Group			Significance Test		Effect Size (Cohen's d)	
Without controlling laboratory sequence	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**t**	**df**	**Standardizer**	**Point Est**
Within Subjects: E vs C1	90	7.167	1.743	90	6.333	2.006	3.928***	89	2.013	0.414
Within Subjects: C2 vs C1	52	6.731	1.561	52	6.308	1.744	1.612n.s.	51	1.893	0.224
Between Subjects: E vs C2	90	7.167	1.743	52	6.731	1.561	1.490n.s.	140	1.679	0.260
Controlling laboratory sequence	**N**									
Between Subjects: E vs C1 as 1st Lab	18	6.389	2.004	72	6.139	2.125	0.451n.s	88	2.102	0.119
Between Subjects: E vs C1 as 2nd Lab	72	7.361	1.630	18	7.111	1.183	0.611n.s.	88	1.554	0.161
Within Subjects: C2 vs C1 as 2nd Lab	52	6.731	1.561	52	6.308	1.744	1.612n.s.	51	1.893	0.113
Between Subjects: E vs C2 as 2nd Lab	72	7.361	1.630	52	6.731	1.561	2.163*	122	1.601	0.394

n.s. not significant.
* p <0.05
*** p <0.001

TABLE VI
PERFORMANCE SCORE DIFFERENCE BETWEEN EXPERIMENTAL SETTING E AND CONTROL SETTING C2

	E			C2			Significance Test	
Question Set	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**t**	**df**
Baseline Individual Questions (Four Questions)	69	3.326	0.412	20	3.389	0.298	-0.620n.s.	87
Intervention Questions (Three Questions)	22[a]	3.152	0.501	20	2.883	0.533	1.681n.s	40

n.s. not significant
[a] The 69 students in E were grouped into 22 teams for these questions, hence the sample size.

Nevertheless, a similar result was found with the control group C2 (t(19)=-4.344, p<0.001) who answered the same two sets of questions but attempted all of them individually. Hence, this phenomenon was likely related to the differences in question difficulty and not indicative of a lack of improvement in theoretical understanding.

D. H2.2: Students' scores on theoretical understanding are higher for the laboratory session with a collaborative learning component.

Finally, we compared the average score for the baseline and intervention questions between students in the E and C2 settings. As shown on Table VI and Figure 4, the mean scores for the baseline questions between the two groups were almost identical with statistically insignificant difference (t(87)=-0.620, p=n.s.). This suggests that their theoretical understanding was comparable. Though the mean score for the intervention questions were higher for students who worked in teams in E, it was not significantly higher than the mean score of students who attempted the questions individually in C2 (t=1.681, p=n.s). In other words, though collaborative learning might lead to some improvement in theoretical learning, such short-term gains were not significant.

Some students revealed that they did not gain much from collaborative learning as all of them were clueless about the concepts. This might be one reason why there was no significant difference in the performance score between E and C2. Nevertheless as shared earlier, a lot more students shared that having someone was better than having no one to discuss with. Furthermore, there were students from both groups who suggested that while they had sufficient prior knowledge to tackle the laboratory themselves, they found collaborative learning to be useful. For example,

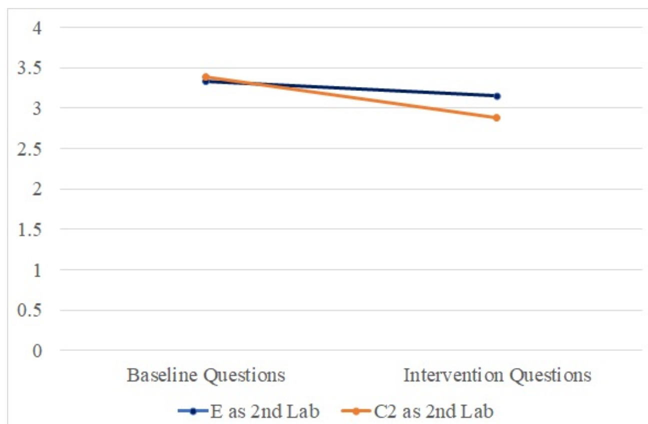


Fig. 4. Student Average Score on Baseline and Intervention Questions under Experimental Setting E and Control Setting C2.

> "As this is a topic that I have had previous knowledge, I felt that my understanding remained relatively similar. But the team discussion definitely helped affirm my knowledge and confirmed what I had previously understood. If it was a new topic, then I do feel that team learning would help in clarifying the concepts with each other and ensure that we are all learning and interpreting the content

correctly." - Student in E

> "I am mostly able to understand the concepts myself, but it would be good to hear other students' perspective to reinforce my understanding." - Student in C2

Hence, the non-significant increase in theoretical understanding with collaborative learning might have masked the gains in terms of affirmative feedback for some students.

V. Discussion and Implication

Taken together, the four hypothesis testings suggest that collaborative learning was valued by students. Like previous studies [20]–[22], students believe that the opportunity to discuss with others had been useful for developing their understanding of concepts. Our key contribution in this aspect was to demonstrate a considerably large and positive effect size before and after collaborative learning and a small but positive effect size when compared with a control group from the same laboratory session. Furthermore, we showed that perceived gain in theoretical understanding may not necessarily translate into significant short-term performance gains.

The non-significant higher performance score in theoretical understanding with the experimental group complements the findings from an engineering class with collaborative laboratory component [23]. However, it differs from Korkmaz [24] who measured significant gains in advanced laboratory skills with collaborative learning. While cultural difference may explain the differences, previous meta-analysis suggested that non-Western students performed better with collaborative learning [18]. Alternatively, collaborative learning might have allowed teams to leverage the strengths of every member more easily in terms of skills than knowledge. Nonetheless, previous classroom-based study such as peer instruction and Team-Based Learning demonstrated significant theoretical gains with collaboration [12]–[15]. A plausible explanation is the type of questions. Those two approaches generally used multiple choice questions while our laboratory questions were open-ended. As stated in another meta-analysis [19] , closed ended collaborative tasks tended to register significant gains.

Regardless, the analysis of the qualitative comments suggests that collaborative learning was seen in positive light by most students in all three settings. Some students further suggested that while their perceived theoretical understanding remained the same after peer discussion, the affirmation they received about their understanding from peers helped them gain confidence in the concepts learnt. In situations where they had knowledge gaps, collaborative learning would have helped them gain new perspectives, identify their mistakes and build a better sense of the concept. In other words, beyond the insignificant performance gains, collaborative learning functions as a great source of both corrective and affirmative feedback for students. Thus, a key implication for this study would be to continue with the collaborative learning component after the individual component for the magnetic field laboratory and for other laboratory classes to consider doing so as well.

VI. Limitations and Future Work

This study has several limitations which provide ample grounds for future research. First, the significant difference in perceived difficulty between magnetic and electric field laboratory suggests that direct comparison between the two laboratory settings need to be interpreted with caution. Unfortunately, we are not able to introduce collaborative components into the electric fields laboratory to ascertain if this approach would result in significantly increased theoretical understanding. Nevertheless, given that most students suggest their theoretical understanding would have increased should they be given the chance to discuss with peers, we are fairly confident that collaborative learning would be valuable for students. Nevertheless, such tests should be repeated for the electric field laboratory in the future.

Second, the study did not control for variation in terms of instruction. The laboratory sessions were managed by different faculty members. Several students suggested in the comments that their laboratory teaching assistants "explain clearly" and "provide guidance" that helped them gain understanding of the related theories. On the other hand, others suggested that the instructors "were not clear" and "difficult to understand". Several studies have suggested that clarity in teaching matters [2], [44]. In fact, some studies suggest that peer explanation may not be as elaborate as tutor feedback [45]. Hence, a future study that control the quality of the tutors' instruction would be helpful to ascertain the extent to which collaborative learning contribute to the development of theoretical understanding in laboratory classes.

Third, the sample sizes in some of the tests had been small and disproportionate. Though they passed the test for normality, it would be prudent to future studies to include larger samples to mitigate the probability of a false negative result. Finally, our experimental approach did not study the impact of repeated collaborative learning on theoretical understanding. This could be the experimental setup for a future study.

VII. Conclusion

In conclusion, our study had provided some of the first quasi-experimental evidence in support of collaborative learning to develop students' theoretical understanding within a laboratory class. For engineering schools who wishes to provide laboratory experience for large cohorts of students, including a collaborative learning component after individual laboratory work could potentially provide students with much needed immediate feedback and support. Though the paper suggests that short term performance gains might not be significant, the qualitative analysis of students suggests that collaborative learning serves as a great source of affirmative and corrective feedback for theoretical knowledge development. Thus, in laboratory situations like ours where faculty member needs to delay their feedback to maintain academic honesty, collaborative learning appears to be a good solution to support students in their theoretical knowledge development.

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