Comparison of Labatorials and Traditional Physics Labs

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Calvin S. Kalman, has been at Concordia for over 51 years (35 as full Professor). He has served many roles at the Canadian Association of Physicists (CAP) including Chair, Division of Physics Education, councillor (in charge CAP tour - Ontario & Quebec), Chair, CAP teaching medal committee. He has also had many administrative positions at Concordia including Principal, Science, College, Chair, Physics and chair of many faculty committees. Internationally he was for many years, chair of the Hyperons Charm and Beauty Hadrons conferences series and is presently Co-Chair Strand 1, NARST. His editing responsibilities include Guest Associate Editor Frontiers and series editor- Science and Engineering Education Sources. He is currently on the editorial board of Science & Education and Disciplinary and Interdisciplinary Science Education Research. He has had 13 books published, written 142 papers for journals and supervised 25 theses. He regularly serves as a referee for journals. He has been honoured to be a member of the Provost's Circle of Distinction at Concordia University, received the Arts and Science Dean's lifetime achievement award for teaching excellence, Canadian Association of Physicists Medal for Excellence in Teaching and the Concordia University Council on Student Life Teaching Award . He is frequently invited to be a keynote speaker, most recently (2019) at two conferences in Bejing and (2020) in Puebla, Mexico.

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Franco La Braca obtained his bachelor's degree in physics with a minor in computer science from McGill University in Montreal in 2018, during which time he developed a passion for education. During his undergraduate years, he also had the opportunity to get involved in computer graphics and animation research with Dr. Paul Kry, working on the development of an algorithm for animating elastic surface deformations, as well as in research in machine learning and early universe cosmology with Dr. Robert Brandenberger, applying convolutional neural networks to the detection of cosmic strings. Upon graduating, he participated in a two-month internship at Safecast in Tokyo, working on expanding the non-profit's educational outreach materials on radiation science and facilitating workshops for youth.

He has since then gone on to obtain a master's degree in physics at Concordia University in Montreal in 2020, where he researched physics lab pedagogy and conceptual learning in the context of labatorials under the supervision of Dr. Calvin Kalman. He also went on a two-month research trip at the University of Washington in Seattle in 2019, where he examined the Physics Education Group's 'Tutorials in Introductory Physics' system and 'Physics by Inquiry' curriculum in comparison to labatorials as well as observed their ongoing physics laboratory reform.

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introduction

The physics lab has long been a distinctive part of physics education [1, 2, 3, 4, 5]. Physics labs play a central role in teaching and learning physics at the high school and undergraduate levels. There is, however, little research done on the educational influence of physics labs on students [6]. Based on our experience and the published reports, we know that many students believe that traditional physics labs are uninteresting and tiresome [6]. In traditional physics labs, students spend 2 to 3 hours collecting data, carrying out calculations, plotting graphs to present their results, and verifying a relationship. Unfortunately, much of the traditional lab experience of students focuses on recipe experiments, which include limited challenges and often choke their creativity [2, 7]. Traditional physics labs can be important in the development of many experimental skills and in demonstrating physics concepts, but they generally do not foster creativity in methodology or experimental design [3]. Moreover, in a study of 3 institutions, taught by 7 instructors, and taken by nearly 3000 students with a high degree of precision, there was no statistically measurable benefit on student course performance from enrolling in the associated lab course [8].

Labatorials (combination of “lab” and “tutorial”) developed at the University of Calgary were inspired by the introductory physics tutorial system entitled ‘Tutorials in Introductory Physics’ at the University of Washington [9]. The Tutorials are worksheets that require students to work through concepts that have been identified by research to be particularly difficult. Some tutorials require students to perform experiments and answer questions based on their observations. However, there is still a traditional lab system for the first year physics courses at the University of Washington.

Labatorials are an approach that combines the conceptual learning benefits and pedagogical approach of Tutorials with essential elements of a physics lab course. Labatorials have been described by Ahrensmeier et. al. [7,10], but there has not been any research to examine students’ perspectives on labatorials including their positive and negative aspects, in particular in direct comparison to traditional labs. In this paper, a mixed methods study is presented that examines and compares the advantages and disadvantages of labatorials and traditional labs in terms of the student experience and conceptual change.

labatorials

Similarly to Tutorials, students in labatorials progress through a worksheet, which now may also include calculation problems and computer simulation questions. Furthermore, the worksheets are fundamentally driven by a core experiment (or set of experiments), and so students are asked to make predictions about the outcome, perform the experiment, collect data, and interpret the results. Students may be given direct instructions for some experimental parts of the lab, while for other parts students may be asked to design their own simple protocol for investigating the concept at hand.

Labatorials highlight the physics concepts covered in lectures and encourage students to present and share their ideas with one another. After performing the experiments, they discuss whether or not the results support their hypothesis. There are typically 3 to 6 checkpoints in each labatorial to encourage an ongoing interaction between the students and the lab instructor and provide feedback in the lab. Each time the students reach a checkpoint, they review the answers with the lab instructor. All students in one group must have the same answers. If the answer to a question is wrong or students are not proceeding in the right direction, the lab instructor leads the students to find the correct answer by themselves, exploring and discussing alternative ideas.

The major goals of using labatorials in introductory physics labs are to improve the overall student experience in the lab and to help students: (1) gain a better understanding of physics concepts; (2) investigate applications of physics principles in real life; (3) evaluate their preconceptions and compare them with their observation; and (4) interact with their peers and the lab instructor in a collaborative learning environment.

The impact of labatorials in conjunction with reflective writing [11], an activity that allows students to metacognitively examine textual material, on students' epistemological beliefs was also explored by Author [12], and it was found that such a combination of interventions can promote positive epistemological change. The scaffolding mechanisms of labatorials and their impact on students' affective lab experience and conceptual learning were further characterized by Author [13], who found that labatorials lower student anxiety and promote deeper engagement in the lab. Similar results were also found by Author [14] when labatorials, which were originally designed for introductory university physics courses, were implemented for the high school level, particularly emphasizing the relative ease-of-implementation of the approach.

However, there has not yet been any research that has directly compared and contrasted the learning that takes place in both labatorials and traditional labs. In particular, students' perspectives on labatorials including their positive and negative aspects have not been thoroughly explored. Therefore, we build on the existing literature by examining and comparing the advantages and disadvantages of labatorials and traditional labs in terms of the student experience and conceptual change.

In labatorials, the idea of scaffolding is manifested in three distinct ways as purposeful aspects of their design. At the forefront is the collaborative learning aspect of labatorials, wherein students actively engage in peer-instruction. This form of interaction is the main means by which students are intended to learn in labatorials, as this is where the bulk of students' independent thinking takes place. Because students often come from different backgrounds and each possess their own strengths and weaknesses, peer-instruction is a natural process in such an instructional setting, with teammates helping each other learn and proceed through the worksheet. In this case, the students are provided scaffolding by their potentially more knowledgeable peers. However, this does not imply that the instructor no longer plays a role. Rather, they serve as the next level of scaffolding for students. Although students will discuss ideas with each other, there will be moments when the group needs to verify their understanding, either due to encountering some difficulty or arriving at a checkpoint. This role is critical as the instructor is typically an expert in the subject matter of the course. Additionally, as an educator, they are in the best position to guide students' thinking in the right direction and to help arrange their learning experience so as to optimize their learning.

For labatorial students, the forms of scaffolding inherent to the design of labatorials all play a significant role in students' conceptual growth. In particular, peer instruction is an important mechanism to assist students' learning. This occurs in part because of the reciprocal nature of the process. In particular, Derek (pseudonym), a labatorial student interviewed for the study, noted that he and his teammates did not simply provide each other with the solution to a problem or the answer to a question, but rather frequently engaged in discussion, saying that:

It wasn't just like, 'Here is the equation that you use for this. Solve for this.' [...] That's what was really helpful for the groups. It's that back and forth talking about which direction we should take it.

The highly supportive nature of the teamwork in labatorials also encourages more meaningful discussion between peers, often strengthened by the heterogeneity of the teams. Catherine perceived both of these benefits, saying that:

To feel like you're in a safe enough space that it's like, 'Hey, I actually don't know what I'm doing. Could you explain to me why you understand this?' We all had moments like that, where one of us was the one who knew more, and the other was the one who knew less. We were even, but we all came out of it more knowledgeable.

As such, students in labatorials are deeply cognitively engaged with the concepts of the lab, discussing until they all come to the same answer. This type of collaboration is also encouraged by the design of the labatorial questions themselves, which are challenging enough that students usually need to collaborate if they want to proceed. Therefore, students become more engaged in the problem solving process while simultaneously developing their ability to think independently.

methodology

In this study, labatorials are implemented for the course 'PHYS 224 – Introduction to Experimental Mechanics' in the summer 2019 semester. Corresponding to our goal to compare labatorials and traditional labs, we explore the following research question and sub-questions:

How does the experience of learning differ between labatorials and traditional labs?

a. How do social interactions in the lab impact the student learning experience?
b. What elements of labs play a role in providing a satisfying learning experience?
c. In what ways do labatorials affect student perspectives on physics?
d. In what ways does students' self-efficacy evolve through physics labs?
e. In what ways do labatorials and traditional labs differ in promoting the development of conceptual understanding?

The mixed methods design involves concurrent qualitative and quantitative data collection, which was integrated at the data interpretation phase of the research using a triangulation strategy. Throughout the research process, we take a social constructivist epistemological stance with particular emphasis on the role of scaffolding in knowledge construction [15, 16].

The labatorial (experimental) group consists of $N = 30$ students divided over 3 sections and the traditional (control) group consists of $N = 24$ students divided over 2 sections (each with one instructor), each performing 6 weekly labs. Equivalence of the two groups at the beginning of the course was established using a pre-test containing 6 questions sampled from the Force Concept Inventory [17]. This sample from the Force Concept Inventory was only used pre - not post and only to determine how similar the two groups are and indeed established that the two groups were effectively equivalent in terms of their conceptual understanding before the labs took place. With this result, subsequent performance of the groups could be meaningfully compared. Due to curricular constraints, we could not implement meaningful pre-post testing for each of the groups, and so different assessments were instead used for comparing the two groups throughout the course. In particular, common post-tests designed for the study were administered at the end of each lab for all students, and a common final exam was administered to all students at the end of the course. As such, these assessment results are analysed and compared between the two groups.

The qualitative portion of the data is comprised primarily of semi-structured pre- (after the first session) and post- interviews with 6 labatorial students and 6 traditional lab students. To then gain further insight and perform triangulation, class observations, semi-structured interviews with the 3 different teaching assistants (TAs) for the course, and the labatorial worksheets and lab reports of the respective interview participants are analysed.

qualitative results

How can the learning experience differ between labatorials and traditional labs?

In considering the learning experience of the students between both groups, threading across the interviews is the core theme of "support." Namely, we adopt the interpretation that through various mechanisms of support or scaffolding, students are made to feel more comfortable in the lab through the lessening of their various sources of stress. Therefore, we address the research question by comparing and contrasting the mechanisms of scaffolding present in both types of labs and the impact those have on students' experiences.

Based on the student pre-interviews, the types of scaffolding provided by labatorials fall into one of three categories: (1) peer support, (2) TA support, and (3) grading-related support. In labatorials, peer support was very important for creating a positive experience for students. When asked what was most special about the teamwork in labatorials, Derek stated that:

...it's the, I don't know if it's the right word, but the camaraderie of it. Because by myself in labs, if I get frustrated, I just feel so lost. You kind of feel like, 'Oh god, everyone else maybe gets it and I don't. What's wrong with me?' But when you're in a group it's more like, 'Oh, they

don't understand either!' Or I know more about some things and they know more about some things. It's a lot more just relaxing, easier to just focus on the lab itself. And it's good to bounce off ideas and ask for help from your partners. So I'd say it's just a better experience, just less stressful like in terms of being by yourself.

Jessica also strongly resonated with this idea, additionally commenting that the team's mutual dependence instills a sense of group accountability as individual accountability:

So when you're doing it with the misery of... Not that we were miserable, but if you're going through something that's challenging, it's much easier to do when you're with other people who are in the same boat and feeling the same stresses and things like that. And that they're rooting for you, because their success also depends on you, whereas in other labs it's like, 'Screw you, I'm just gonna do my own thing and you can go ahead and drown.'

Interestingly, many interviewees indicated that this sense of camaraderie extended beyond their peer interactions to their interactions with the TA as well. Jessica stated that she "really liked, like not working with him, but how he came through" whenever they were struggling. Catherine additionally expressed that "the nice thing about [the lab] is that even with the TA [...] it felt like a team effort toward understanding." This suggests that the TA relationship was one of collaboration as much as one of guidance. Additionally, all students expressed that they felt that the TA was always very involved, regularly checking in on students. This helped Catherine "really feel supported by the TA."

The checkpoints in the labatorials in particular helped encourage students to share their doubts with the TA and feel supported by him, particularly due to the checkpoints being a core element of the lab itself. Namely, Emma expressed that:

...it's expected to ask questions, and it's expected to get the go-ahead before moving on. I like that so much more than just feeling like you're on your own if you don't understand it because you haven't prepared properly. I like having the help available, and that you're expected to use the resources and help of somebody there.

The checkpoints additionally helped alleviate students' stress in the lab by helping them feel confident in progressing in the worksheet.

As a result of the various forms of support present in labatorials, many students also underwent changes in their perspectives on and feelings toward physics. One common sentiment was that they felt more confident not only problem solving, but in thinking about physics in general. In addition to improvements in self-efficacy, Catherine, whose feelings about physics before taking PHYS 224 were bleak, underwent a major transformation in outlook. She now "[thinks] that [she] feels better about moving forward in physics in general," and she and Jessica both expressed that physics became less scary to them by the end of the course. Additionally, Stacy said that she came to better appreciate the importance of "not just accepting the equations as they are, but trying to figure out what each letter is doing, what each component is doing," suggesting a shift toward expert-like thinking.

In contrast, Wieman [18] notes that in a typical instructional lab class, the student uses a given apparatus to confirm an established scientific result. So one can see that most of the cognitive tasks have already been carried out and the students are simply given the result. For example:

- Given — research question: "Measure g"
- Given — data to collect: "period and length of pendulum"
- Given — feasibility analysis
- Given — apparatus design
- Given — construction
- Given — components already built and tested
- Not given — data, must collect
- Given — analysis methods
- Not given — statistical uncertainty
- Given — what the correct answer is, what the instructor wants to see
- Given — format for write-up, data tables, and graphs
- Given — significance and context (making clarity of presentation and argument largely irrelevant)

As such, there is no time to go through multiple iteration cycles.

In traditional labs, the support mechanisms fall into one of three categories: (1) peer support, (2) TA support, and (3) procedural support. However, the ways in which these types of scaffolding manifested in the lab and the role they played for students are different than they were for the labatorials. In particular, the group aspect of the lab was not as fundamental a part of the lab experience as it was for labatorials. While there were labs where students needed to work in teams, the interviewees appeared to often not work in a very unified way. Students would at times proceed at a similar pace, but take their own approach to different steps of the experiment. Although not an experience from PHYS 224, Catherine expressed that in many of her past non-physics labs that were run under a similar traditional format, although "[they've] all read the same lab [...], you kind of come at it with a different approach, or you don't know who's gonna do what." As such, the interviewees' group work experience was often more akin to working individually in their groups rather than collaboratively driven. As stated by Lauren, a traditional lab interviewee, *"It's like [you're] checking with your partner, but still working individually."*

The TA in the traditional labs served as another source of support for similar reasons. While students would ask their peers first if they were not sure about something, they felt comfortable asking the TA questions if they needed additional help. Evelyn said that "he seemed to be receptive to the sort of questions that [she] had," with Amir adding that "he's always willing to help [them] figure out things in a way that works for [them]." As with the questions peers would ask each other, the support provided by the TA typically involved clarifications or verifications. Furthermore, the TA would always answer students' questions very directly, "without being hesitant or questioning what's going on," as phrased by Zion. While the students all appreciated this support by the TA, many also indicated that the TA was less directly involved throughout the lab, taking instead a more managerial approach. Although most of the interviewees appeared to be satisfied with the support present in the labs since they could get help whenever they needed it and felt at ease doing so, the need to get a good grade in the lab may still have been a large motivator and source of stress for some students.

As such, the general mindset regarding interacting with their peers and the TA in the lab may reflect a focus on error avoidance, i.e. obtaining the correct numerical results. This stems from the pressure to get a good grade in the lab, which necessitates obtaining an accurate enough result and low enough error in order to receive full marks. This is why Lauren "[hasn't] enjoyed very number-specific corrections that [she] had" until now, appearing to be a source of stress in her labs. However, she stated that she enjoyed the PHYS 224 labs because the instructions were detailed and straightforward to follow. They acted as a form of support to her in the sense that they helped her feel more confident that she was proceeding correctly. This corroborates an error-avoidance mindset, incurred by the grading structure of the lab. Lauren also felt that having instructions helped her understand the material better:

A very recipe-like lab is very good, I think, since you won't miss something and you'll follow the steps very well, which helps you actually understand. And it helps you understand before the lab [since] you know what's happening step-by-step, rather then when it's just like a vague text where you have to pick out the steps for the procedure.

How do labatorials and traditional labs differ in promoting the development of conceptual understanding?

We centre our discussion on the theme of cognitive dissonance [19], namely, the possible conflict between students' pre-understanding and what they perceive in the lab. In this sense, the resolution of the associated cognitive dissonance is essential to addressing conceptual change.

The interviews indicated that labatorials promote conceptual change by the following means: (1) real-world connections, (2) peer-instruction, (3) deeper engagement, and (4) their structure, namely the checkpoints and conceptual scaffolding. Due to labatorials' emphasis on real-world applicability and inquiry, students often perceived a sense of relevance through the labatorial activities or related them to their intuitive experience, increasing student interest and motivation and helping them make the connection between theory and reality. Furthermore, students collaborated and helped each other when one or more student did not understand something as they progressed through the worksheet, discussing until they all came to the same answer. In particular, Derek noted that he and his teammates did not simply provide each other with the solution to a problem or the answer to a question, but rather frequently engaged in discussion, saying that:

It wasn't just like, 'Here is the equation that you use for this. Solve for this.' [...] That's what was really helpful for the groups. It's that back and forth talking about which direction we should take it.

This type of collaboration was also encouraged by the design of the labatorial questions themselves, which were challenging enough that students must usually collaborate if they wanted to proceed. Students therefore got more engaged in the problem solving process and simultaneously developed their ability to think independently. This was furthered by the way the TA approached helping the students by guiding them and directing their thinking instead of answering questions directly. Such strategic interventions at the checkpoints, in particular, helped scaffold students to an understanding of the concept while ensuring that all students came to the same conclusion and did not build on misconceptions. As expressed by Catherine:

I'm seeing step-by-step what's happening, and the fact that he would come over and check in with us each time and affirm, 'Yes, you're doing this right,' or, 'Actually, why don't we think about it this way instead?' is very helpful. It makes me feel like, 'Yeah, this makes sense.'

The prediction questions of the labatorials were also important for developing students' conceptual understanding. According to Quincy:

All the predictions, they just helped you write out and then discuss with your teammate about your own ideas, about that event, about that problem. And then when you go through the lab, they start to change because not exactly everything you think is right. After you go through the lab, you go through all the experiments and all the work, and you will find the final result of that problem. And then you will understand that, 'Ok, I was thinking wrong at first, and now I need to think in that way for things to make more sense.'

Quincy's description of this learning process in the lab, which most of the interviewees expressed in one form or another, is exactly consistent with the elicit-confront-resolve sequence for tackling misconceptions described by McDermott & Schaffer [9] in the context of the Physics by Inquiry curriculum on which the approach of labatorials is intrinsically based; the worksheet elicits students' pre-understanding of the concept, allows students to confront their misconception(s) through the experiment, and then resolve the conflict(s) in their understanding (and the associated cognitive dissonance) through discussion. It is the extensive scaffolding inherent in labatorials that allows this development of conceptual understanding to occur.

In traditional labs, conceptual change is promoted primarily by (1) the theory explanation given by the TA at the beginning of the lab, (2) the real-life connections of the experiment, and (3) peer collaboration. Mentioned by two students, having a brief summary of the theory needed for the lab at the beginning of the session helped them in performing the lab. Seeing the concepts then applied hands-on in the experiment helped some students make the connection between the theory and reality, although the connection was purely in terms of tangibility rather than personal relevance. Furthermore, some students mentioned how they would occasionally verify each other's results, and one student mentioned how they would help each other if someone was confused. However, students' responses indicated that the discussions did not typically exceed procedural aspects of the lab.

The emphasis on error avoidance in doing the lab expressed by most students may have acted as an inhibitor to conceptual change (particularly in terms of numerical correctness and correct execution of the experimental steps). While accuracy and precision are certainly important from an experimental standpoint, it can lead students to focus solely on following the lab instructions as closely as possible and not think through the core conceptual ideas as they work through it. While students may certainly still care about understanding the concepts, this recipe-like, correctness-focused lab structure is generally less conducive to conceptual learning in the lab, which is well-explicated through Zion's response:

You would have to kind of do a little extra work if you really want to understand it. And if you don't, then you're going to go in, you're going to follow a bunch of steps [...] and then that's it.

Amir additionally expressed that the learning experience in the lab was not scaffolded enough overall. In particular, the recipe-like lab instructions of the labs made him unmotivated to learn:

I found when I started off, 'Ok just memorize everything in the lab manual. Read it, memorize it, memorize it.' And then I just stopped kind of... Like I'd read it, take a few notes, make sure I see [the basics]. But that doesn't really encourage, you know? It kind of just makes you... Makes me go complacent, apathetic.

This sentiment extended to the lab reports for the course, saying that he "found [the format] really formulaic."

As a result of this lack of scaffolding, students may go through the motions of the experiment without thinking through the concepts deeply, and so they may not address any conceptual difficulties while in the lab. In most traditional lab courses, where lab reports are written at home, submitted a week later, and then returned the following week, students will often only begin trying to understand the ideas of the lab after the lab has already ended. The reflection of Stacy, a labatorial student, on her past traditional lab experiences also echoed this sentiment, adding that:

I think [traditional labs are] less about thinking, and more about if you can follow steps. [...] Sometimes we just try to rush and do whatever we can to get results, and then we get home and deal with it. In class, you have the opportunity to talk with your lab mates, and the TA trying to figure out [a problem] on the spot, and sometimes that's more valuable than trying to Google it once you get home.

Triangulation with the TA interviews, class observations, and TA surveys leads to similar results. Notably, the TA interviews are consistent with the student interviews overall regarding students' affective learning experience. The TAs stated that while TA and peer support play a role in both labatorials and traditional labs, the nature of these forms of support is different in the two types of labs, with the labatorial interactions involving more scaffolding and the traditional lab interactions involving more results-oriented, independent work. These were also apparent from the classroom observation data and the surveys that the TAs answered at the end of each lab. The themes of grading support from the labatorial interviews and procedural support from the traditional interviews did not arise in the TA interviews, perhaps due to both involving highly subjective aspects of the lab experience that students were not likely to visibly express, and so we cannot triangulate for those themes. Nevertheless, all the pertinent sources of data are in agreement with the student interviews.

Similar results hold for the ways that labatorials and traditional labs promote conceptual understanding. Namely, the promoters and inhibitors of learning in labatorials identified from the student interviews were confirmed by the TA interviews. They stated that students' interactions with their peers and the TA created an environment that promoted discussion and assisted students in resolving their conceptual difficulties, which was apparent in observing the class sessions. Contrariwise, the TAs did not refer to any particular promoters of learning in traditional labs, instead identifying inhibitors strongly related to those indicated by students. As such, all three TAs felt that labatorial students learned the concepts more deeply than the traditional lab students, with Isaac in particular stating that “[he] would actually put money that they [understood] better in labatorials because of the [lab report] conclusions that [he] read from the traditional lab [students].” However, they also indicated that due to the reduced focus on experimental techniques in labatorials, they might have become less proficient at these than the traditional lab students. Additional research would be required to investigate this claim.

quantitative results

How do students’ learning outcomes compare between the two approaches?

The two main types of assessments that were used in the course were the post-tests after each lab and the common final exam, the latter of which contained six targeted conceptual questions designed for the study. We compared the mean scores for the total of the post-tests, the final exam as a whole, and the targeted conceptual questions of the final exam. We concluded that the score distributions do not differ significantly and thus that neither group performed better than the other on average on the post-tests.

For some questions (typically the conceptual questions), labatorial students appear to perform better, while for others (typically the numerical questions), traditional lab students appear to perform better. These results are confirmed and further refined by qualitatively analyzing the questions under consideration and triangulating all of the above results with the classroom observations, TA surveys, and students’ labatorial worksheets or lab reports: labatorial students generally exhibit mastery of the concepts targeted in the lab, while traditional lab students exhibit mastery of standardized procedures and memorization-based calculations. These results both make sense considering the focus of each type of lab; labatorials are designed to reinforce concepts, while traditional labs involve recipe-like work.

Although all students had access to resources during the final exam (i.e. the worksheets for the labatorial students and the lab notebooks for the traditional lab students) with all the same essential information and equations, the labatorial students did not seem to be as proficient at questions about linearization or plotting a line of best fit, for example. This may have been due to labatorial students’ minor graphing errors not always getting caught by the TA at a checkpoint. There is also the possibility that due to the nature of the questions in the worksheet, they would try and explain more than needed or overthink somehow and thus make a mistake. This also occurred quite often in the one-step, formula-based exam questions, and so the underlying cause of the discrepancy may be the same. However, it does make sense that despite this, both groups performed equally well on the longer calculation questions.

While we would have expected labatorial students to perform better than traditional lab students on all of the conceptual questions, there could be a multitude of reasons pertaining to the design of the course or the questions themselves that could have rendered this implementation of the course suboptimal. The results nevertheless suggest a general trend for the types of questions (i.e. conceptual or memorization-based numerical) that students in each type of lab learn to solve, which is a valuable result since it may hold generally for the two lab types regardless of the specific course content. However, additional research would be required to confirm this.

These results are mostly consistent with the literature on labatorials and traditional labs. For example, Wieman &Holmes [8] showed that in a lecture course, there was no statistically detectable difference in exam performance between students who had or had not taken the associated lab course. Both this result—which considered the final exam questions pertaining to the lab concepts—and our own—which considered the final exam and post-test questions specifically targeting the lab concepts—suggest that indeed traditional labs are not productive for students' conceptual learning. While this is not necessarily contradictory to the result that labatorial and traditional lab students did not perform any differently on the longer calculation problems, prior work has shown the benefit of conceptual understanding on problem solving ability [20]. Why this discrepancy exists despite the labatorial student interviewees indicating several learning benefits with regard to problem solving should be investigated in a future study.

conclusion

Labatorials have been compared side-by-side with traditional labs for the first time. The mixed methods study presented aimed to understand how each lab approach affects the student experience and students' conceptual learning. Labatorials appear to improve students' learning experience and promote conceptual change more effectively than traditional labs due to the learning approach and structure utilized, increasing students' engagement with each other and the concepts. This in turn led to a stronger understanding of the concepts addressed in the lab, as illustrated through the course assessments.

Students' interactions between both peers and the TA in labatorials served as a form of scaffolding that was affectively perceived as mechanisms of support. Although the constant scaffolding (in particular by the TA) could be seen as restrictive by stronger students, most students indicated that the overall lack of stress and sense of ease incurred by such support made for a more enjoyable overall learning experience, with many additionally undergoing positive shifts in their self-efficacy and their perspectives on physics. This is reinforced by several unprompted vocalizations of satisfaction by all the interviewees regarding the labatorial style.

The integration of diverse mechanisms of scaffolding in labatorials provided numerous benefits for students' conceptual development. Although the risk of over-depending on one's peers exists due to the extensively collaborative nature of labatorials, peer-instruction was nevertheless a powerful means to assist learning. The additional affective benefits of such scaffolding (as well as those due the overall absence of pressure due to grading) also allowed students to focus more on their learning in the lab, which—in conjunction with the inherently scaffolded worksheet structure—improved their overall engagement with their peers and the concepts in the lab. Furthermore, although labatorials emphasize understanding concepts over developing experimental skills in this way by design, such an approach also proved to be beneficial to students' understanding of the experiments. These benefits were further enhanced by the explicit connections of the lab content to the real world.

In traditional labs, there were certain forms of support present, namely procedural support provided by the lab manual and that provided by peers and the TA in acting as a resource for students that enabled them to voice their doubts and verify their work. These often helped students to partially cope with some of the sources of stress in the lab and thus feel more at ease, albeit with some students feeling that the lab experience was not scaffolded enough. While the traditional lab interviewees all had different takeaways from the course, many were not affective in nature and, unlike the labatorial interviewees, none referred to their general outlook on physics. With the exception of Adrian, who expressed that the lab "wasn't as bad as [he] thought it was going to be," none of the interviewees vocalized satisfaction with the course without the prompt of a question.

While peer interactions in traditional labs played a role in student's learning in the lab, the style of cooperation was typically not collaborative enough to promote deeper learning. The labs themselves did not emphasize learning concepts, although the theory explanation at the beginning of each lab helped direct students' thinking. Furthermore, both the hands-on and visual aspects of performing experiments helped solidify concepts for many students as well as helped them see connections with the real world. Nevertheless, one student in particular felt that the overall lab experience was not scaffolded enough, with the recipe-like instructions of the lab not encouraging students to thoroughly think through the ideas of the lab. This, combined with the focus on error avoidance induced by the pressure due to grades and further encouraged by the recipe format, made the traditional labs generally less conducive to conceptual learning.

Therefore, while conceptual learning may be possible in both types of labs, labatorials appear to be better suited to promoting conceptual understanding while traditional labs emphasize experimental lab skills. This is because the regular discussion and conceptual scaffolding that occur in labatorials are more conducive to the acknowledgment and resolution of cognitive dissonance. This can also largely be attributed to the difference in focus that students have in the lab, namely focusing on learning as opposed to error avoidance, which respectively tend to result in understanding while doing as opposed to doing without understanding.

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