Enhancing students' views of experimental physics through a course-based undergraduate research experience

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Course-based undergraduate research experiences (CUREs) have emerged as a promising approach to enhance undergraduate STEM education by engaging students in authentic discovery. CUREs integrate genuine research projects into undergraduate courses, providing students with a real research experience while earning academic credit. While CUREs offer similar benefits to traditional research experiences, they have the advantage of reaching a larger student population and being accessible to all enrolled students. In this study, we assess the outcomes of the first reported large-enrollment physics CURE within an introductory physics laboratory. One of the primary learning objectives of this CURE, which took place at the University of Colorado Boulder from 2020 to 2021, was to foster the development of more expertlike attitude and beliefs about experimental physics among the students. To evaluate the impact of the CURE along this dimension, we employed the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS). Precourse and postcourse E-CLASS responses were collected from the CURE participants and compared with data from 363 other first-year physics labs, representing over 20 000 students. We found that students enrolled in the C-PhLARE CURE led to significantly higher scores on many of the E-CLASS items, even when controlling for precourse scores, students' majors, and students' genders. In particular, we observed that the C-PhLARE CURE had a significant effect on many of the E-CLASS items aligned with the objectives of the course; notably, students had more expertlike views in areas such as communicating scientific findings to peers, understandings of authentic research practices, and students' belief in their own research capabilities. Additionally, we found no statistically significant negative impacts on any of the E-CLASS items as compared to the effects of other first-year physics labs. These results demonstrate the efficacy of this CURE in impacting students' views of experimental physics.

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I. INTRODUCTION

Course-based undergraduate research experiences (CUREs) offer numerous benefits to undergraduate students, providing them with the valuable opportunity to engage in authentic scientific research within the structure of a course. CUREs expose students to the authenticity and challenges of conducting real research. Students get to experience not only the satisfaction of discovery and scientific "success" but also the challenges of setbacks and complexities that can arise during the research process when working with real data. This exposure helps students develop resilience [1,2] and confidence [2–4], as well as providing a realistic understanding of scientific research [5]. In turn, this can help students make informed decisions about pursuing further careers in research science, as they gain insight into the day-to-day activities of researchers and their ability to make meaningful contributions to science [5].

CUREs have been shown to have other benefits; for example, because CUREs often involve collaborative work, where students interact with their peers, instructors, and the larger scientific community, they can foster the development of key skills in collaboration and communication [2]. These skills, in turn, can contribute to the students' ability to communicate scientific information in a professional manner, which is considered an important learning outcome for an undergraduate lab curriculum [6].

Despite their significant potential benefits, the assessment and evaluation of CUREs have been limited to a few studies, primarily in biology and chemistry courses. Furthermore, only a few of these studies have compared

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CUREs with other laboratory experiences (e.g., traditional or inquiry-based labs) [4,7] and even fewer studies have looked directly at changes in students' epistemologies surrounding experimental science [2,7]. Overall, there are clear gaps in knowledge regarding the outcomes and experiences of students in CUREs, and even more so in the case of CURES in physics.

This work focuses on measuring the impacts of the Colorado Physics Laboratory Academic Research Effort (C-PhLARE) CURE, using The Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) [8]. This well-established and validated assessment tool [9] is used to measure students' attitudes and beliefs about experimental physics and their understanding of the nature of science in the context of experimental physics before (pre) and after (post) students participated in the C-PhLARE CURE.

In particular, the E-CLASS aims to capture students' views by presenting them with statements related to experimental physics and asking them to indicate their level from strongly disagree to strongly agree [10]. The statements cover various aspects such as the importance of hands-on experimentation, the role of collaboration in physics, and the nature of scientific research [10].

The C-PhLARE CURE is of particular interest as the first reported instance of a large-enrollment physics CURE [11]. It was implemented as a redesign of the introductory physics laboratory at The University of Colorado (CU) Boulder for three semesters from 2020 to 2021, driven by the need to adapt to remote teaching during the COVID-19 pandemic. The primary goals of this CURE were to teach students essential research skills, promote effective teamwork, create a unique and motivating learning experience, and foster the development of more expertlike attitudes and beliefs about experimental physics among the students [11]. The C-PhLARE CURE focused on analyzing the energy distribution of solar flares to address an open question in solar physics: What are the dominant mechanisms behind the anomalous heating of the Sun's corona, which has a much higher temperature than the photosphere despite being farther from the Sun's center. Various theories have been proposed to explain coronal heating, suggesting that multiple interconnected mechanisms are likely involved [11,12]. However, it is important to narrow down the list of contributing mechanisms and determine which ones play a dominant role [11,12].

To answer this question and teach students about how physics research is conducted, the course was structured into six phases mirroring a typical research project, including onboarding, research planning, data analysis, peer review, final analysis, and reflection [11].

Our goal is to compare gains in E-CLASS item scores between students who participated in the physics CURE and other first-year physics labs using open-sourced historical E-CLASS data. More specifically, we answer the research question:

RQ: How did the C-PhLARE CURE impact the views of students on individual E-CLASS items, particularly those that align with the course goals and design principles, as compared to the effects of other introductory physics labs on students' views of these specific items?

This study provides valuable insights into the impact of different course elements and course structures on students' epistemology and views about experimental physics, which can be used to improve lab learning experiences in future course planning.

We begin by providing relevant background information on CUREs, the C-PhLARE course design, prior education research findings on the C-PhLARE CURE, and the importance of investigating their impact on student attitudes and beliefs in experimental physics through the E-CLASS (Sec. II). This is followed by a description of the methodology used in our investigation (Sec. III). We explain the procedure for data collection and outline the analysis of the E-CLASS assessment data, including control variables and statistical analysis techniques employed. The results and discussion section (Sec. IV) presents the findings of the study, as well as provides an interpretation of the findings and their alignment with the research question. We discuss the implications of the positive impact of the C-PhLARE CURE on student epistemologies surrounding experimental physics and highlight the significance of the results in relation to the broader literature on CUREs and their impact on students' confidence, teamwork skills, and authenticity. Finally, the conclusion (Sec. V) summarizes the key findings of the study, reiterating the impact of the C-PhLARE CURE on student attitudes and beliefs in experimental physics. We emphasize the importance of innovative curricular approaches in engaging students and promoting their development as researchers. We conclude by highlighting the potential and significance of CUREs in undergraduate physics education.

II. BACKGROUND

In this section, we provide an overview of the background of CUREs, focusing on their implementation and relevant education research. We specifically delve into the course context of the C-PhLARE CURE at CU Boulder. Additionally, we review previous studies that have utilized the E-CLASS assessment tool and highlight the significant findings they have yielded.

A. Course-based undergraduate research experiences

The CUREnet (Course-Based Undergraduate Research Experiences Network) [13] was established in 2012 with funding from the National Science Foundation to promote the integration of CUREs into undergraduate courses. A report published by CUREnet in 2014 [2] highlighted the increasing evidence of the positive outcomes of undergraduate research experiences and the growing emphasis on inclusivity and accessibility in incorporating these experiences into course structures, leading to calls for expanded implementation of CUREs in science and engineering courses. The report characterized CUREs as unique learning environments that distinguish themselves from traditional and inquiry-based labs.

In traditional laboratory courses, often dubbed "cookbook" labs, topics, and methods are predetermined by the instructor, often providing specific directions where students seek to confirm known outcomes. These labs are often paired with a lecture and have the goal of reinforcing concepts, which has been shown to be ineffective in several cases [14]. Additionally, these labs tend to fall short of replicating the cognitive tasks needed for authentic physics experiments [15] and potentially hinder the development of expertlike epistemologies in experimental physics for students [16].

As a response, inquiry-based laboratories gained prominence in undergraduate science curricula. The National Research Council (NRC) [17] defined "inquiry-based learning" as an approach where students engage in activities and thinking processes similar to practicing scientists. Further, the NRC provided a wide array of evidence supporting the effectiveness inquiry-based learning in science education, including encouraging students to go beyond factual knowledge and enabling them to build and refine their understanding by modifying and expanding on existing concepts [17]. This approach is particularly significant in undergraduate laboratory curriculum, as it mirrors the cognitive and behavioral practices of scientists, challenging students to formulate their own research questions and methods with uncertain outcomes. While inquiry-based labs typically do not contribute to broader scientific knowledge, they have been found to be a more effective alternative to traditional labs for developing scientific skills, learning concepts, and developing more expertlike epistemologies [16,18].

A traditional undergraduate research experience or internship is an experience where a student is apprenticed to a senior researcher. This researcher could be a faculty member, postdoc, graduate student, or industry researcher. The goal of these experiences is for students to learn the practices of science, as well as help advance science knowledge [19]. Student experiences with traditional undergraduate research have been found to be overwhelmingly positive with benefits including personal or professional gains, "thinking and working like a scientist," gains in various skills, clarification or confirmation of career plans (including graduate school), enhanced career or graduate school preparation, and shifts in attitudes to learning and working as a researcher [19].

CUREs sit between inquiry-based labs and traditional undergraduate research experiences in terms of students' intellectual responsibility [20]. CUREs have been defined based on five key dimensions: engagement in multiple scientific practices, facilitation of scientific discovery, opportunities for broader impact and action, promotion of collaborative teamwork, and emphasis on iteration as an integral part of the scientific process [2]. Similar to inquiry-based labs and traditional undergraduate research experiences, CUREs engage students in multiple scientific practices and engage in iteration. However, unlike inquiry-based labs, during a CURE, students address a research question or problem that is of interest to the broader community with an outcome that is unknown both to the students and to the instructor similar to a traditional undergraduate research experience [2]. Despite this similarity, there are key tradeoffs between traditional undergraduate research experiences and CUREs. One example is balancing of the scalability of a CURE with the resources typically found in traditional undergraduate research experiences [21]. In traditional undergraduate research settings, undergraduates typically work in a one-on-one mentorship model. This allows students to receive in-depth scientific training, from reading the literature, framing scientific hypotheses, and running experiments, to interacting with other professional scientists and presenting their work at conferences [21]. These experiences not only provide students with research involvement but also career mentorship, sense of belonging, and scientific identity [21]. CUREs have been shown to have many of the same benefits as traditional undergraduate research experiences, such as developing research skills and clarification of intentions to pursue further education or careers in science [2]. However, due to the large number of students, they often require more structure and less one-on-one mentorship. Additionally, a study by Russell and Weaver [7] compared students' views of the nature of science after completing a traditional laboratory, an inquiry laboratory, or a CURE. They found that students in all three environments made gains in their views of the nature of scientific knowledge as experimental and theory based, but only students in the CURE showed progress in their views of science as creative and process based.

So far, most CUREs have been implemented in biology and chemistry. Likewise, much of the research about CUREs has been done on large, multisite programs biology and chemistry CUREs such as the SEA-PHAGES Program [22], the Small World Initiative [23], and the Genomics Education Partnership [24].

For example, the Phage Hunters CURE [25] has the goal of characterizing mycobacteriophages—viruses that infect the mycobacteria and also other bacterial hosts in the phylum Actinobacteria. It was developed at—and is maintained by—the Pittsburgh Bacteriophage Institute and the University of Pittsburgh. Education research on this CURE found that the students' experiences were overwhelmingly positive and students described many benefits such as personal or professional gains, "thinking and working like a scientist," gains in various skills, and clarification or confirmation of career plans [25]. However, there is little work on CUREs in physics [26] and most physics CUREs have been conducted on a smaller scale [27,28].

B. Course context

In the summer of 2020, the C-PhLARE CURE was developed in response to the COVID-19 pandemic as an effort to continue to teach essential physics experimental skills in the online teaching environment. The learning goals of the course focused on developing experimental research skills such as conducting literature reviews, working with code, developing research plans, performing data analysis, and engaging in peer review. Experience with teamwork, which had been replaced by individual work in many courses during the pandemic [29], was emphasized as a course outcome due to the potential benefits for students' motivation, creativity, and collaboration skills. Creating a unique and motivating experience in experimental physics was another goal, influenced by evidence suggesting that authentic practices in a CURE could improve students' beliefs about the nature of experimental science and enhance their persistence in the sciences [2,7].

Several constraints influenced the development of the C-PhLARE CURE [11]. Time was a significant constraint, as the entire curriculum development had to be completed within a few months during Summer 2020. The large class size of approximately 400–700 students per semester required clear grading expectations and consistent procedures across all student teams. Accessibility was a crucial consideration, and Google Colaboratory [30] was chosen to provide an accessible coding environment for students using different devices [11,31]. Finally, the course had to be designed for fully online teaching [11].

The research conducted by the C-PhLARE aimed to understand the mechanisms behind coronal heating in the Sun's atmosphere, in particular, whether small flares called "nanoflares" could contribute to coronal heating. To this end, the students analyzed the flare frequency distribution (FFD) with respect to total flare energy, which represents the rate of occurrence of flares at different energy levels. The FFD follows a power law, in which exponent alpha (α), extracted as the slope of the distribution in log space, indicates the prevalence of nanoflares. A value of alpha above the critical value $\alpha_c = 2$ suggests a higher frequency of small flares and therefore a dominant contribution to coronal heating [11,12]. An alternative finding of $\alpha < 2$ suggests that nanoflares are not the leading mechanism.

The research involved teams of 3–4 students using data from the Space Weather Data Portal [32] and Google Colaboratory [30] to analyze the energy of individual flares. The course structure included synchronous lab meetings and asynchronous prelab lecture videos to provide "just-in-time" skills and knowledge [33] for students to successfully conduct the research project. Following documented best practices for prelab instruction [34,35], the prelab videos did contain elements designed to address the affective domain. In terms of content, however, they were focused on supportive information and "demystifying" black-box formulas [35] and explicitly did not aim to teach broad coding skills or specific physics content knowledge surrounding solar flares.

The course spanned 15 weeks and encompassed different phases to teach students about physics research, including (i) project on-boarding consisting of teamwork training, literature review, and a meeting with the principle investigator (PI); (ii) research plan development consisting of articulating a plan and practicing the analysis techniques on a test flare; and (iii) data analysis where teams of students chose their own flares from the Space Weather Data Portal to analyze, conducted peer review, iterated on their analysis based on the feedback from peers, and combined all the teams data together to determine a value for α from the FFD. More details surrounding each of these phases can be found in Ref. [11].

Upon conclusion of the C-PhLARE research, the senior research team, comprising scientists from CU Boulder, the Laboratory for Atmospheric and Space Physics (LASP), the Applied Physics Laboratory (APL), and the National Aeronautics and Space Administration (NASA), reviewed and compiled the student-generated data. The results were published in the peer-reviewed *Astrophysical Journal* [12] where the C-PhLARE student researchers were able to review a draft of the paper and opt-in to being coauthors. With over 1000 coauthors, this publication described the unprecedented effort resulting in the analysis of more than 600 case studies of solar flares [12]. This enabled the incorporation of two nontrivial analytical methods: preflare baseline subtraction and computation of flare energy, which have not been done previously in such a large study of solar flares [12]. These collective analyses yielded $\alpha = 1.63 \pm 0.03$. This value falls below the critical threshold, indicating the significant role of Alfvén waves in driving coronal heating, thus contributing valuable insights to the broader scientific understanding of solar behavior [12].

C. Prior findings

Prior education research studies on the C-PhLARE CURE have analyzed the impact of the CURE on student learning, confidence, affect, teamwork, and student perspectives of authenticity [11,31,36,37]. Preliminary studies of the CURE indicated multiple positive impacts including gains in research skills and coding confidence, engagement in productive and enjoyable teamwork experiences, and feeling motivated and interested in experimental physics research [11].

Furthermore, teamwork in the CURE was extensively studied through the lens of socially shared regulation theory. For example, students struggled with version control issues when simultaneously writing, editing, and saving their work which led them to use socially shared regulatory strategies, including assigning and rotating roles from week-to-week and having clear, regular communication [31]. Additionally, a 2022 study on the C-PhLARE CURE by Werth *et al.* [36] used two data sources: the adaptive instrument for the regulation of emotions questionnaire and students' written memos to future researchers. These data were used to measure the students' teamwork goals, challenges, use of self-, co-, and socially shared regulations, as well as perceived goal attainment. That work found that students in the C-PhLARE CURE successfully achieved their teamwork goals by employing socially shared regulatory strategies, despite facing various obstacles. Furthermore, the majority of students expressed the belief that teamwork played a crucial role in their research experience.

Finally, work by Oliver *et al.* [37] identified the specific aspects of authentic research in which students felt they were involved and to what extent they perceived their participation as authentic. The results indicated that a significant majority of students in the course believed they engaged in genuine research activities. Moreover, when asked to provide a broader description of their course experience, a substantial number of students emphasized their encounter with authentic research.

D. E-CLASS

The E-CLASS is designed to evaluate students' perspectives on their strategies, habits of mind, and attitudes toward experimental physics while conducting experiments in the lab [10]. There has been significant past work on attitudes and beliefs about knowing and learning in physics. For example, the Views of the Nature of Science Questionnaire (VNOS) [38], the Maryland Physics Expectation Survey (MPES) [39], and the Colorado Learning Attitudes about Science Survey (CLASS) [40] all have been created and used to better understand changes in student epistomologies about physics. However, unlike E-CLASS, most of these have been used in introductory physics lectures and do not ask students specific questions about experimental physics [41].

E-CLASS was designed based on common learning goals for experimental lab courses. It asks students to respond to a series of 30 questions related to affect, confidence, math-physics-data connections, the physics community, statistical uncertainty, troubleshooting, argumentation, experimental design, modeling the measurement system, purpose of labs, and systematic error [41]. However, these categories are not meant to be latent variables of the E-CLASS survey, where one would expect a high degree of correlation among the items within these categories. For instance, the two statements about the physics community: "scientific journal articles are helpful for answering my own questions and designing experiments" and "communicating scientific results to peers is a valuable part of doing physics experiments" both express how experimental physics extends beyond the individual researcher, but clearly represent distinct practices, and any particular lab course could emphasize them to varying degrees [41]. Thus, the designers have cautioned against using E-CLASS total scores to interpret results [42,43].

The development of the E-CLASS stemmed from the growing need to align laboratory curricula with the skills and abilities required for professional experimental physics research [10]. The E-CLASS allows instructors to identify areas where improvements and adjustments are needed to bridge the gap and better prepare students through their physics laboratory courses. The E-CLASS is administered both at the beginning and end of the semester to measure changes in student responses.

Additionally, the E-CLASS has an open-access dataset, which includes over 70,000 responses to the E-CLASS survey [44]. These data cover 133 institutions, 599 unique courses, and 204 instructors and were collected between 2016 and 2019 [44].

Several previous studies have explored the influence of physics laboratory instruction on student E-CLASS scores [43,45–49]. For instance, Wilcox and Lewandowski [43] discovered that incorporating open-ended lab activities in a lab course was associated with more expertlike responses in postinstruction E-CLASS scores, compared to courses that solely included traditional-guided lab activities. Notably, this correlation persisted even after controlling for factors such as preinstruction scores, course level, student major, and student gender [43]. Subsequent research by Wilcox and Lewandowski in 2017 revealed that courses focused on developing laboratory skills demonstrated more expertlike postinstruction E-CLASS responses, compared to courses that concentrated on reinforcing physics concepts or pursuing both goals [46]. Additionally, within first-year courses, this effect was more pronounced for women students [46]. A study conducted in 2022 by Walsh *et al.* had consistent findings using an expansive database of survey responses from more than 20,000 students across 100 different educational institutions. Their research revealed that laboratory experiences that prioritized the development of experimentation skills have a positive influence on students' critical thinking abilities and their perspectives on experimentation [50]. Furthermore, this study also found that these beneficial effects of skills-based labs persisted irrespective of students' gender and race or ethnicity [50].

Sulaiman *et al.* [48] conducted further research focusing on the differential impact of physics laboratory course transformations on women and men. Their study analyzed more than 3000 student responses collected before and after a particular course transformation in an undergraduate laboratory, examining overall E-CLASS scores as well as item-by-item scores [48]. The results indicated a statistically significant increase in the average E-CLASS score after the transformation, irrespective of gender [48]. Moreover, the item-by-item analysis revealed larger improvements in specific E-CLASS items, particularly those associated with the new course learning goals [48], but notably, some of these items exhibited different gains for women and men [48].

Furthermore, work has been conducted looking specifically at physics laboratory courses during the emergency remote instruction due to the COVID-19 pandemic. Fox *et al.* [49] analyzed responses from over 1600 students in both the spring and fall semesters of 2020 and compared them to the same courses in 2019. The overall findings indicated that students' total E-CLASS scores in 2020 were not lower compared to 2019 [49]. However, when examining the Fall 2020 data specifically, there were variations in the mean E-CLASS scores for certain individual questions when compared to previous years [49].

III. METHODOLOGY

A. E-CLASS

The E-CLASS survey is comprised of 30 items that evaluate students' perspectives and attitudes toward experimental physics. Using a five-point Likert scale, students indicate their level of agreement with statements, specifically focusing on their thoughts during physics lab experiments. The survey also includes a section where students can share their insights on factors important for achieving a good grade. Students have the option to provide additional demographic information like gender, race or ethnicity, and major.

Each item in the survey is scored based on expertlike responses, which are collapsed into a three-point scale. Scores are assigned according to the level of agreement with expert views, ranging from $+1$ for consistent responses, 0 for neutral, to -1 for inconsistent responses. Average scores per question can be computed for a group of students, with values falling between -1 and 1.

The survey's design encompasses various learning objectives for college-level physics lab courses, accommodating both introductory and advanced levels. However, it is important to note that not all statements may be relevant or applicable to a specific lab course.

E-CLASS scores serve as a measure of students' epistemological beliefs and expectations regarding experimental physics, which are known to influence the development of science identity [8,51]. In turn, science identity has been identified as a strong predictor of student engagement, performance, and persistence in STEM fields [52].

The E-CLASS was administered via an online system at the beginning (pre) and the end (post) of a semester to measure the change in students' views about experimental physics. The E-CLASS scores from the CU Boulder introductory physics CURE are compared to historical, open-source E-CLASS data from first-year physics lab courses. The data are from 363 courses, with 123 unique instructors, and at 88 unique institutions. In total, there are 24 796 matched student responses analyzed. Among the colleges and universities, 32 (8.8%) were 2-year colleges, 67 (18.5%) were 4-year colleges, 30 (8.3%) were master's granting institutions, and 212 (58.4%) were Ph.D. granting institutions. Out of the first-year courses represented in the dataset, 141 (38.8%) were algebra based and 222 (61.2%) were calculus based.

We gathered data from three offerings (Fall 2020, Spring 2021, and Fall 2021) of CU Boulder Physics CURE. Of the 1438 students enrolled in the course during these three semesters, there were 1027 students, who were over 18 years old, agreed to participate in the research and completed both the presurvey and postsurvey. These were the responses used in our analysis.

Figure 1 presents the demographic information for both populations. It is worth noting that the CU Boulder C-PhLARE CURE population exhibits significant differences in the distribution of majors, gender, and race or ethnicity compared to the students represented in the historical dataset, as indicated by a Mann-Whitney U test. Specifically, CU Boulder C-PhLARE CURE enrolls a greater proportion of physics and engineering majors compared to the comparison dataset. However, by employing linear and logistic regression analyses, we were able to assess the impact of these differences and none of our analyses revealed any significant interaction terms between major or gender and the course type (i.e., the relationship between E-CLASS post scores and the course type changes based on students' major or gender).

B. Analysis methods

We employed an ordinal logistic regression model to analyze the individual E-CLASS items. The ordinal logistic regression allows us to assess the relationship between the course transformation (C-PhLARE CURE vs other physics lab courses) and the likelihood of students' agreement for each E-CLASS item while considering the influence of the E-CLASS prescores as a covariate.

The coefficients of the ordinal logistic regression model were obtained using maximum likelihood estimation. We compute the robust standard errors based on the observed Hessian matrix. This ensures that the parameter estimates and their standard errors are reliable even if the assumption of normally distributed errors is violated.

Student major (i.e., physics, engineering physics, and astrophysics vs other engineering vs other) and student gender have been identified as significant predictors of E-CLASS postscores when controlling for prescores in previous research [53]. As such, these variables could impact our conclusions about the effect of course type

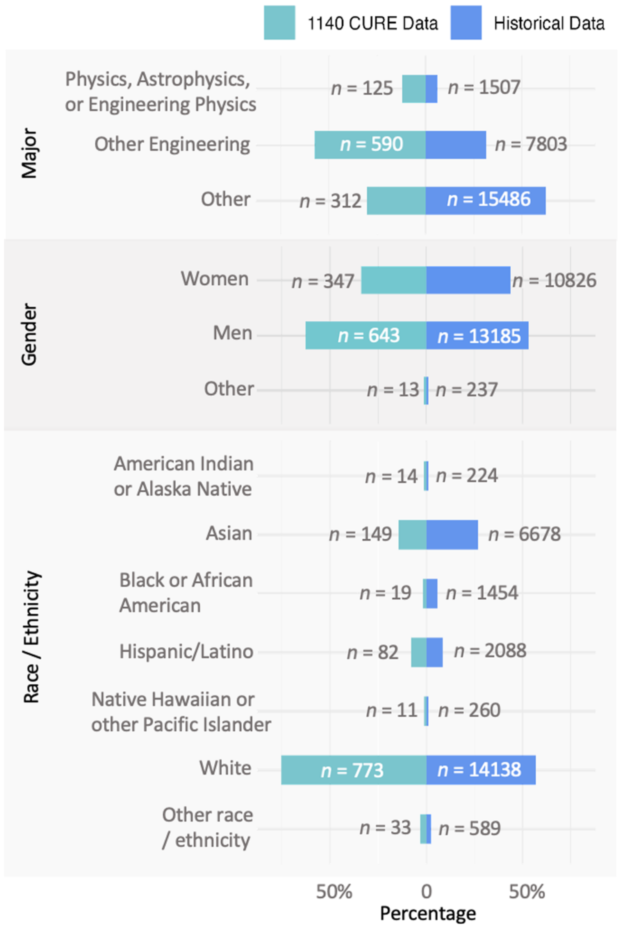

FIG. 1. Self-reported demographic information of CU Boulder C-PhLARE CURE students ($n = 1027$) and the students in other physics lab courses that are part of the open-source, historical E-CLASS dataset ($n = 24796$). Major, gender, and race or ethnicity demographics all show statistically significant differences between the distributions of the two populations using a Mann-Whitney U test.

(C-PhLARE CURE vs other), given that there are differences in the populations of different courses. To investigate this, we initially include student major, gender, and the relevant interaction terms in the logistic regression model. However, in this version, we found no statistically significant interaction terms. Consequently, we opt to remove the interaction terms and model E-CLASS postscores as a function of course type with E-CLASS prescore as a covariate, as well as gender and major as confounding variables.

The ordinal logistic regression model can be represented as follows:

$$\log\left(\frac{\Pr(E_{\mathrm{post}} \leq j)}{\Pr(E_{\mathrm{post}} > j)}\right) = \alpha_j + \beta_1(\mathrm{CourseType}) + \beta_2(\mathrm{Major}) + \beta_3(\mathrm{Gender}) + \beta_4 E_{\mathrm{pre}}, \quad (1)$$

where $\Pr(E_{\mathrm{post}} \leq j)$ represents the cumulative probability of the E-CLASS postitem response category j (e.g., "disagree," "neutral," or "agree") or lower, $\Pr(E_{\mathrm{post}} > j)$ represents the complementary cumulative probability of the E-CLASS postitem response category j or higher, α_j is the intercept for response category j, β_1 is the coefficient for the course-type variable (C-PhLARE CURE vs other physics lab courses), β_2 represents the coefficient for the student major variable, β_3 represents the coefficient for the student gender variable, and β_4 represents the coefficient for the E-CLASS prescore.

To assess the significance of the coefficients β_1, we computed the p value using the t distribution. A p value less than 0.05 indicates a statistically significant relationship between the predictor variables (course type and E-CLASS prescores) and the odds of a more expertlike student response.

We also calculated odds ratios (OR) by exponentiating the coefficient estimates of the model. The odds ratios represent the multiplicative change in the odds of moving up a response category (e.g., from disagree to neutral or from neutral to agree) associated with being enrolled in the CURE compared to the other physics lab courses. For example, an OR with a value greater than 1 indicates a higher likelihood of having a more expertlike response, while a value less than 1 suggests a lower likelihood. For each item, we report the OR along with their 95% confidence intervals written as $\mathrm{OR}_{\mathrm{lowerbound}}^{\mathrm{upperbound}}$. If the confidence interval does not include 1, it suggests a statistically significant difference in the odds of higher response categories between the CURE and the other physics lab courses.

Furthermore, we used the Holm-Bonferroni procedure to correct for multiple comparisons in the analysis. This procedure adjusts the significance level (p value) for each individual item, accounting for the increased chance of obtaining a significant result by chance alone when conducting multiple statistical tests.

IV. RESULTS AND DISCUSSION

In this study, we aim to assess the C-PhLARE CURE at CU Boulder in fostering students' attitudes and beliefs about experimental physics compared to other types of physics labs. Through the analysis, we can examine the individual items that align most strongly with the goals of the CURE, such as "physics experiments contribute to the growth of scientific knowledge" and "if I wanted to, I think I could be good at doing research." Appendix presents a list of all the individual E-CLASS items, their corresponding question numbers, and whether providing a more expertlike response to each question aligns with the goals and instructional emphases of the C-PhLARE CURE along with the odds ratios, confidence intervals, and p values.

From Fig. 2, we see that a large majority of individual E-CLASS items had odds ratios > 1, indicating that, when controlling for prescores, a student in the C-PhLARE

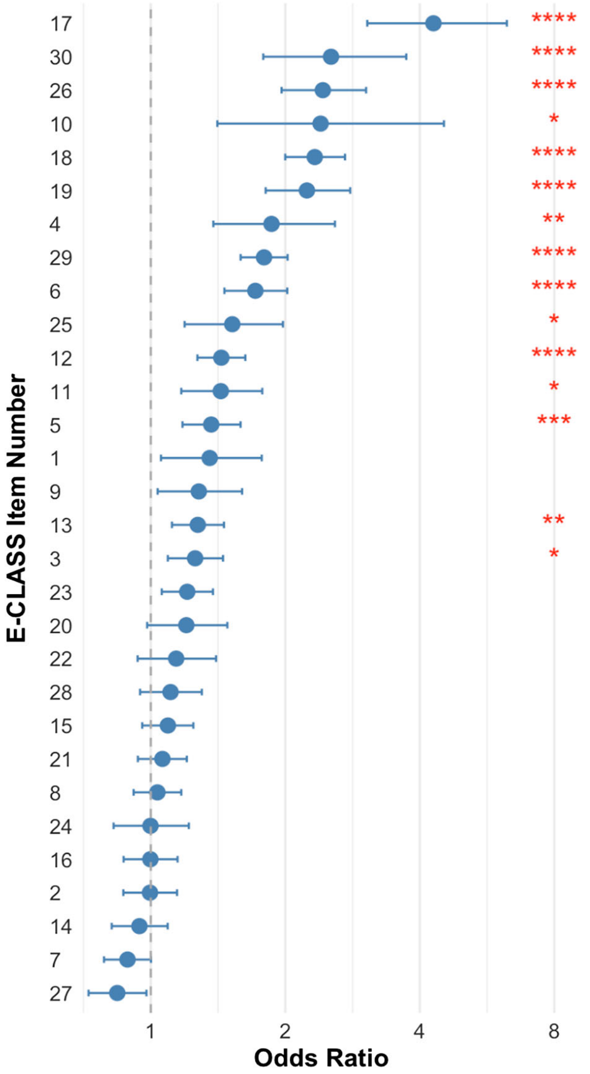

FIG. 2. Odds ratios and their corresponding 95% confidence intervals. An odds ratio greater than 1 (indicated by the vertical dashed line) signifies a higher likelihood of students in the CURE group having a more expertlike postresponse for the respective E-CLASS item compared to students in other first-year labs. It is important to note that the odds ratios on the x axis are presented on a logarithmic scale. Additionally, significance levels are denoted next to each item. Significance at a Holm-Bonferroni corrected p value of less than 0.0001 is represented by ****, p less than 0.001 is ***, p less than 0.01 is **, p less than 0.05 is *, and p values greater than 0.05 are not symbolized.

CURE was more likely to respond in an expertlike way on the post-test than a student in other first-year physics labs. Moreover, 15 out of the 30 items demonstrated statistically significant odds ratios ($p < 0.05$) after the Holm-Bonferonni correction, all of which favored the C-PhLARE CURE. This overwhelmingly positive impact of the C-PhLARE CURE indicates that physics CUREs have the potential to develop many aspects of expertlike epistemologies surrounding experimental physics. We address each item through themes that we identified and discuss the potential elements of the CURE that may have contributed to higher odds of a more expertlike response compared to other first-year physics labs.

We identified six key themes in the C-PhLARE CURE design that could have influenced students' likelihood of responding with more expertlike attitudes and beliefs on the E-CLASS items: (i) Teamwork and scientific communication, (ii) authenticity of the research, (iii) confidence and self-efficacy, (iv) working with equipment, (v) relating experiment to theory, and (vi) understanding measurement uncertainty. It is worth noting that the E-CLASS does not exhibit strong factors according to previous research that conducted a factor analysis [42,44]; thus, these categories are not meant to be latent variables of the E-CLASS survey, but features of the course design could have influenced multiple E-CLASS items.

A. Teamwork and scientific communication

The C-PhLARE CURE was specifically designed to emphasize teamwork and communication as scientific practices. Several instructional strategies were employed to underscore teamwork throughout the course, including consistent and purposeful messaging about its importance, prelab lectures that showcased teamwork as a scientific practice (e.g., collaborations like CERN and smaller lab settings), explicit advice on effective team coding in Google Colaboratory, training for TAs to address common teamwork challenges, and incorporation of authentic collaboratory research practices, such as peer review and group meetings with the principal investigator. Previous research on the impact of the CURE indicated that students greatly enjoyed their teamwork experience, considered it an essential part of their research in the course, and emphasized the significance of effective communication for successful research collaboration [31,36].

Given this emphasis on teamwork and communication, it is understandable that E-CLASS item 17, "communicating scientific results to peers is a valuable part of doing physics experiments," exhibited the highest odds ratio of $4.29^{+1.97}_{-1.24}$. Additionally, item 19, "working in a group is an important part of doing physics experiments," demonstrated a significant odds ratio of $2.24^{+0.55}_{-0.43}$.

B. Authenticity of the research

An essential aspect of a CURE is student participation in authentic scientific discovery, where students tackle research questions that have answers that are initially unknown to both themselves and the scientific community. Throughout the course, students were consistently reminded that their research was contributing to genuine scientific knowledge, culminating in a publication of the findings in *The Astrophysical Journal* [12].

Furthermore, a previous study on the C-PhLARE CURE showed that students felt they engaged in real-world research and frequently highlighted their experience with authentic research when asked to describe their experience in the course more broadly [37]. When discussing the authentic aspects of the C-PhLARE CURE, students particularly emphasized the societal impact and the discovery nature of their research. This likely contributed to the increased odds of items 30 and 29. Item 30, with the second-highest odds ratio of $2.53^{+1.20}_{-0.74}$, states that "physics experiments contribute to the growth of scientific knowledge." Similarly, item 29, with an odds ratio of $1.79^{+0.23}_{-0.20}$, suggests that "the primary purpose of doing physics experiments is to confirm previously known results," with the more expertlike response disagreeing with the statement.

In addition, many course elements were intentionally designed to actively engage students in the scientific practices of authentic research. For instance, the course began with a literature review where students familiarized themselves with existing research on determining flare frequency distributions. Consequently, it is not surprising to find that item 18, "scientific journal articles are helpful for answering my own questions and designing experiments," exhibited a statistically significant odds ratio of $2.33^{+0.39}_{-0.33}$ in favor of the C-PhLARE CURE. Additionally, students regularly utilized computer tools such as Google Colaboratory for data analysis and plotting, likely leading to item 10, "computers are helpful for plotting and analyzing data," having a statistically significant odds ratio in favor of the C-PhLARE CURE.

While students in the C-PhLARE CURE had some agency in making methodological choices during their solar flare analysis (e.g., selecting a flare, choosing baseline correction methods, determining start and end points), many of other components were prescribed due to the large number of introductory students. This may explain why item 7, "if I don't have clear directions for analyzing data, I am not sure how to choose an appropriate analysis method," had an odds ratio overlapping with 1. However, it is surprising to note that item 12, "when doing an experiment, I usually think up my own questions to investigate," had a significant, positive odds ratio, and further investigation is needed to determine the factors contributing to this outcome in the C-PhLARE CURE.

Moreover, although communication of results through informal means and code annotations was emphasized in the class as an authentic scientific practice, scientific writing was not a primary focus of the course. Therefore, it is expected that items 20 and 21, related to scientific communication, have odds ratios overlapping with 1.

C. Confidence and self-efficacy

A fundamental objective of the C-PhLARE CURE was to foster students' confidence in their ability to conduct scientific research in the future. Previous research by Hanauer *et al.* [54] demonstrated that CUREs positively influenced student self-efficacy, science identity, understanding of scientific community values, and networking, leading to increased persistence in the sciences. Several epistemological beliefs related to self-efficacy were examined in the E-CLASS, including item 13, "when doing an experiment, I just follow the instructions without thinking about their purpose," item 23, "I don't enjoy doing physics experiments," item 25, "if I try hard enough, I can succeed at doing physics experiments," and item 26, "if I wanted to, I think I could be good at doing research." Consistent with the findings of Hanauer *et al.*, items 13, 25, and 26, all exhibited significant, positive odds ratios in favor of the C-PhLARE CURE. Item 25 had a positive odds ratio that did not overlap with 1, but this item was not found to be significant. Item 13 had an odds ratio of $1.27^{+0.19}_{-0.15}$, item 23 had an odds ratio of $1.21^{+0.17}_{-0.15}$, item 25 had an odds ratio of $1.52^{+0.46}_{-0.33}$, and item 26 had an odd ratio of $2.43^{+0.60}_{-0.47}$, the third highest of all of the E-CLASS items.

Two items that we anticipated might have significantly higher odds in the C-PhLARE CURE were items 15, "when I encounter difficulties in the lab, my first step is to ask an expert, like the instructor," and 24, "nearly all students are capable of doing a physics experiment if they work at it." While item 15 exhibited an odds ratio greater than 1 with a confidence interval that did not include 1, we lack statistical power to draw strong conclusions, and perhaps students were impacted by the remote environment making it difficult to communicate with the course instructors. We are not sure what might have impacted student responses to item 24, though it may have its roots in authenticity as well as the collaborative aspects of the course.

D. Working with equipment

A crucial aspect of the C-PhLARE CURE was its design to accommodate remote learning in response to the constraints imposed by the COVID-19 pandemic. Due to the inability of students to access the lab space in person and the limitations on purchasing and shipping equipment, it is not surprising that we did not observe significant, positive odds ratios for many of the E-CLASS items related to the hands-on nature of experimental physics or working with equipment. Items 1, 2, 8, 14, 16, 22, and 27 did not yield statistically significant odds ratios in favor of the C-PhLARE CURE. Notably, item 27, "when I approach a new piece of lab equipment, I feel confident I can learn how to use it well enough for my purposes," exhibited the lowest odds ratio among all the E-CLASS items, with an odds ratio of $0.84^{+0.14}_{-0.11}$.

E. Relating experiment to theory

The design of the C-PhLARE CURE was influenced by several constraints, including its limited duration of 2 h per week, one credit hour, large enrollment, and introductory level. Consequently, our emphasis was on student learning of the research process rather than specific physics content knowledge, theories, or equations. This decision is reflected in the results, as items 8, 9, and 28, which pertain to these aspects, yielded odds ratios that overlap with 1.

F. Understanding measurement uncertainty

We made the deliberate decision not to cover measurement uncertainty in the CURE course, since calculating the uncertainty in total flare energy was complex, and we did not require students to make predictions based on theoretical understandings. However, surprisingly, we observed significant, positive odds ratios for items 3, 4, 5, 6, and 11, which involve calculating uncertainties, evaluating systematic error, understanding performance limitations, and making predictions. We are uncertain about the specific elements of the C-PhLARE CURE that may have contributed to these outcomes and warrant further investigation, but perhaps, it may stem from the students' consideration of the societal impact of their published CURE research and from the discussion of these results in the classwide meeting with the PI.

V. CONCLUSIONS

This study examined the impact of the C-PhLARE CURE, the first reported large-enrollment, introductory physics CURE, on student attitudes and beliefs toward experimental physics. By utilizing the validated E-CLASS assessment and open-source historical E-CLASS dataset, we gained valuable insights into the development of more expertlike attitudes and beliefs in the CURE compared to other types of first-year physics labs.

Our findings demonstrated that the implementation of the C-PhLARE CURE had a positive influence on students' epistemologies surrounding experimental physics. Controlling for precourse scores, gender, and major, we observed statistically significant higher E-CLASS scores across many of the E-CLASS items and no statistically significant negative impact compared to the other first-year physics labs.

Students enrolled in the C-PhLARE CURE were over 4 times more likely to develop more expertlike beliefs about communicating scientific findings to peers and almost 3 times more likely to develop more expertlike beliefs that physics experiments contribute to the growth of scientific knowledge. They also demonstrated an increased likelihood of developing more expertlike beliefs surrounding other authentic scientific practices, confidence in their ability to conduct physics research, and understandings of measurement uncertainty. These findings align with previous research on the C-PhLARE CURE, confirming its positive influence on students' confidence [11], teamwork skills [31,36], and authenticity [37].

Further investigation is necessary to explore how the C-PhLARE CURE compares to other lab formats, such as traditional "cookbook" labs, investigative learning environments, project-based labs, and other labs conducted remotely. Furthermore, we encourage future analyses to explore how the C-PhLARE CURE specifically impacted students from diverse demographic backgrounds and majors, as such analysis is crucial for identifying any potential disparities and ensuring equitable educational experiences for all students.

Finally, our study contributes to the growing body of evidence supporting the positive impacts of CUREs [2] and emphasizes the ability of CUREs to develop more expertlike scientific epistemologies—key for fostering persistence in the sciences [8,51,52]. This is crucial given that CUREs have a greater potential to reach a diverse group of students than traditional undergraduate research experiences and have the potential to provide students with meaningful research experiences early in their undergraduate careers.

In conclusion, the C-PhLARE CURE exemplifies the potential of innovative curricular approaches to engage students, promote their development as researchers, and lay a strong foundation for their future academic and professional endeavors. This study contributes to the broader understanding of CUREs' positive impacts and highlights their ability to cultivate expertlike scientific epistemologies, benefiting students' persistence in the sciences.

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APPENDIX: TABLE OF RESULTS FROM LOGISTIC REGRESSION ANALYSES

Table I presents individual E-CLASS items along with their item number and alignment with C-PhLARE CURE goals and instructional emphases (Goal). The odds ratios (OR), confidence intervals (CI), p values (p), and Holm-Bonferonni corrected p values (p') of the ordinal logistic regression analysis of each item are also provided.

TABLE I. Individual E-CLASS items, alignment with C-PhLARE CURE goals and instructional emphases (Goals), odds ratios (OR), confidence intervals (CI), p values (p), and Holm-Bonferonni corrected p values (p').

No.	E-CLASS item	Goal	OR	CI low	CI high	p	p'
1	When doing an experiment, I try to understand how the experimental setup works.	No	1.35	1.05	1.77	0.022	0.30
2	I don't need to understand how the measurement tools and sensors work in order to carry out an experiment.	No	1.00	0.87	1.15	0.96	1
3	When doing a physics experiment, I don't think much about sources of systematic error.	No	1.26	1.09	1.45	0.0016	0.027
4	It is helpful to understand the assumptions that go into making predictions.	No	1.86	1.38	2.58	9.54×10^{-5}	0.0020
5	Whenever I use a new measurement tool, I try to understand its performance limitations.	No	1.37	1.18	1.59	4.45×10^{-5}	0.0010
6	Calculating uncertainties usually helps me understand my results better.	No	1.71	1.46	2.02	6.70×10^{-11}	1.67×10^{-9}
7	If I don't have clear directions for analyzing data, I am not sure how to choose an appropriate analysis method.	Yes	0.89	0.79	1.00	0.053	0.58
8	I am usually able to complete an experiment without understanding the equations and physics ideas that describe the system I am investigating.	No	1.03	0.92	1.17	0.59	1
9	When doing an experiment, I try to understand the relevant equations.	No	1.28	1.04	1.60	0.026	0.31
10	Computers are helpful for plotting and analyzing data.	Yes	2.40	1.41	4.53	0.0030	0.049
11	When I am doing an experiment, I try to make predictions to see if my results are reasonable.	No	1.43	1.17	1.78	0.00069	0.013
12	When doing an experiment, I usually think up my own questions to investigate.	No	1.44	1.27	1.63	8.09×10^{-9}	1.94×10^{-7}
13	When doing an experiment, I just follow the instructions without thinking about their purpose.	No	1.27	1.12	1.46	0.00040	0.0080
14	Designing and building things is an important part of doing physics experiments.	No	0.94	0.82	1.09	0.43	1
15	When I encounter difficulties in the lab, my first step is to ask an expert, like the instructor.	Yes	1.09	0.96	1.25	0.19	1
16	A common approach for fixing an experiment is to randomly change things until the problem goes away.	No	1.00	0.87	1.15	0.98	1
17	Communicating scientific results to peers is a valuable part of doing physics experiments.	Yes	4.29	3.05	6.26	1.68×10^{-15}	4.55×10^{-14}
18	Scientific journal articles are helpful for answering my own questions and designing experiments.	Yes	2.33	2.00	2.72	5.59×10^{-27}	1.68×10^{-25}
19	Working in a group is an important part of doing physics experiments.	Yes	2.24	1.81	2.79	4.29×10^{-13}	1.12×10^{-11}
20	If I am communicating results from an experiment, my main goal is to make conclusions based on my data using scientific reasoning.	Yes	1.20	0.98	1.48	0.082	0.82
21	If I am communicating results from an experiment, my main goal is to have the correct sections and formatting.	Yes	1.06	0.94	1.20	0.35	1
22	I enjoy building things and working with my hands.	No	1.14	0.93	1.40	0.20	1
23	I don't enjoy doing physics experiments.	Yes	1.21	1.06	1.38	0.0053	0.079
24	Nearly all students are capable of doing a physics experiment if they work at it.	Yes	1.00	0.83	1.22	0.99	1
25	If I try hard enough, I can succeed at doing physics experiments.	Yes	1.52	1.19	1.98	0.0011	0.020
26	If I wanted to, I think I could be good at doing research.	Yes	2.43	1.96	3.03	1.38×10^{-15}	3.87×10^{-14}
27	When I approach a new piece of lab equipment, I feel confident I can learn how to use it well enough for my purposes.	No	0.84	0.73	0.98	0.023	0.30
28	I do not expect doing an experiment to help my understanding of physics.	No	1.11	0.95	1.30	0.21	1
29	The primary purpose of doing physics experiments is to confirm previously known results.	Yes	1.79	1.59	2.02	3.25×10^{-21}	9.44×10^{-20}
30	Physics experiments contribute to the growth of scientific knowledge.	Yes	2.53	1.79	3.73	7.19×10^{-7}	1.65×10^{-5}

[1] *Confronting Failure: Approaches to Building Confidence and Resilience in Undergraduate Researchers*, edited by L. A. Corwin, L. K. Charkoudian, and J. H. Heemstra (Council on Undergraduate Research, 2022).

[2] L. C. Auchincloss, S. L. Laursen, J. L. Branchaw, K. Eagan, M. Graham, D. I. Hanauer, G. Lawrie, C. M. McLinn, N. Pelaez, S. Rowland *et al.*, Assessment of course-based undergraduate research experiences: A meeting report CBE Life, Sci Educ. **13**, 29 (2014).

[3] G. A. Szteinberg and G. C. Weaver, Participants' reflections two and three years after an introductory chemistry course-embedded research experience, Chem. Educ. Res. Pract. **14**, 23 (2013).

[4] S. L. Rowland, G. A. Lawrie, J. B. Behrendorff, and E. M. Gillam, Is the undergraduate research experience (URE) always best?: The power of choice in a bifurcated practical stream for a large introductory biochemistry class, Biochem. Mol. Biol. Educ. **40**, 46 (2012).

[5] D. Lopatto, Science in solution, Tucson, AZ: Research Corporation for Science Advancement (2010).

[6] AAPT Committee on Laboratories, *AAPT Recommendations for the Undergraduate Physics Laboratory Curriculum* (American Association of Physics Teachers, College Park, MD, 2014).

[7] C. B. Russell and G. C. Weaver, A comparative study of traditional, inquiry-based, and research-based laboratory curricula: Impacts on understanding of the nature of science, Chem. Educ. Res. Pract. **12**, 57 (2011).

[8] B. R. Wilcox and H. Lewandowski, A summary of research-based assessment of students' beliefs about the nature of experimental physics, Am. J. Phys. **86**, 212 (2018).

[9] B. R. Wilcox and H. J. Lewandowski, Students' epistemologies about experimental physics: Validating the colorado learning attitudes about science survey for experimental physics, Phys. Rev. Phys. Educ. Res. **12**, 010123 (2016).

[10] B. M. Zwickl, T. Hirokawa, N. Finkelstein, and H. J. Lewandowski, Epistemology and expectations survey about experimental physics: Development and initial results, Phys. Rev. ST Phys. Educ. Res. **10**, 010120 (2014).

[11] A. Werth, C. G. West, and H. J. Lewandowski, Impacts on student learning, confidence, and affect in a remote, large-enrollment, course-based undergraduate research experience in physics, Phys. Rev. Phys. Educ. Res. **18**, 010129 (2022).

[12] J. P. Mason, A. Werth, C. G. West, A. Youngblood, D. L. Woodraska, C. L. Peck, A. J. Aradhya, Y. Cai, D. Chaparro, J. W. Erikson *et al.*, Coronal heating as determined by the solar flare frequency distribution obtained by aggregating case studies, Astrophys. J. **948**, 71 (2023).

[13] CUREnet, https://serc.carleton.edu/curenet/.

[14] N. G. Holmes, J. Olsen, J. L. Thomas, and C. E. Wieman, Value added or misattributed? A multi-institution study on the educational benefit of labs for reinforcing physics content, Phys. Rev. Phys. Educ. Res. **13**, 010129 (2017).

[15] C. Wieman, Comparative cognitive task analyses of experimental science and instructional laboratory courses, Phys. Teach. **53**, 349 (2015).

[16] B. R. Wilcox and H. J. Lewandowski, Developing skills versus reinforcing concepts in physics labs: Insight from a survey of students' beliefs about experimental physics, Phys. Rev. Phys. Educ. Res. **13**, 010108 (2017).

[17] National Research Council, *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning* (National Academies Press, Washington, DC, 2000), https://doi.org/10.17226/9596.

[18] C. Beck, A. Butler, and K. Burke da Silva, Promoting inquiry-based teaching in laboratory courses: Are we meeting the grade?, CBE Life Sci. Educ. **13**, 444 (2014).

[19] E. Seymour, A.-B. Hunter, S. L. Laursen, and T. DeAntoni, Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study, Sci. Educ. **88**, 493 (2004).

[20] G. C. Weaver, C. B. Russell, and D. J. Wink, Inquiry-based and research-based laboratory pedagogies in undergraduate science, Nat. Chem. Biol. **4**, 577 (2008).

[21] A. R. Burmeister, K. Dickinson, and M. J. Graham, Bridging trade-offs between traditional and course-based undergraduate research experiences by building student communication skills, identity, and interest, J. Microbiol. Biol. Educ. **22**, e00156 (2021).

[22] R. Laungani, C. Tanner, T. Durham Brooks, B. Clement, M. Clouse, E. Doyle, S. Dworak, B. Elder, K. Marley, and B. Schofield, Finding some good in an invasive species: Introduction and assessment of a novel cure to improve experimental design in undergraduate biology classrooms, J. Microbiol. Biol. Educ. **19**, 19.2.68.(2018).

[23] E. D. E, T. Sloan *et al.*, Antibiotic discovery throughout the small world initiative: A molecular strategy to identify biosynthetic gene clusters involved in antagonistic activity, Microbiologyopen **6**, e00435 (2017).

[24] C. D. Shaffer *et al.*, The genomics education partnership: Successful integration of research into laboratory classes at a diverse group of undergraduate institutions, CBE Life Sci. Educ. **9**, 55 (2010).

[25] E. Seymour, A.-B. Hunter, S. L. Laursen, and T. DeAntoni, Establishing the benefits of research experiences for undergraduates in the sciences: First findings from a three-year study, Sci. Educ. **88**, 493 (2004).

[26] M. M. Wooten, K. Coble, A. W. Puckett, and T. Rector, Investigating introductory astronomy students' perceived impacts from participation in course-based undergraduate research experiences, Phys. Rev. Phys. Educ. Res. **14**, 010151 (2018).

[27] J. R. Walkup, R. A. Key, S. P. Duncan, A. E. Sheldon, and M. A. Walkup, Catastrophic cancellation in elastic collision lab experiments, Phys. Educ. **55**, 015010 (2020).

[28] J. T. Beckham, S. Simmons, G. M. Stovall, and J. Farre, The freshman research initiative as a model for addressing shortages and disparities in stem engagement, in *Directions for Mathematics Research Experience for Undergraduates* (World Scientific, Singapore, 2015), pp. 181–212.

[29] A. Werth, J. R. Hoehn, K. Oliver, M. F. J. Fox, and H. J. Lewandowski, Instructor perspectives on the emergency transition to remote instruction of physics labs, Phys. Rev. Phys. Educ. Res. **18**, 020129 (2022).

[30] G. LLC, Google Colaboratory welcome page (2018).

[31] A. Werth, K. A. Oliver, C. G. West, and H. J. Lewandowski, Engagement in collaboration and teamwork using Google Colaboratory, presented at PER Conf. 2022, Grand Rapids, MI, 10.1119/perc.2022.pr.Werth.

[32] J. Knuth, G. Lucas, C. K. Pankratz, T. E. Berger, R. D. Clark, and T. M. Skov, SWx TREC's space weather data portal: A launch pad for space weather research, in *AGU Fall Meeting Abstracts* (2020), Vol. 2020, pp. SM003–0018, https://agu.confex.com/agu/fm20/meetingapp.cgi/Paper/747723.

[33] G. M. Novak, E. T. Patterson, A. D. Gavrin, and W. Christian, *Just-in-Time Teaching: Blending Active Learning with Web Technology* (Prentice-Hall, New Jersey, 1999).

[34] H. Y. Agustian and M. K. Seery, Reasserting the role of pre-laboratory activities in chemistry education: A proposed framework for their design, Chem. Educ. Res. Pract. **18**, 518 (2017).

[35] H. Lewandowski, B. Pollard, and C. G. West, Using custom interactive video prelab activities in a large introductory lab course, presented at PER Conf. 2020, Provo, UT, 10.1119/perc.2019.pr.Lewandowski.

[36] A. Werth, K. Oliver, C. G. West, and H. J. Lewandowski, Assessing student engagement with teamwork in an online, large-enrollment course-based undergraduate research experience in physics, Phys. Rev. Phys. Educ. Res. **18**, 020128 (2022).

[37] K. A. Oliver, A. Werth, and H. J. Lewandowski, Student experiences with authentic research in a remote, introductory course-based undergraduate research experience in physics, Phys. Rev. Phys. Educ. Res. **19**, 010124 (2023).

[38] N. G. Lederman, F. Abd-El-Khalick, R. L. Bell, and R. S. Schwartz, Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science, J. Res. Sci. Teach. **39**, 497 (2002).

[39] E. F. Redish, J. M. Saul, and R. N. Steinberg, Student expectations in introductory physics, Am. J. Phys. **66**, 212 (1998).

[40] W. K. Adams, K. K. Perkins, N. S. Podolefsky, M. Dubson, N. D. Finkelstein, and C. E. Wieman, New instrument for measuring student beliefs about physics and learning physics: The Colorado learning attitudes about science survey, Phys. Rev. ST Phys. Educ. Res. **2**, 010101 (2006).

[41] B. M. Zwickl, N. Finkelstein, and H. J. Lewandowski, Development and validation of the Colorado learning attitudes about science survey for experimental physics, AIP Conf. Proc. **1513**, 442 (2013).

[42] B. R. Wilcox and H. J. Lewandowski, Students' epistemologies about experimental physics: Validating the Colorado learning attitudes about science survey for experimental physics, Phys. Rev. Phys. Educ. Res. **12**, 010123 (2016).

[43] B. R. Wilcox and H. J. Lewandowski, Open-ended versus guided laboratory activities: Impact on students' beliefs about experimental physics, Phys. Rev. Phys. Educ. Res. **12**, 020132 (2016).

[44] J. M. Aiken and H. J. Lewandowski, Data sharing model for physics education research using the 70 000 response colorado learning attitudes about science survey for experimental physics dataset, Phys. Rev. Phys. Educ. Res. **17**, 020144 (2021).

[45] B. R. Wilcox and H. J. Lewandowski, A summary of research-based assessment of students' beliefs about the nature of experimental physics, Am. J. Phys. **86**, 212 (2018).

[46] B. R. Wilcox and H. J. Lewandowski, Developing skills versus reinforcing concepts in physics labs: Insight from a survey of students' beliefs about experimental physics, Phys. Rev. Phys. Educ. Res. **13**, 010108 (2017).

[47] B. R. Wilcox and H. J. Lewandowski, Students' views about the nature of experimental physics, Phys. Rev. Phys. Educ. Res. **13**, 020110 (2017).

[48] N. Sulaiman, A. Werth, and H. J. Lewandowski, Students' views about experimental physics in a large-enrollment introductory lab focused on experimental scientific practices, Phys. Rev. Phys. Educ. Res. **19**, 010116 (2023).

[49] M. F. J. Fox, J. R. Hoehn, A. Werth, and H. J. Lewandowski, Lab instruction during the Covid-19 pandemic: Effects on student views about experimental physics in comparison with previous years, Phys. Rev. Phys. Educ. Res. **17**, 010148 (2021).

[50] C. Walsh, H. J. Lewandowski, and N. G. Holmes, Skills-focused lab instruction improves critical thinking skills and experimentation views for all students, Phys. Rev. Phys. Educ. Res. **18**, 010128 (2022).

[51] X. Guo, X. Hao, W. Deng, X. Ji, S. Xiang, and W. Hu, The relationship between epistemological beliefs, reflective thinking, and science identity: A structural equation modeling analysis, Int. J. STEM Educ. **9**, 40 (2022).

[52] M. J. Graham, J. Frederick, A. Byars-Winston, A.-B. Hunter, and J. Handelsman, Increasing persistence of college students in stem, Science **341**, 1455 (2013).

[53] B. R. Wilcox and H. J. Lewandowski, Research-based assessment of students' beliefs about experimental physics: When is gender a factor?, Phys. Rev. Phys. Educ. Res. **12**, 020130 (2016).

[54] D. I. Hanauer, M. J. Graham, and G. F. Hatfull, A measure of college student persistence in the sciences (pits), CBE Life Sci. Educ. **15**, ar54 (2016).