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Exploring problem-based cooperative learning in undergraduate physics labs: student perspectives

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Abstract

This study examines the potential of problem-based cooperative learning (PBCL) in expanding undergraduate physics students' understanding of, and engagement with, the scientific process. Two groups of first-year physics students ($n = 180$) completed a questionnaire which compared their perceptions of learning science with their engagement in physics labs. One cohort completed a lab based on a PBCL approach, whilst the other completed the same experiment, using a more traditional, manual-based lab. Utilising a participant research approach, the questionnaire was co-constructed by researchers and student advisers from each cohort in order to improve shared meaning between researchers and participants. Analysis of students' responses suggests that students in the PBCL cohort engaged more in higher-order problem-solving skills and evidenced a deeper understanding of the scientific process than students in the more traditional, manual-based cohort. However, the latter cohort responses placed more emphasis on accuracy and measurement in lab science than the PBCL cohort. The students in the PBCL cohort were also more positively engaged with their learning than their counterparts in the manual led group.

Supplementary material for this article is available online

Keywords: problem-based cooperative learning, undergraduate laboratory education, student perception of scientific process

1. Introduction

An objective of experimental undergraduate physics is to provide an environment for students to develop the scientific 'habits-of-mind' [1] associated with doing physics; practices such as designing, modelling and executing experiments that test hypotheses and, ultimately, lead to the student constructing knowledge [2]. Many current undergraduate physics laboratories employ a traditional, 'recipe-book' approach to laboratory exercises [3], whereby students follow direct instructions from a manual and report on their experiments using a pre-determined framework [4]. This approach to undertaking experiments has been shown to have a limited impact on student learning [5]. Furthermore, this approach neither requires nor encourages students to develop a strong sense of the scientific experimental process routinely practised by research scientists or to practice problem-solving skills [5, 6]. Research suggests that students should be encouraged to positively engage in their learning, since their degree of engagement can be a strong predictor of academic achievement and impacts positively on mitigating student attrition [7, 8].

Against a local background of poor learning outcomes from undergraduate physics laboratory classes with low student engagement and little evidence of students acquiring scientific habits-of-mind, we sought to investigate the impact of introducing a new approach to learning in lab classes on students' perceptions of and engagement with the scientific process and the higher-order cognitive skills associated with that [9]. In an attempt to engage students in reflecting critically on their own learning (metacognition) and on the scientific process, we implemented an approach suitable for large class groups, which combined problem-based and cooperative learning (PBCL) in a physics lab. Student responses from the PBCL lab were compared with those from students who completed the same experiment but using a traditional, lab manual-led approach.

1.1. Problem-based cooperative learning (PBCL)

Problem-based learning (PBL) is a learner-centred instructional approach in which students take responsibility for their own learning as active problem solvers [4, 10]. This approach has been shown to have positive effect on motivating learners and encouraging them to reflect on their learning [11]. It does not, however, have a strong focus on collaboration, which is helpful in solving unfamiliar problems [6, 12]. Solving problems in a social context is an important scientific habit of mind which requires students to cognitively engage with the content and work together to develop a solution. Cooperative learning (CL) provides such an approach to teaching and learning where students work together and communicate in small groups to accomplish a common goal, while also being individually accountable for their work within the group [13, 14].

PBCL incorporates these approaches to experimentation in the lab, whereby students can develop and practice a spectrum of scientific habits-of-mind. PBCL research, focusing on physics tutorial classes, [15] has shown that in well-functioning, cooperative groups, students share conceptual and procedural knowledge and argument roles, as well as seeking elaboration and justification from one another. This work seeks to further explore the impact of PBCL on students' engagement and understanding of the science process during practical laboratory sessions.

2. Methodology

Two-hundred first-year undergraduate physics students took part in five compulsory laboratory sessions as part of a physics module. All students were from the same degree programme; they took lectures as one group and were familiar with one another. The class group was divided into two cohorts based on the students College ID number. Both cohorts completed all laboratory classes within the same academic term, but took their lab classes on different days of the week. One cohort followed a traditional, manual-based approach for all five experimental sessions (the manual-led cohort). The other cohort carried out four experiments using a manual-led approach and one utilising the PBCL approach (the PBCL cohort) to experimentally determine a value for acceleration due to gravity.

The lab manual-led cohort were asked to find a value for acceleration due to gravity using a pendulum, an equation, and an explicit step-by-step procedure given in the lab manual [3, 6]. Students worked in pairs and, at the end of the three-hour lab, reported on their findings in a pre-designed template. A student's work was assessed against their' ability to follow procedure and arrive at a pre-determined solution. For the PBCL approach, students worked in teams of three or four. Posed with an experimental problem, student teams were encouraged to construct and critique their own approaches, using any equipment or technology available to them in the lab or online. Following a class discussion (in groups of approximately 20 students) with the tutor about the format of the lab, they were challenged to determine acceleration due to gravity using creative and original methods (and without a lab manual). After 1 h (of the three-hour lab), student teams in the PBCL cohort presented their initial ideas, strategies and findings to one another. Student teams were encouraged to peer-review each other's strategies, could suggest modifications to one another's strategies, and use ideas from the review session in their own team's experiments. Approaches employed to determine acceleration due to gravity varied greatly, from strategies covered in standard university physics text books to more creative methodologies. Students recorded their experimental findings in a 'free' format and were encouraged to record all of their ideas and thinking in attempting to find a value for acceleration due to gravity. Student reports were assessed in terms of their creativity, as well as the reliability and validity of any findings. A similar completion rate of the submitted lab report was seen in both cohorts.

Following completion of this physics module, both cohorts (manual-led and PBCL) were invited to participate in an online questionnaire.

2.1. Data collection

Utilising a participant research approach [16], researchers and two student advisory groups (one for each cohort, where student volunteers were selected at random), co-constructed a questionnaire where student advisers provided a variety of different responses to open questions which, they felt, would represent the range of views of their peers in their respective cohorts. A selection of these responses, purposefully representing diverse and contrasting views, was selected by the advisory groups and incorporated as prompts within the questionnaire. In the online questionnaire, some of the open questions asked of both cohorts were the same (the prompts seen by each cohort differed, however, reflecting the views of each student advisory group). The remaining open questions, while broadly similar, were phrased to reflect differences between the cohorts' experiences. The complete questionnaire can be found in the appendix. An example of a question asked of the PBCL cohort is

We asked some students in your class about their physics labs. Please read the student comments and add your own response—you can indicate your level of agreement/disagreement with any of them in your response if you wish:

We asked them: 'What did you think of the PBCL approach for physics labs'? They said:

- *'More enjoyable, as I was allowed to use my imagination when thinking of a method of experimentation.'*
- *'I found it less mundane, rather than simply following the rules; I could do the experiment my way.'*
- *'I found it more difficult with less guidance from demonstrators.'*
- *'It was a more engaging and interesting approach to carrying out investigations.'*
- *'Having not done physics, I found the approach very challenging to carry out an investigation without guidance.'*

Please write what did you think of the PBCL approach for physics labs.

This research approach is grounded in children's rights-based methodology. It relies on prompts from an advisory group to help inform the 'voice' of respondents to questionnaires. Students in the advisory group were not asked to give their own views, but to objectively include a range of views which might reflect those of peers. These prompts ensure that participants of the online questionnaire are 'facilitated in expressing their view' [16, page 590], by giving them a broad framework to confidently express their views as related to their peers, rather than being led to a pre-determined researcher's conclusion. Research has shown that such prompting by people '*like them*' encourages respondents to engage more fully and enthusiastically with survey items and provides a bridge between the researchers and those participating in the research [16]. Consequently, in the context of this research, the responses from students generated a virtual conversation, where participants engage with ideas of other students, as opposed to responding to questions posed by researchers with no direct experience of these labs as learners. The online questionnaire took approximately 15–25 min to complete and had a completion rate of 90%.

2.2. Data analysis

Student responses ($n = 92$ for PBCL cohort and $n = 88$ for lab manual-led cohort) were coded using a recursive and iterative process according to parsed phrases, with the three authors establishing an agreed coding framework [17]. After the first iteration for a selection of data, inter-rata reliability was established at 85% and the framework was refined. A second and third iteration of analysis was then completed by each researcher, with the following three themes emerging (indicative quotes are given):

1. Students' conceptualisations of the scientific process

– '*You are thinking more about why and how the results of the experiment are formed.'* (student from PBCL cohort)

2. Students' engagement with the physics lab classes

– *'It was the easiest out of the* 5 *experiments.'* (student from manual-led cohort)

3. Correlations between student engagement and scientific habits-of-mind

– *'The experiment was quite simple but I feel that I would have enjoyed it more if I understood where the equations for the period of the pendulum came from, rather than just collecting data and putting it into the formula.'* (student from manual-led cohort)

Responses from both manual-led and PBCL cohorts evidenced depth, analysis, and thoughtful engagement with the question, where many responses exceed 100 words in length. Responses often contained multiple codes.

3. Findings and discussion

We found that most students in the PBCL cohort conceptualised the scientific process as the way they believe scientists work—which they identified as requiring creativity, criticality, inventiveness and systematicity. In contrast, the manual-led cohort generally described more technical aspects of the scientific process and only as it applied to the specific experiments they were carrying out, referring to accuracy, error and careful attention to procedure. Findings under the three specific themes are detailed below.

3.1. Student conceptualisations of the scientific process

Responses from the PBCL and manual-led cohorts were coded according to their conceptualisations of the scientific process and a representation of these codes, comparing both cohorts, is shown in figure 1.

More than one third (38%) of the comments from PBCL students focused on the role of creativity in the scientific process. Additionally, 6% of student remarks emphasised the need to '*use a variety of methods*' and to '*think outside the box*'.

> *'I do think it [PBCL] promotes learning because you are forced to understand what is going on when coming up with your own method. It is too easy to let the demonstrator/manual tell you what to do.'*

A further 20% of comments referred to need to '*challenge your preconceptions*' when applying the scientific process with a further 9% saying one should not '*just accept things*'. Interestingly, 4% of responses acknowledged the role of failure in the scientific process, accepting that there's a '*risk you could be wrong*'. A small proportion of responses mentioned the roles of error, calculating terms, application of theory and, accuracy through repetition.

> *'I wasn't sure of the whole idea of this new way [PBCL], but I understood as I went through that this is exactly how a real physicist would have to do it. They would have to design an experiment to find an unknown that they had theorised.'*

Comments from the manual-led cohort relating to their conceptualisation of the scientific process were more focused on mechanistic or technical elements. 41% of their remarks highlighted the importance of errors, carefulness, and uncertainty.

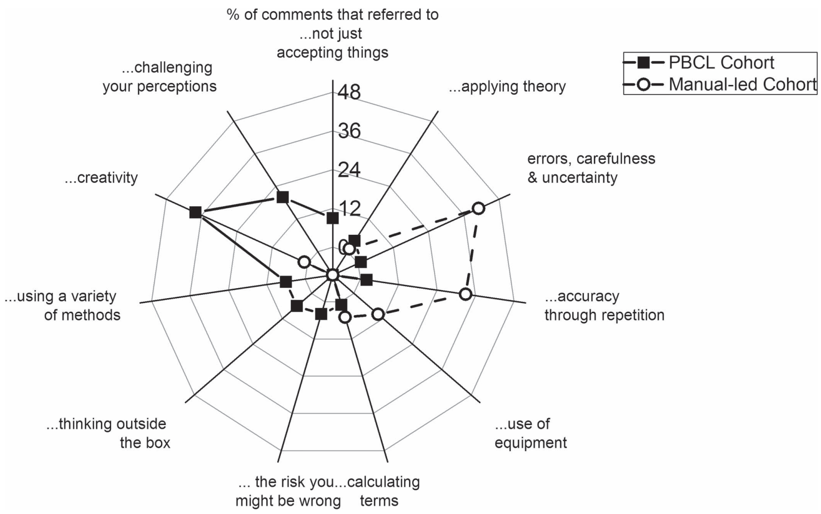

Figure 1. Spider chart representing categories of student ideas about the scientific process from the PBCL ($n = 87$ responses) and manual-led ($n = 82$ responses) cohorts. All codes emerging from the data are shown.

> *'The scientific method I learned in this lab is, to obtain data you have to be really careful and concentrate otherwise the results will end up in error. Although in an experiment there are always some unintentional errors, I think it's best to lessen as much error as possible, which means reading the whole method before doing the experiment and carefully conducting the process.'*

A further 33% of student comments alluded to the importance of accuracy and repetition, such as

> *'Different apparatus have different levels of accuracy and taking errors into account is mandatory to see the accuracy of your answer. The answer is never perfect but we are told to try and stick to the method.'*

> *'Increased repetitions of the experiment lead to better results.'*

Other responses mentioned '*use of equipment*' (10%) and the '*calculation of terms*' (5%). Only 1% of the manual-led student cohort mentioned '*applying theory*' or the need to be creative in their conceptions of scientific method.

From the PBCL cohort, students' views of the scientific process contrasted with their peers in the manual-led cohort. While comments from students in the manual-led cohort reflected the importance of procedure and accurate measurement in the scientific process, comments from their peers in the PBCL cohort demonstrated an appreciation of higher-order learning and thinking in science, as referred to in Bloom's taxonomy of learning [18], such as creativity, evaluation and analysis. It is worth noting, however, that comments from the PBCL cohort do not refer to accuracy and measurement—both essential aspects of the scientific process. While a grasp of principles, not alone skills in manipulation, are essential in all aspects of an undergraduate physics course [19], approaches to laboratory teaching must ensure the development of each. Further research is required to understand if the PBCL approach outlined in this paper can encourage students to conceptualise accuracy and measurement as essential aspects of the scientific process.

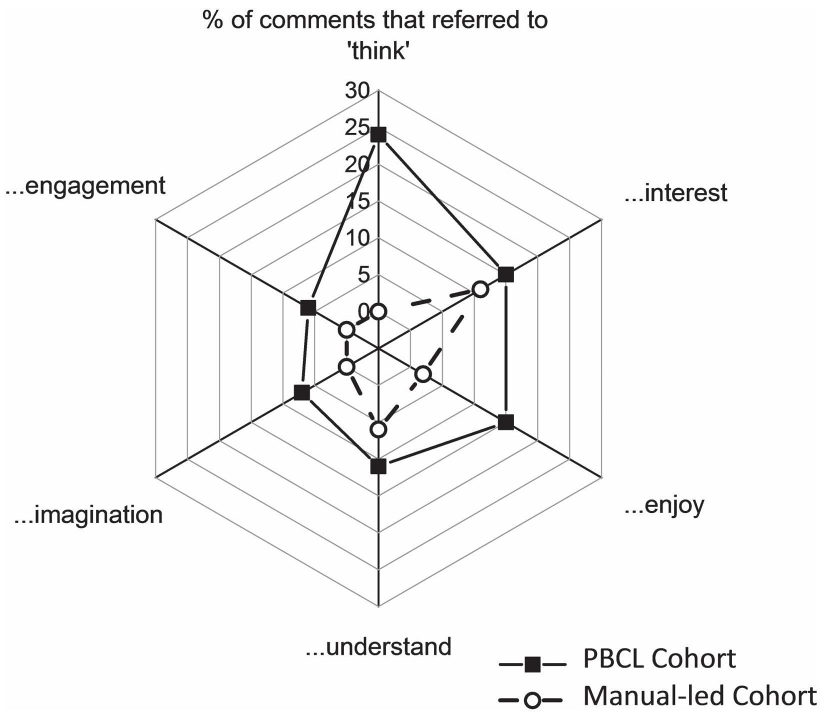

Figure 2. Spider chart showing the frequency of terms/words associated with engagement for PBCL and manual-led student cohorts. These data are based on $n = 90$ responses from the PBCL cohort and $n = 84$ for the manual-led cohort.

3.2. Student engagement in the physics labs

Reflecting on the lab, comments from students in the PBCL cohort evidenced a higher frequency of words relating to *interest, enjoyment* and *imagination* than those in the manual-led cohort (figure 2). This analysis suggests that facilitating students to have a more genuine experience of science in their laboratory class may make it more enjoyable for them. Whilst comments from PBCL students indicated a high level of engagement during labs, comments from the manual-led cohort were more muted in this regard. While students from the manual-led cohort reported on their labs as interesting, their comments had few mentions of terms associated with enjoyment. Indicative comments included

> *'It meant that the team could yes, pool their resources, add their individual approaches and ideas to the experiment leading to new possibilities and expanding imagination. It also does give you a different view of the phenomenon in question. The lack of instructions from a lab handbook is also much more enjoyable provided that it is understood what exactly should be done.'*

This finding agrees with work from Ambrose *et al* [19], which shows that despite the fundamental relationship between metacognition and cognitive growth, explicit instruction methods often neglect to build students' metacognitive capacities.

Manual-led / PBCL	Student led strategies	Externally led	Enjoyable/Interesting/Engaging	Boring	Challenge/Difficult	Easy	Think/Understand/Remember/Learn	No learning
Student led strategies								
Lab-Manual led	2 /							
Enjoyable/Interesting/Engaging	/	/						
Boring	/	/	1 /					
Challenge/Difficult	/ 13	14 / 2	/ 6	/				
Easy	/ 3	25 /	7 / 3	1 /	21 / 3			
Think/Understand/Remember/Learn	/ 28	1 /	4 / 28	/	/ 10	4 /		
No learning	/	1 /	/	/	1 /	/	/	
Behaving as a physicist	/ 13	/	/ 13	/	/ 5	/ 1	/ 16	/

Figure 3. Correlation table between identified themes. The numbers quoted refer to the % of student comments that referred to both of the themes listed (n = 90 comments from PBCL cohort, n = 84 comments from manual-led cohort).

3.3. Correlation between student engagement and scientific habits-of-mind

Further analysis of students' responses to the questionnaire allowed us to correlate student sentiment with their perceived learning, sense of challenge, and sense of independence (figure 3). A positive correlation is shown for students in the PBCL cohort, between their positive engagement and terms such as '*student-led strategies*', '*thinking*', '*improved understanding*', '*sense of challenge'* and '*behaving like a physicist'*. For example, one student responded:

> *'I thought that though it was quite difficult to think of a solution without much guidance from the demonstrators, but it was much more interesting challenge in that way: we were permitted to use absolutely any method for measuring the value of acceleration due to gravity we liked. It encouraged independent thinking and imagination, and I found the challenge far more interesting than trying to understand specific instructions from a lab book.'*

Not all commentary from students in the PBCL cohort were favourable. A small proportion of these students (4%) found the experiments challenging and, at times, frustrating:

> *'The experiment was too easy, and done too many times for anyone to think of something good, they hadn't done before; it led to a lack of structure and was a waste of time.'*

Students in the manual-led cohort appeared to most appreciate the ease of the experiment to measure acceleration due to gravity. Figure 3 shows a correlation between their perceptions of the experiment being 'easy' with the fact that the process was lab manual led. Interestingly, and somewhat contradictory, we also note a correlation between the students' perceptions of the experiment being easy and it also being challenging or difficult. Indicative comments include

> *'Carrying out the experiment was easy. Some of the theory however was more difficult.'*

> *'I thought the experiment was relatively straightforward as I have already done the experiment for the Leaving Cert*[5]*. However I found it challenging calculating the errors in the data and then showing the error bars on my graph using Excel. The manual wasn't quite clear enough in explaining some of these things.'*

Comments such as these and the data in figure 3 suggest that students may not have been challenged by following the step-by-step, lab manual-led experiment but found it difficult to link that procedure to forming a conceptual understanding of the underlying physics content. This might hint at the idea that while the lab may have been '*easy*', it led to shallower engagement, and therefore poorer learning outcomes, in relating the experiment to concepts and theories studied in lectures [20]. Student responses from this cohort did not make reference to engagement, with only 1% of comments referring to their enjoyment.

There is an increasing body of literature to show that students who are engaged and enjoy learning evidence improved learning outcomes over those who find it less enjoyable [7, 8, 21–23]. Bjork and Bjork [21] refer to 'desirable difficulties' as beneficial for long-term retention of knowledge. They relate these desirable difficulties to metacognitive tasks, such as self-regulation and self-monitoring. They also refer to the importance of varying the conditions of learning, rather than keeping them constant and predictable. These are all attributes of the social, peer-regulated, problem-based environment of the PBCL lab that students have identified through their responses.

4. Conclusions

In recent decades, many science educators have made considerable efforts to design and assess strategies that provide undergraduate physics students with deep learning opportunities in practical laboratories. Many of the essential 'habits-of-mind' associated with being a physicist are particularly suited to lab-based learning [1]. These include creativity, team-work, and testing ideas. Many innovations designed to incorporate these in labs tend to be small-scale, not implemented across faculties, and not sustainable [24]. Novel, sustainable approaches are needed to transform undergraduate teaching labs where student engagement can be positively impacted and where students can build on and develop higher-order cognitive skills [9]. The PBCL approach outlined in this paper, and applied to one undergraduate lab experiment, combines two active learning environments. The findings suggest this combination has resulted in responses from PBCL students which indicate more engaged and broader thinking. Further work is required to understand if this single intervention can be scaled beyond one lab.

Smith *et al*'s review of undergraduate student learning [13] compiles evidence pointing to the positive effect that both CL and PBL have had on students' learning outcomes and levels of engagement, but highlights the lack of literature for implementing these methodologies in the classroom or laboratory. Findings herein suggest that in this research, students who participated in a PBCL approach to labs reflected on enjoying the challenge of

[5] State examinations at the end of secondary schooling in Ireland.

designing their own experiments and demonstrated a better understanding of the scientific process in devising and verifying their own experimental work—practices associated with students constructing knowledge physics labs [2]. Students' responses from the PBCL cohort contrasted with those of students in the lab manual-led cohort, who showed an alternative understanding of the scientific process from their learning experiences in the lab (e.g. following procedure) and were not as positively engaged in their learning. Whilst small-scale in nature, our findings are in-line with a recent report [2] from the American Association of Physics Teachers on undergraduate laboratory curricula that emphasised 'sense-making' strategies over excessively procedural approaches. Our data agrees with the findings of Reigosa and Jimenez-Aleixandre [25], showing that students who are asked to follow a sequence of pre-established and fixed steps in laboratory classes tend to adopt behaviours that avoid the assumption of responsibilities needed for self-directed learning.

While it is acknowledged that students who followed the PBCL approach did not reflect on the importance of some of the technical aspects of experimentation such as uncertainties, it clear that they appeared more engaged, and that their perceptions of the scientific process emphasised creativity and criticality. It is interesting to note in this regard that Holmes *et al* [26] have linked increased student engagement to more 'authentic science practices and clear learning goals in labs'.

In this paper, we have attempted to address the implementation of incorporating such approaches to teaching and learning for large student numbers in undergraduate science laboratories and this study provides further evidence of the positive outcomes of incorporating PBL and CL approaches in undergraduate physics education.

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