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Practice-Based Learning Activities: Conceptual Understanding and Motivation in a Non-Major Electric Circuits Course

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After earning my doctorate in Engineering Education from Utah State University, I became a postdoctoral fellow at the University of Nebraska-Lincoln, where I conducted educational research within the Department of Electrical and Computer Engineering. I participated in an NSF-funded study focused on identifying the abstraction threshold in electrical engineering and exploring relationships between students' cognitive processing and course outcomes.

I bring industry experience from the telecommunications sector, where I served as a Project Manager developing high-speed transmission solutions for internet and mobile service enterprises. My role included training engineers and technicians through formal courses, on-the-job training, and field supervision.

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ABSTRACT

Hands-on activities in the classroom are learning experiences where students physically engage with tasks, materials, and technologies to reinforce theoretical concepts introduced in lectures, instead of just passively receiving information during class time. These activities typically involve students manipulating objects, models, and tools while participating in interactive, problem-solving exercises. They can lead to better understanding of course concepts and can significantly enhance students' motivation by making learning more engaging, relevant, and rewarding. However, improving students' conceptual knowledge and motivation largely depends on how well these hands-on activities are integrated into the broader class context.

This study introduces Practice-Based Learning Activities (PBLAs) – a specific form of hands-on activity aimed at enhancing students' conceptual understanding and motivation – and attempts to integrate them into the content and structure of an introductory circuits course. The purpose of this study is to investigate how those integrated PBLAs impact students' conceptual understanding and motivation, with a focus on four specific motivational factors proposed by Keller: attention, confidence, relevance, and satisfaction. A total of 213 undergraduate engineering students enrolled in the "Electrical Engineering Concepts for Non-Majors" course at a northeast university in the U.S. participated in this study. A pre-post, quasi-experimental design was used, with one section of the course receiving PBLA instruction (experimental group) and the other receiving traditional, lecture-based instruction (control group). Conceptual understanding for both groups was measured using an electric circuit concept inventory. While both groups showed slight gains in conceptual understanding, no statistically significant difference was found between them. However, on specific conceptual items requiring explanation, the experimental group scored 23 percentage points higher than the control group, which is significant. Additionally, students in the experimental group responded to a motivational survey at the midpoint and end of the semester. Responses at both time points were slightly positive, but no statistically significant differences were found between the groups in three out of the four motivational factors: attention, confidence, and satisfaction. The relevance factor showed a significant difference, though the experimental group reported higher average relevance *before* receiving PBLA instruction than afterwards.

Practice-Based Learning Activities have the potential to help students better understand course concepts and improve their motivation to learn. However, based on these findings, further work may be needed to uncover more effective ways to integrate PBLAs into course content and structure. Moreover, future studies should explore ways to design PBLAs that explicitly focus on motivational factors and make their learning benefits more apparent to students. Emphasizing how PBLAs can support students' future careers may further enhance their motivational impact.

Keywords: Hands-On Activities, Practice-Based Learning, Conceptual Understanding, Motivation, Undergraduate Electric Circuits Course

1. INTRODUCTION AND PURPOSE

Much of the fundamental engineering education research in the last twenty years promotes student-centered learning as part of active learning principles. These principles suggest that when students are actively engaged with their learning, they are more likely to understand the concepts introduced to them in class [1]. In general, the more involved the student is in the learning process, the greater their knowledge acquisition and cognitive development are [2], and the more they engage in critical thinking processes such as analysis, synthesis, and evaluation [3]. Additionally, Biggs [4] states that the more motivated students are, the more they adopt a deep learning approach. He claims that one way to resolve the gap in students' understanding is to involve them in activities that are engaging and require high levels of cognitive reasoning from them [1], [4]. Moreover, successful group collaboration during these activities is valuable for students' academic development because it encourages the learning approaches needed to understand the concepts applied [1], [4].

Practice-based learning activities (PBLAs) have the potential to afford students the same benefits listed above, *if* they properly attend to students' engagement, motivation, and collaboration. In recent years, PBLAs have established themselves as a new norm in higher education to foster the development of knowledge, skills, and innovative thinking in young learners [5]. Through PBLAs – a specific form of hands-on activities – students engage in a well-established pedagogical methodology that can also be facilitated in a variety of educational environments [5]. PBLAs are particularly effective in undergraduate engineering course contexts, as they inherently link conceptual knowledge with practical application, thereby promoting deeper learning and enhanced motivation [6], [7]. Looking into other studies on PBLAs in engineering education contexts, Aston University identified the PBLA teaching approach as the best practice for better understanding the critical design-to-engineering spectrum. This program was introduced in 2008 and involved both Mechanical Engineering and BSc Designers working in mixed teams for the entire first two years of their undergraduate studies [8]. Zhang et al. introduced a novel method for developing engineering curricula with sustainability at its core using PBLAs. The purpose of this curriculum was to provide students with the skills required to integrate sustainability practices into every engineering project they may work on [9]. It gave students the opportunity to infuse sustainable principles into their engineering coursework via these activities, which is a critical step for educating environmentally conscious engineers of the future. The benefits of PBLAs were further demonstrated by Hu et al., where their findings showed increased student engagement in course activities. Students were found to have more interest and confidence in facing collaborative engineering projects by participating in PBLAs that were inspired by authentic, real-world scenarios [10]. Thus, these activities may better prepare engineering graduates to compete and succeed in technical fields like electronics [11].

This study focuses on the knowledge acquisition and engagement students may demonstrate as a result of participating in PBLAs, in terms of their conceptual understanding and motivation. Rittle-Johnson et al. define conceptual understanding as "implicit or explicit understanding of the principles that govern a domain and the interrelations between units of knowledge in a domain" [12]. Based on these interrelations, learners are more engaged in the concepts they are learning and can begin to make connections with larger ideas to develop more expert-like knowledge structures [12]. Conceptual knowledge "serves as the foundation of conceptual understanding because it represents the core understanding of principles, relationships, and connections between ideas within a subject area, which allows for deeper comprehension and the ability to apply knowledge in various contexts, essentially forming the basis for a meaningful and interconnected understanding of a concept" [13]. Streveler et al. posit that gaining conceptual knowledge in engineering science is a vital factor in the development of competence and expertise as professional engineers. Conceptual knowledge is crucial for developing competencies in engineering students and professionals [14], and hands-on activities have been proposed as a means to improve students' conceptual knowledge by situating them in real-world scenarios [15]. Moreover, Cartensen and Bernhard [16] developed a problem-solving activity for learning transient responses in electric circuits. In their design, certain classes and laboratories were replaced by extended "problem-solving" activities. The idea behind these activities was that knowledge is constructed by learning the component pieces and making explicit links between them. Hence, the more links that are made, the more complete the conceptual knowledge becomes, and students accomplish this by participating in hands-on activities [16].

According to Labib et al. [17], motivation can be defined as the procedure where a goal-oriented activity is activated and sustained. Motivation is closely linked with the level of academic engagement, which is considered to have the greatest impact on students' achievement [17], [18]. A student's motivation plays a strong role in their academic success by serving as the impetus for their engagement in learning activities [19]. According to Driscoll, a student's motivation is comprised of their curiosity, interest, goals, and self-efficacy beliefs when making choices to engage in a learning activity [20]. Motivated students tend to engage with class content for extended periods of time, demonstrate more persistence, and achieve higher levels of learning than students who are less motivated [21], [22]. Furthermore, Fong et al. suggest that students with higher motivation more actively engage in the learning process and are more likely to achieve desired learning outcomes [23]. On the other hand, lack of motivation is one of the noteworthy reasons for underperformance and dropouts among engineering students [23], [24]. Keller [25] found that motivation consists of four key components: attention, relevance, confidence, and satisfaction (the ARCS model). Attention is how to capture the interest of the learner and how to stimulate the curiosity within them. Relevance refers to meeting the personal and/or professional needs or goals of the learner to affect a positive attitude. Confidence is helping the learners to believe that they will succeed and have agency in controlling their success. Satisfaction refers to reinforcing a learner's sense of accomplishment. We decided to use Keller's model to define and measure students' motivation because this model emphasizes building confidence, reinforces relevance and satisfaction, and explicitly connects motivation with academic success via direct engagement.

The purpose of this study is to investigate how Practice-Based Learning Activities (PBLAs) impact students' conceptual understanding and motivation, with a specific focus on the four motivational components proposed by Keller's ARCS model. This model of motivation emphasizes these four factors as critical components for designing instructional strategies that enhance learner engagement and persistence [25]. Previous research has demonstrated that the ARCS model can be applied in Science, Technology, Engineering, and Mathematics (STEM) education contexts to improve student motivation and achievement [25]. By integrating PBLAs into the structure of an introductory circuits course, this research study seeks to explore how these PBLAs align with those motivational factors, and if they improve engineering students' conceptual understanding as well.

2. RESEARCH METHODS

The goal of this study was to integrate PBLAs into the content and structure of an introductory circuits course and then examine their impact on particular learning outcomes of interest. Specifically, this research investigates how students' conceptual understanding and motivation change when PBLAs are incorporated into course instruction. The study focuses on conceptual knowledge and four specific motivational factors, including attention, confidence, relevance, and satisfaction, as defined by Keller [25]. A pre-post, quasi-experimental design was used in this study, with one group of students receiving PBLA-based instruction (experimental group) and another group receiving traditional lecture-based instruction (control group). Since the experimental group participated in the practice-based learning activities, while the control group received traditional instruction, an ethical dilemma could exist here because the control group could have been treated unfairly, or held at a disadvantage, by not receiving the PBLA instruction. However, the control group continued to receive a standard instructional approach that aligns with established educational best practices for introductory circuits courses. The PBLA interventions supplemented, rather than replaced, this standard instruction, ensuring that all students received a meaningful educational experience either way. Moreover, participation in this study was completely voluntary for students, and they had the opportunity to enroll in either section of the class that received either form of instruction. Lastly, this study was reviewed and approved by the Office of the Institutional Review Board (IRB), which assessed its design and ensured that all ethical concerns were properly addressed.

In this study, students' conceptual understanding was assessed both before and after participating in the PBLAs, while their motivation was measured at the midpoint and at the end of the semester. A descriptive parametric analysis was used to establish statistically significant conclusions from the data collected. The following research questions guided this work:

I. *How does conceptual understanding differ between students receiving PBLA instruction and students receiving traditional lecture-based instruction?*

II. *How does students' motivation change as a result of receiving PBLA instruction?*

2.1 Course Selection and Participants

The course selected for this study was "Electrical Engineering Concepts for Non-Majors" at a mid-sized university in the northeastern United States. This is a second-year course and has a typical enrollment of 120 students in the fall semester and 320 students in the spring semester. This course introduces fundamental topics of electrical engineering useful to all the engineering disciplines. Course material includes basic circuit analysis and networks, fundamentals of electromagnetics, energy conversion, and transmission. The course is intended for students registered in Aerospace Engineering, Biomedical Engineering, Civil Engineering, Industrial Engineering, and Mechanical Engineering majors. A total of 235 undergraduate students decided to participate in the study, but 22 participants were removed because of missing data, so the final sample consisted of 213 undergraduate engineering students. Participants identified themselves as male (n = 172, 81.13%), female (n = 39, 18.40%), and two participants preferred not to say. Participants identified themselves as White/Caucasian (n = 137, 64.32%), Asian (n = 38, 17.84%), Black/African American (n = 12, 5.63%), Latino (n = 11, 5.16%), two or more ethnicities (n = 9, 4.23%), unknown ethnicity (n = 2, .94%), Native American (n= 1, .43%), and three participants preferred not to say (n = 3, 1.41%). Participants were not randomly assigned to the control and experimental groups. The study was carried out with student participants from four different sections and taught by the same facilitator to eliminate the instructor effect. Student participants were informed on the first day of classes of the purpose of this study, and they signed the IRB-approved informed consent form before the data collection process began. Specific compensation for research participation was considered, and students who decided not to participate received other opportunities for compensation.

2.2 Instruments

Two instruments were applied to participants to measure the effect of the PBLAs conducted in the class. The first instrument is the Electric Circuits Concept Evaluation (ECCE) by Ron Thornton and David Sokoloff [26], and it was used to measure students' conceptual understanding. This instrument evaluates both students' prior knowledge and preconceptions, which are critical factors influencing conceptual understanding [27]. It consists of a 45-item, multiple-choice survey that probes student understanding of direct- and alternating-current circuits concepts. Some items include questions related to capacitors and inductors, some items required brief explanations, and it should take about one hour to complete.

The second instrument is the Instructional Materials Motivation Survey (IMMS), and it was used to measure students' motivation. It consists of 36 items and four subscales [25], which are attention (12 items), relevance (9 items), confidence (9 items), and satisfaction (6 items). It measures learners' motivation level by applying a 5-point symmetrical Likert scale. There are ten reverse items (e.g., item 7 of the relevance subscale) in the IMMS instrument. In the reverse item, the lower score the learners give to the reverse items, the higher learners' motivational score is. When using this instrument, the scores of the reverse items should be manually reversed [28].

2.3 PBLAs Conducted

The Practice-Based Learning Activities designed for this research study covered topics related to the content of the course. Topics related to the fundamentals of DC circuit analysis were the primary focus of these activities: a) Ohm's Law, b) Series and Parallel DC Circuits, c) Kirchhoff's Voltage and Current Laws, d) Thevenin Equivalent Circuit, and e) Capacitive Transient Response. We selected these topics because they provide an opportunity to assess students' ability to apply conceptual knowledge to practical problem-solving scenarios and help us to measure how students better understand the concepts from the course. The activities were explained in the hands-on activity guides provided to students, and they were taken from the *Laboratory Manual to Accompany Introductory Circuit Analysis* by Robert L. Boylestad and Gabriel Kousourou [29]. While these activities, consisting of 3 to 5 tasks, were originally designed to be completed in a two-hour session, they were shortened to fit within the 80-minute class period of the course. For example, one of the activities consists of four tasks to build four different circuit configurations (two parallel circuits and two series-parallel circuits). This activity was shortened for students in two tasks, to build one parallel circuit and one series-parallel circuit. Because the original tasks were not modified, we decided not to conduct a pilot test for the activities. Regarding the activity guides, they all include a description of the objectives (terminal, performance, and enabling objectives), required hardware, summative evaluation information, and the learning activities. The learning activities include tasks and a detailed description of the steps to follow during the activity. The six PBLAs that were conducted over the course of the semester are listed in Table 1. The activity PBLA #1 was included for students to become familiar with the electronic components, equipment, and instruments to be used during the subsequent activities.

Table 1. List of PBLAs Conducted

PBLA #	PBLA Name
1	Instrumentation (Resistance, Protoboard, and Arduino® microprocessor)
2	Ohm's Law
3	Series DC Circuits
4	Parallel DC Circuits
5	Thevenin Equivalent Circuit
6	Capacitor Transient Response

Students arrived at the classroom with a copy of the PBLA activity and they were asked to form groups of up to three members through self-selection rather than instructor assignment. Equipment and electronic components were pre-arranged on a round table to speed up the development of these activities. The instructor of the course reviews the guide with the students to ensure they understand the circuit diagrams, components, and expected outcomes before starting. The instructor also ensures that students have all the necessary resistors, capacitors, wires, and power sources before assembling. Finally, the instructor ensures all meters and protoboards are working properly. During the development of the activity the instructor and three teaching assistants monitored that all the groups were assembling the circuits step by step and double-checking connections before powering on. They helped students in case they needed assistance in building the circuit or measuring voltages, currents, or resistances. After students finish the activity, they are asked to organize the equipment and electronic components similar as they found them in the tables and submit the report with the results of the activities and their conclusions according to the learning objectives of the PBLA activity.

2.4 Data Collection Procedure

We administered both instruments to participants through the online learning management system provided by the university for the circuits course. Again, we used the ECCE exam and the IMMS to measure changes in students' conceptual understanding and motivation, respectively. We administered these instruments to both the control and experimental groups two times during the semester. On the first day of classes, we informed students about the research study, and after they signed informed consent forms, we guided participants to navigate into the learning management system where these instruments were available to take. We asked participants to complete the first ECCE quiz (ECCE-PRE) by the end of the first week of classes. An additional set of four questions were added to this quiz to collect demographic information from participants. At the beginning of the sixth week of classes, we asked participants to complete the first IMMS survey (IMMS-PRE) by the end of that week. Similarly, during the second-to-last week of classes, we asked participants to complete the second ECCE exam (ECCE-POST) and the second IMMS survey (IMMS-POST). The data analysis process started after the class officially ended and students' official final letter grades had been submitted to the university. The names of study participants were anonymized to maintain the confidentiality of the data collected.

3. DATA ANALYSIS PROCEDURE AND RESULTS

We downloaded and tabulated all instrument response data in Microsoft Excel® spreadsheets, reviewed, anonymized, organized, and cleaned it, and then analyzed it using SPSS® statistics software. We took necessary steps to manage blank or missing data, verify instrument reliability, and examine data normality. To clarify, all three researchers conducted all data analysis steps explained in the following sections and then compared results, to agree on findings and ensure consistency and reliability of results [30]. We did not review or organize the data, nor did we begin processing and analyzing it, until after the course ended and student final grades were submitted, just to ensure that students' instrument responses had no effect on their performance in the class. All data analysis was conducted in multiple stages over the course of June to August 2024.

To test reliability, we calculated the Cronbach's alpha coefficient of both instruments to evaluate the internal consistency of the responses collected with them. To test normality, we considered the data collected as continuous in the average values. Thus, a Shapiro-Wilk test was conducted to verify normality, and consequently, to help us decide whether or not to use a parametric approach to analyze the data. Descriptive statistics and group differences were calculated for each survey with a Likert-scale response, and they were reported for descriptive purposes. The data analysis procedure for both instruments is as follows:

3.1 Reliability

To verify the reliability of the ECCE instrument, we ran Cronbach's alpha tests on participants' responses to the ECCE-PRE and the ECCE-POST exams, for both the control and experimental groups. The alpha values calculated were 0.817 and 0.893 for pre and post datasets, respectively. To verify the reliability of the IMMS instrument, we ran Cronbach's alpha tests on participants' responses from both groups as well, both the pre- and post-intervention datasets (IMMS-PRE all and IMMS-POST all). The alpha values calculated were 0.916 and 0.917 for pre and post datasets, respectively (alpha > 0.7 considered very good). According to the rule of thumb proposed by George and Mallery [31] and Kline [32], Cronbach's alpha scores ranging from 0.655 to 0.855 (or higher) are acceptable for education research purposes, so both of our instruments' scores were well above that threshold. Moreover, to ensure the validity of the IMMS instrument's content, we had three other teaching faculty members give feedback on specific questions to adjust wording, improve clarity, and make the instrument more consistent. Because of these measures taken, we can conclude that the questions in both instruments are reliable, consistent, and measure the phenomena (i.e., conceptual understanding and motivation) that they are intended to measure.

3.2 Normality

Next, we checked the normality of each dataset and then decided whether to use parametric or nonparametric statistical analysis to answer our research questions. To determine if our collected data was normally distributed, we ran Shapiro-Wilk normality tests on all ECCE and IMMS data from both the experimental and control groups, both pre- and post-PBLA intervention. The Shapiro-Wilk tests yielded the following:

Table 2. Shapiro-Wilk Test Results

	ECCE-PRE	**ECCE-POST**
Control Group	$S\text{-}W = 0.964$, $df = 71$, $p = 0.040$	$S\text{-}W = 0.938$, $df = 71$, $p = 0.002$
Experimental Group	$S\text{-}W = 0.969$, $df = 120$, $p = 0.007$	$S\text{-}W = 0.962$, $df = 120$, $p = 0.002$

	IMMS-PRE	**IMMS-POST**
Control Group	$S\text{-}W = 0.942$, $df = 71$, $p = 0.003$	$S\text{-}W = 0.967$, $df = 71$, $p = 0.038$
Experimental Group	$S\text{-}W = 0.951$, $df = 120$, $p = 0.006$	$S\text{-}W = 0.968$, $df = 120$, $p = 0.029$

Based on these results (*p-value* < 0.05 for all), we concluded that all datasets involved in analysis were normally distributed. Therefore, we decided to conduct a parametric statistical analysis to answer our proposed research questions.

3.3 Answering Research Questions

I. How does conceptual understanding differ between students receiving PBLA instruction and students receiving traditional lecture-based instruction?

Since our data was sufficiently-normally distributed, we performed multiple t-tests to compare findings between the different groups and different datasets. First, we ran two independent-samples t-tests to compare the ECCE responses from the control and experimental groups at both time points – one for the pre-intervention data from both groups and one for the post-intervention data from both groups. These tests yielded $t(210) = -0.340$ with $p = 0.489$ and $t(210) = -0.601$ with $p = 0.548$, respectively. These results indicate that there were no statistically significant differences in students' conceptual understanding between the groups at both time points when the instrument was administered (*p-values* > 0.05). Now, while this does confirm that there was no significant difference between both student groups' understanding of circuits concepts *before* the experimental treatment (i.e., experimental group students participating in PBLAs), thereby establishing an even baseline for comparison between the groups, this also means that there was no significant difference between both student groups' understanding of circuits concepts *afterwards* either – i.e., no difference (ideally, gain) found in the experimental group that could be attributed to receiving the PBLA instruction. However, the ECCE data did yield one other interesting finding – for specific conceptual questions that required students to choose the correct explanation, the experimental group scored 23 percentage points higher on average than the control group did post-intervention, which is a substantial and positive difference.

II. How does students' motivation change as a result of receiving PBLA instruction?

Next, we ran a dependent-samples (paired) t-test to compare the IMMS responses from the experimental group at both time points during the semester, which yielded $t(94) = 1.490$ with $p = 0.139$. This result indicates that there was no statistically significant difference in the overall motivation of experimental group students over the course of the semester (*p-value* > 0.05). While overall IMMS responses at both time points were generally slightly positive, there was not a significant-enough difference between the sets of responses (increase or decrease) that could be attributed to participating in PBLAs.

To clarify, the reason we analyzed the IMMS data from the experimental group only (and not the control group) is because we were only interested in measuring potential changes in the motivational aspects of students who participated in the PBLAs, to see if those activities had any effect on their perceived confidence, attention, relevance, and satisfaction with fundamental circuits concepts and their applications.

Lastly, because of this result, we further analyzed the IMMS response data we collected from the experimental group by looking individually at the four components of motivation represented within the instrument. Specifically, we ran separate dependent-samples (paired) t-tests on the groups of questions for each motivational component of the IMMS, to compare the different categories of responses from the experimental group at both time points. Again, no statistically significant differences were found in three out of the four motivational components: attention [$t(94) = 2.441$ with $p = 0.170$], confidence [$t(85) = 1.790$ with $p = 0.077$], and satisfaction [$t(94) = 0.508$ with $p = 0.612$]. However, there *was* a statistically significant difference in the relevance component [$t(93) = -3.553$ with $p < 0.001$], but it was a decrease; the experimental group students reported higher average relevance *before* receiving PBLA instruction than afterwards. This means that students perceived *less* relevance to the circuits concepts they were learning in class (and applying in the PBLAs) because of participating in practice-based learning activities.

4. DISCUSSION

Overall, based on the results of the ECCE and IMMS instruments administered to participants in this study, implementing practice-based learning activities into the introductory circuits course for non-majors did not have a significant effect on students' conceptual understanding or motivation. Specifically, the PBLAs did not seem to benefit or increase students' knowledge of circuits concepts, their confidence in their own abilities to understand and apply those concepts, nor their satisfaction with learning and mastering them. Moreover, the PBLAs may have even *reduced* how relevant students perceived the circuits concepts they were learning in class to be to their other studies, to their eventual careers, and to everyday life.

To situate these findings within the context of existing literature on PBLAs, many previous studies on the topic espouse a variety of ways in which practice-based learning activities benefit student learning, such as improving their critical thinking skills and exposing them to core professional engineering practices [5], helping them bridge the gap between design and engineering implementation [8], teaching them how to better integrate sustainability principles into engineering projects [9], and increasing their engagement by promoting collaboration and emulating real-world scenarios [10]. With so many other studies demonstrating different benefits of PBLAs, our findings certainly conflict with those, since they led us to reasonably expect gains in students' conceptual understanding and motivation from participating in these activities as well. Additionally, these results are counterintuitive to us as well, since they conflict with our own experiences of students benefiting from analogous hands-on, in-class activities that have helped them deepen their understanding of circuits concepts and their applications, in particular.

Now, it is possible that practice-based learning activities do not increase students' conceptual understanding of circuits concepts or their motivation to learn and apply them; however, more work is needed to verify that conclusion beyond just this study alone. More likely, there are a few possible reasons to justify these outcomes and explain why we may have obtained these results in this study, most of which are environmental factors. First, the timing of when we administered the instruments to students the second time (post-intervention) coincided with the very end of the semester (the final exam period), when it was very possible that inordinate stress and overwhelming class workload for students negatively influenced their self-reported responses to the motivational survey questions.

Next, based on our experiences conducting these practice-based learning activities with students during several class sessions throughout the semester, it became apparent that there were logistical challenges with effectively facilitating these activities in such large class sections with so many students. The student-teacher or student-TA ratio was quite high [33], so it was practically challenging to provide appropriate assistance and scaffolding [34] to all student groups in real time while they were working on the activities. Additionally, we suspect that the length of time allotted for said activities to take place during class sessions was not nearly enough. It was difficult to restructure the course in such a way that allowed us to devote a significant amount of time to these activities during the actual class meeting sessions; we could not afford to take as much time as was likely necessary out of lecture periods to dedicate to the practice-based learning activities that were conducted. So, students were under rather difficult time constraints when doing the activities, and possibly lacked timely support from facilitators, too. Students very likely did not have enough time, or enough on-demand assistance, to fully complete several of the activities, let alone finish them *and* simultaneously achieve a sufficient level of understanding of the purpose of said activities and the circuits concepts they were required to apply during them. These facilitation obstacles likely reduced the effectiveness of the conducted PBLAs as it relates to desired learning outcomes, mitigating gains in students' conceptual understanding of the circuits concepts at play and the development of their motivation to learn them.

5. IMPLICATIONS AND LIMITATIONS

We contend that practice-based learning activities in the classroom have the potential to improve students' conceptual knowledge by helping them connect course content with meaningful, hands-on experiences. We also believe they have the potential to improve students' motivation to learn and master those concepts as well. However, based on the findings of this study and the likely reasons for them, it has become clear that further work is needed to determine more effective ways to *integrate* PBLAs into the structure and logistics of a target course. This is necessary to then be able to confirm or refute other learning benefits that PBLAs can potentially afford students, whether that be in service of their conceptual understanding, motivation, or otherwise.

Similarly, instructors looking to implement some kind of PBLAs into their own courses will be forced to contend with the same logistical constraints on time and facilitation that we encountered in the execution of this study. Effectively integrating PBLAs into existing courses comes with inherent demands on limited class time and resources, and doing so will inevitably require tradeoffs to be made, possibly at the cost of sacrificing content covered, lecture time, or other staples of traditional lecture-based instructional formats. In order to achieve the desired learning benefits that have been demonstrated by other studies on PBLAs, as well as the potential benefits that we still allege they can afford students here, we recommend that instructors ensure there is sufficient time and assistance allocated for students to complete these activities in a satisfactory manner *and* simultaneously obtain a comprehensive understanding of the purpose of said activities and the course concepts applied during them. Additionally, PBLAs may be challenging for classes with a large number of students, where the student-facilitator ratio is too high for them to be effective, combined with the other constraints we mentioned. If that is not logistically possible, or comes at too great a cost, then an alternative solution to these constraint issues is to devote a separate session dedicated to these activities that supplements standard lecture meeting times of the target class. The results of this study imply that it may be necessary to have a standalone session like this, wherein activities similar to PBLAs are implemented – certainly for introductory circuits classes, at least.

Besides that, we also recommend that instructors implement PBLAs in such a way that they explicitly attend to specific motivational factors for student learning [25], so as to make the activities' benefits more directly apparent to students. For example, it seems as though there is a need to make it clear to participating students the ways in which individual PBLAs are *relevant* to their future work endeavors and even to everyday life scenarios, as well as to demonstrate clear, practical, and relatable use cases of the specific concepts and skills applied during them. Within the activities themselves, emphasizing how PBLAs connect to situations that students encounter in everyday life, or how they can support students' future careers, may further enhance the activities' perceived relevance by the students, and thus their overall motivational impact.

The same recommendations we have given for instructional implementation can be said for future studies that explore PBLAs as well. Finding effective ways to integrate PBLAs into the structure of a target course is absolutely necessary to avoid the logistical challenges we faced in this study. Future studies must overcome these constraints in order to be able to confirm or refute other learning benefits that PBLAs can potentially afford students, whether that be in service of their conceptual understanding, motivation, or otherwise.

Lastly, two major limitations in the experimental design of this study may have affected our results as well. First, participating students self-selected the groups they were in while working on the practice-based learning activities conducted in this study. Collaboration dynamics within these groups – especially those arising from preferential group selection – could have influenced individual group effectiveness at completing these activities and thus the results of this study [35]. While we did not account for the effects of group dynamics in the design of our study, future studies could explore whether instructor-assigned or randomly-assigned groups make any difference or yield different outcomes in desired learning metrics. Second, there was potential cross-contamination among participants in the control and experimental groups in this study [36]. Specifically, students from the experimental groups could have shared knowledge and resources gained from participating in the PBLAs with students in the control group, who did not participate in them. As a result, that could have affected the responses of students in the control group to the ECCE and IMMS instruments, which would make it much more difficult to claim that any demonstrated gains in conceptual understanding, motivation, or other desired learning metrics are attributable to the activities themselves. Again, while we did not take any measures to mitigate the effects of cross-contamination in the design of our study, future studies would do well to account for this as well. Because of these two major limitations, future studies might benefit from avoiding pseudo-experimental designs when investigating aspects of PBLAs.

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