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Embedding Research Directly into the Chemistry Curriculum with an Organic to Analytical Sequence

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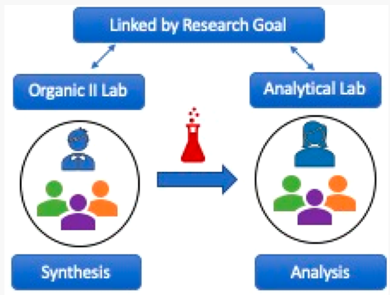

ABSTRACT: This manuscript describes the implementation of a Course-based Undergraduate Research Experience (CURE) sequence in chemistry that uses research to link a lower division, organic chemistry course to an upper-division, analytical chemistry course. In the CURE sequence, students created a library of modified sugar molecules during CURE-1, Organic, and then evaluated the behavior of those molecules within membranes during CURE-2, Analytical. In order to ascertain the causal mechanisms underlying the effectiveness and sustainability of CUREs within the standard chemistry curriculum, we conducted research on students in CURE laboratories and Standard Instruction (SI) laboratories. Results from the Classroom Undergraduate Research Experience (CURE) Survey, the Laboratory Course Assessment Survey (LCAS), and an end-of-course assessment are presented. Equivalency of the CURE and comparison groups was established based on demographic factors, reported gender and minority status, expected major, and grade in the prerequisite course. A direct comparison of this nature revealed the benefits of the CURE sections and equality in assessment performance regardless of the instructional method.

KEYWORDS: *Second-Year Undergraduate, Upper-Division Undergraduate, Analytical Chemistry, Organic Chemistry, Inquiry-Based/Discovery Learning, Undergraduate Research, Chemical Education Research*

FEATURE: Chemical Education Research

■ INTRODUCTION

Participation in undergraduate research has been identified as a high-impact practice which can lead to increased persistence in science,[1−3] improved science process skills,[4,5] and increased entry into graduate school.[6] The apprenticeship model, in which students conduct independent research projects in an individual faculty member's laboratory, is a well-established approach to providing undergraduate research experiences. However, this model is limited by an individual faculty member's laboratory program, laboratory space, and instructional commitments. Embedding research within the curriculum through course-based undergraduate research experiences (CUREs) is a recognized strategy for increased access to research.[7,8] The institution in this study, a primarily undergraduate institution (PUI), has recently developed a CURE sequence that bridges a lower division organic chemistry laboratory with an upper division analytical laboratory. The concept of a CURE sequence, i.e., a multicourse research project, was based on a collaborative research program focused on developing a blood preservative. The research team consisted of an organic chemist who was working on synthesis of the target molecules and an analytical chemist conducting analysis on the ability of the molecules to displace water in the phospholipid membrane. The research project designed for the CURE sequence involved undergraduate students in research-based laboratory courses focused on synthetic organic chemistry and bioanalytical/biophysical chemistry, each lasting a single semester. Students in organic chemistry synthesized a set of substituted trehalose molecules to produce molecules with a wide range of hydrophilic and lipophilic properties which were subsequently studied in the analytical laboratory course. The overarching research question that the linked CUREs, "How do we preserve blood for more than 42 days?", is currently being researched in the wider bioanalytical field.[9−11] Both courses were designed to align with the five components of a CURE—science practices, discovery, relevance, collaboration, and iteration—that have been previously recommended.[12]

■ LITERATURE REVIEW

Students entering college may not know that research exists, and if they know that research would be beneficial to their education, they may not know how to apply or have the confidence to approach a faculty member. This is particularly true of groups that are traditionally marginalized in science.[8] When students enroll in a course that includes research as part of the curriculum,

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they can engage in research without applying or being selected. In this way, CUREs can greatly increase both access and equity in research opportunities for undergraduates.[8] Nationally, science faculty members have been experimenting with such an approach, creating CUREs across the scientific disciplines. Tested models are available, and there is a growing body of literature on the efficacy of this approach for both students and faculty.[13,14]

The Freshman Research Initiative (FRI) has implemented CUREs across multiple disciplines.[15] Investigation of the long-term effects of students in the FRI program found that students who participated in three semesters were significantly more likely than their non-FRI peers to earn a STEM degree and had a 94% probability of graduating within 6 years. The effect, however, was moderated by the number of semesters students participated in the FRI courses. FRI students that only completed one or two semesters had a predicted probability of graduating in 6 years equivalent to non-FRI students.[16]

A chemistry-focused example of broad implementation of the course-based research concept is the Center for Authentic Science Practice in Education (CASPiE).[17,18] CASPiE studies showed several benefits for students, including an increase in students' connections between science and everyday life, increased critical thinking skills, and increased engagement for women and underrepresented groups.[13,19] Research supporting chemistry-focused CUREs at the introductory and upper division levels has been published, indicating the communities' interest in this instructional practice. Emory University reported a positive effect on student understanding of research and confidence in conducting research after participating in a physical chemistry CURE.[20] The study utilized student survey data comparing the students in the study ($N = 22$) to a national data set of students who took the survey. They report statistically significant differences for CURE students in three course-benefit items, *tolerance for obstacles*, *readiness for research*, and *skill in science writing*. Implementation of research in a two-semester analytical chemistry sequence has been described previously, but findings of student impact were minimal.[21] Students in an inorganic CURE were tasked with a self-designed research project to identify new catalysts for dehydrogenation. Survey results indicated gains in research experience and elements of the nature of science.[22] The development and implementation of a research module within a large-enrollment organic laboratory course, i.e., a blended traditional and research experience, was recently published.[23] The authors observed significant growth in scientific self-efficacy based on a pre/post survey. The post self-efficacy scores also significantly correlated with the Laboratory Course Assessment Survey (LCAS) score and students' rating of their sense of project ownership.

All but one of these examples are one-semester experiences with varying amounts of research opportunity and no direct comparison to traditional laboratory experiences. In addition, the metrics are all self-report surveys and interviews with no assessment of student learning in moving from the long-established model of laboratory instruction to a CURE. In light of this, recent calls have been made for innovative and rigorous assessment strategies to better understand the efficacy and impact of CUREs on key disciplinary skills.[24] These studies need powerful and generalizable assessments that can document student progress, help distinguish effective and ineffective aspects of the experiences, and illustrate how students interpret the research experiences they encounter.[12,13]

RESEARCH QUESTIONS

Implementation of the CURE sequence into the standard chemistry curriculum provided an opportunity to add to the existing literature by providing a direct comparison between students in a CURE with students in Standard Instruction (SI) laboratory courses. The following questions were addressed:

RQ1.
What are student perceptions of research in an Organic CURE compared to a SI laboratory course?

RQ2.
How does student content understanding on an end-of-course exam in an Organic CURE compare to a SI laboratory course?

RQ3.
What are student perceptions of course design elements collaboration, iteration, and discovery and relevance in an Analytical CURE compared to a SI laboratory course?

RQ4.
How does student ability to analyze familiar and unfamiliar experimental information in an Analytical CURE compare to a SI laboratory course?

METHODOLOGY

Participants

The CURE sequence followed the recommended curriculum structure, Organic II Laboratory (CURE-1) in the Spring and Analytical Laboratory (CURE-2) in the Fall. This study was approved by the East Carolina University Internal Review Board (No. 16002076), and consent was obtained from all participants. The participants for CURE-1 for the first cohort of the CURE sequence were recruited from the Organic I lecture course. All students were given an informational flyer with a portion to indicate interest in the CURE (Yes/No) and to provide identifying information. The CURE participants were selected from the "yes" group using matched sampling based on three parameters: major, gender, and under-represented minority (URM) status.[25] We recognize that gender is not a binary construct and therefore those who identify with other genders not listed as options defined by the registrar at the university have been left out of this study. URM status in this study was defined as Black, Hispanic, Native American, or two or more races. Near the end of CURE-1, the analytical professor presented the research continuation for CURE-2, and students indicated their desire to continue the research into a second semester on a short informational form.

χ^2 analysis was conducted to determine significant differences between the students that participated in each CURE and the students that were enrolled in the corresponding lecture courses. For CURE-1, the comparison group from the organic lecture was limited to those that had indicated interest in participating in the CURE through the application process. The CURE-2 students were compared to students enrolled in the corresponding lecture course. χ^2 analysis was conducted on student demographics data for gender and URM status, expected major, and grade in the prerequisite course.

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Standard Instruction Organic Laboratory and CURE-1

The SI Organic Chemistry Laboratory II course was offered as a co-requisite for the lecture course. It was the second semester course of a two-semester sequence focused on spectroscopy and synthesis reactions (e.g., Fisher esterification, aldol condensation). Student performance was evaluated using weekly write-ups, periodic laboratory notebook checks, a formal lab report, and a final exam. CURE-1 was designed to meet the learning outcomes for the SI Organic Chemistry Laboratory II course but in a research focused environment based on relevant and meaningful exposure to instrumentation for research purposes. Published synthetic procedures were adapted by the CURE-1 students.[26]

CURE-1 students were divided into groups of four students each. Target molecules for the groups differed by the number of intervening $-CH_2-$ groups in the linker (e.g., zero, one, three, six, or nine) which attached to an aromatic anchor (pyrene) to trehalose via an ester bond. Groups typically chose to further subdivide into pairs, with each pair pursuing different routes to the desired products. Groups were responsible for all aspects of the synthesis, purification, and characterization of new molecules. Thus, all participants in CURE-1 gained experience in reaction design, extraction, TLC and HPLC, mass spectrometry (MS), and proton NMR.

Details on course activities and desired outcomes for both contexts are available in the Supporting Information. Similar assignments were integrated into both contexts, with some differences; i.e., weekly quizzes were used in the SI course to motivate students to read material before lab, and in the CURE lab a single formal lab report was the principal assessment during the semester. Sections of the formal lab report were written over the course of the semester. Each section was written by a lead author and reviewed by a coauthor. Table 1 provides assignments and grade weighting for both contexts.

Table 1. Graded Assignments for CURE-1 and SI Organic

CURE-1		SI	
Assignment	Percentage (%)	Assignment	Percentage (%)
Notebook Check (2)	22	Notebook Check (2)	23
Formal Lab Report		Formal Lab Report	14
Lead Author	22	Write-Up Sheets (9	33
Co-author	22	Quizzes (6)	20
Poster and Presentation	22	Lab Practical Exam	12
Lab Practical Exam	12		

Standard Instruction Analytical Laboratory and CURE-2

The Analytical Laboratory was considered the second course in the analytical chemistry laboratory sequence. The practical component focused on classical and modern analytical methods (titrations, potentiometric analysis, UV−vis, fluorescence, and chromatography). Student performance was evaluated using weekly lab notebook reports, accuracy and precision, and two comprehensive formal reports on modern instrumental experiments.

CURE-2 was designed to meet the learning outcomes for the SI Analytical Laboratory course through bioanalytical/biophysical chemistry research. A single student from each group came into the lab the day before their scheduled course time to prepare unilamellar liposomes by extrusion. The liposome preparation required 90 min the day before so that the biomembranes could rest overnight in a refrigerator, which leads to more consistent data.

Details on course activities and desired outcomes for both contexts are available in the Supporting Information. Similar assignments were integrated into both contexts, with the primary difference being the single lab report in the CURE course which was written in sections and revised throughout the semester. Table 2 provides assignments and grade-weighting for both contexts.

Table 2. Graded Assignments for CURE-2 and SI Analytical

CURE-2		SI	
Assignment	Percentage (%)	Assignment	Percentage
Notebook Check	24	Excel Spreadsheet	5
Abstract Draft/Revision	4	Notebook Reports (9)	24
Introduction Draft/Revision	4	Experimental Results (9)	35
Experimental Draft/Revision	4	Draft Formal Report	4
Results and Discussion Draft/Revision	4	Peer Reviews	3
Conclusions Draft/Revision	4	Response to Peer Reviews	3
Peer Review	10	Final Formal Report	6
Final Lab Report	10	Instrumental Expt Formal Reports (2)	20
Data and Figure Quality	16		
Presentation	20		

Survey Data

The Classroom Undergraduate Research Experience (CURE) surveys[27] and the Laboratory Course Assessment Survey (LCAS)[28] were used in this study. It is important to stipulate that survey results are based on students self-reporting and should be interpreted with awareness of the potential bias students may have in completing survey questions.[29] The CURE survey and LCAS have been shown to provide valid and reliable data, but due to the small samples size in this study validity and reliability evidence in this specific context was not possible.[5,20,22,28] Both surveys have been shown to differentiate between CUREs and traditional laboratory courses, making both suitable for characterizing and comparing undergraduate laboratory design features in both contexts.

The CURE surveys were administered via Qualtrics during the first 2 and last 2 weeks of the 2018 (Cohort 1) semester in CURE-1 and to the SI Organic laboratory courses. The LCAS was administered to two cohorts (2018 and 2019) of CURE-2 students during the last 2 weeks of the semester and to the SI Analytical students during the first year of the study. It is possible for longer surveys to result in a higher percentage of nonresponse rates which can impact the overall validity of survey assessment.[29] The CURE survey is longer (46 items) in comparison to the LCAS (17 items). The decision to use the CURE survey for the organic course and the LCAS for the analytical course was based on the number of students in each of the CUREs to avoid survey fatigue.

Differences on the CURE survey were investigated between CURE-1 (Cohort-1) students and students within the SI course who had applied for CURE-1. The CURE survey items are divided into four categories; previous experience with course elements, perceived learning gains of course elements, perceived

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Table 3. Evidence Centered Design Components

Student Model	Evidence Model	Task Model
Knowledge, Skills, and Ability Targeted by Assessment	Observations and/or behaviors that will provide evidence of students' proficiency.	Task that student will perform to demonstrate proficiency.
Spectroscopy Interpretation	Use IR, NMR, and Mass Spec to identify a chemical compound.	Using mass spec, IR, and NMR, identify a chemical compound, then assign IR peaks and ^{1}H NMR peaks.
Synthetic Scheme and Experimental Design	Develop a reaction scheme, reactants and reagents, that will produce a target compound.	Write a reaction scheme for the synthesis of a target molecule. Explain what each step is supposed to accomplish. Describe methods to confirm the result of the synthesis.
Proficiency with Chemical Apparatus	Describe the use of chemical apparatus.	Given a chemical apparatus setup explain the purpose, explain potential problems, and predict potential results.
Interpretation of Experimental Data	Use product mass to calculate% yield and formulate conclusion for a chemical reaction.	Given a faux reaction product, obtain the actual mass and determine the percent yield for the reaction, and use melting point data to construct a conclusion.

Table 4. Scoring Rubric Example: Spectroscopy Interpretation

Prompt	Level 0	Level 1	Level 2	Target Response
Identify the correct compound.	Incorrect structure, ether	Incorrect structure, ester	Incorrect structure, aromatic ketone	Correct structure and functional group, ester
Infrared (IR): Assign three (3) IR peaks, by clearly indicating which functional groups of your chosen structure correspond to each peak.	No peaks assigned	Correctly assigned 1 IR peaks	Correctly assigned 2 IR peaks	Correctly assigned 3 IR peaks
*^{1}H NMR:*Assign all ^{1}H NMR peaks, by clearly indicating which H's of your chosen structure correspond to each peak.	Correctly assigned some ^{1}H NMR peaks, but wrong compound	Correctly assigned all ^{1}H NMR peaks, but wrong compound	Correctly assigned some ^{1}H NMR peaks	Correctly assigned all ^{1}H NMR peaks

gains in course benefits. and overall evaluation of the course. A list of all the survey items is provided in the Supporting Information. Previous experience (25 items) was measured on the presurvey and contained a response scale ranging from "No experience or feel inexperienced" to "Extensive experience or mastered this element". Perceived learning gains (25 items) were measured on the postsurvey using the same items as Previous Experience, but with a response scale ranging from "No gain or very small gain" to "Very large gain". Perceived gains in course benefits (21 items) and overall evaluation of the course (4 items) were measured on the postsurvey and were on a response scale ranging from "No gain or very small gain" to "Very large gain" and a Likert scale, respectively. All CURE survey items included a response choice of "Not applicable/ Prefer not to answer". With the small sample sizes in these courses, we chose not to exclude student responses if they chose "Not applicable/Prefer not to answer" or those who omitted items. To account for this, all response scales on the CURE survey were treated as categorical data with "Not applicable/ Prefer not to answer" and "No response" treated as separate categories when students responded in this way on a set of items. Structural validity has not been previously reported for the CURE survey, and the sample sizes are too small to investigate structural validity within this study. For this reason, we chose to look at differences between CURE-1 and SI students at the item level. Fisher's exact tests were performed on student responses to each previous experience item to ensure that student previous experiences did not differ between CURE and SI students. If significant differences were found, post hoc comparison tests with Bonferroni corrections were performed to determine which response group differed between CURE-1 and SI students (e.g., "small gain" or "agree" depending on the response scale for a set of items). This process was repeated for each item to determine differences between perceived learning gains, course benefits, and overall evaluation, respectively, between CURE and SI students. Fisher's Exact tests were performed using the base package in R (version 3.6.1). Post hoc comparisons were performed using the rstatix package (version 0.5.0).

The LCAS had 17 items and used a Likert scale to measure students' perceptions of three design features of laboratory courses: (1) collaboration (6 items), (2) discovery and relevance (5 items), and (3) iteration (6 items). The LCAS was designed to measure design features that make CUREs distinctive as learning experiences, based on input from experts in undergraduate research and thorough review of research on these experiences. An independent comparison analysis was conducted for comparison of CURE-2 (both cohorts) student scores to SI student scores. Assumptions of an independent comparison tests include no extreme outliers, normality, and homogeneity of variance. Extreme outliers were tested using the boxplot method, normality was tested using the Shapiro-Wilk test, and homogeneity of variance was tested using Levene's test. Assumptions and subsequent comparisons were tested using various packages in R (Version 3.6.1). All assumptions were tested using the rstatix package (Version 0.5.0). Mann−Whitney U nonparametric comparisons were tested using the onewaytests package (Version 2.5) package and effect sizes were calculated using the rcompanion package (Version 2.4.0). The thresholds of the effect size, *r*, were 0.10−0.20 (small), 0.30−0.50 (medium), 0.50−0.80 (large), and 0.70−1.30 (very large).

Organic Laboratory Practical Exam

A practical exam was developed to measure how well students in organic laboratory courses were able to use core ideas in organic chemistry to explain phenomena or solve problems. The practical exam was developed and refined in the SI Organic Chemistry Laboratory II, following an Evidence Centered Design (ECD) framework.[30] We began the process by assembling a team of three disciplinary faculty to identify the Knowledge, Skills, and Ability (KSA) that the assessment would target and the evidence of student proficiency to be gathered (Table 3). This process and subsequent revisions provided face and content validity to the final assessment. The KSA's were based on the organic chemistry course content as well as the laboratory activities within the SI laboratory. The tasks were developed and scoring rubric were administered in the SI laboratory courses, which identified logistical issues with administering the exam. Revisions were made; specifically, students did not setup the glassware, rather they were provided a setup to evaluate.

The next iteration was administered to students that had completed the course the previous semester. The education researcher and disciplinary expert conducted follow-up semi-structured interviews to identify points of confusion or misinterpretation of the question. This task model testing provided further face and content validity. Following the interviews, the exam was revised to reflect the issues raised by student responses and interview discussions. The laboratory practical and scoring rubric were modified further based on students' submitted answers in the SI laboratory courses, graduate teaching assistant feedback, and faculty expert review to provide an exam that could be administered and scored consistently. Table 4 provides an example of the scoring for the spectroscopy question.

The organic instrument was administered to the first cohort of CURE-1 students during the last week of the semester in the laboratory course and accounted for 12% of the total grade for the semester. A subset of student exams was scored by an undergraduate researcher and one of the authors (J.P.W.). Inter-rater reliability was established at the 0.70 level indicating substantial agreement, at which point the undergraduate researcher scored the remaining exams. Mann−Whitney U nonparametric comparisons were conducted for comparison of CURE-1 student scores to SI student scores, both from Cohort 1. Assumptions and effect size calculations were tested using R and the packages as previously described.

Analytical Exam

Similarly, we developed an exam to measure how well students were able to work with analytical data in familiar and unfamiliar contexts. The assessment was developed and refined in the SI Analytical chemistry course over several semesters, following an Evidence Centered Design (ECD) framework.[30] We began the process by assembling a team of three disciplinary faculty to identify the Knowledge, Skills, and Ability (KSA) that the assessment would target and the evidence of student proficiency to be gathered (Table 5). Students who had recently completed the course were asked to take the exam and then to meet with the research team in a semistructured interview to identify points of confusion or misinterpretation of the question This process repeated with three graduate students familiar with the analytical chemistry course. The expert development of the instrument, students at the graduate and undergraduate levels' responses and interviews provided face and content validity.

Table 5. Evidence Centered Design Components

Student Model	Evidence Model	Task Model
Knowledge, Skills, and Ability Targeted by Assessment	Observations, and/or Behaviors That Will Provide Evidence of Students' Proficiency	Task That Student Will Perform to Demonstrate Proficiency
Analysis and Reasoning	Given results of a known analytical method evaluate the results and revise an experiment	Experimental results for determination of vanillin in vanilla extracts.
Knowledge Application	Given results of a new analytical method evaluate the results.	Given overview of FRET, analyze data provided.

The analytical instrument was administered in the lecture course to all enrolled students 2 weeks before the end of the semester, and it accounted for 10% of the course grade for the semester.

Scoring was established by the analytical professor in discussion with the education researcher. The exams scores were reviewed by a graduate student (author B.J.W.) and the education researcher (author J.P.W.) to establish a concise rubric (Table 6).

Mann−Whitney U nonparametric comparisons were conducted for comparison of CURE−1 student scores to SI student scores, Assumptions and effect size calculations were tested using R and the packages as previously described.

■ RESULTS AND DISCUSSION

CURE vs SI Participants Comparison

A χ^2 test of independence was performed to examine the relation between student participants "CURE" and "SI" on four parameters: gender, major, URM status, and grade in prerequisite course. The analysis found no significant difference between the CURE and SI students in the four parameters (Table 7). This equivalency of the CURE students with the comparison students is important to keep in mind as we consider the survey and assessment data.

RQ1. What Are Student Perceptions of Research in an Organic CURE Compared to a SI Laboratory Course?

Fisher's Exact Tests indicated no significant differences between CURE-1 and SI students for the previous experience items with the exception of "collect data". Post hoc comparison tests revealed that there were significant differences within the response group "some experience". With more CURE-1 students reporting "some experience" for this item, it could be expected that CURE-1 students would report smaller perceived learning gains on the mirrored item because of their previous experience. Despite more CURE-1 students reporting "some experience" compared to SI students on previous experience item, more CURE-1 students responded with "very large" perceived learning gains compared to SI students.

Ten of the perceived learning gains items showed significant differences in responses between CURE-1 and SI students (Figure 1). Students answered differently when reporting their perceived learning gains for the following course elements: a scripted lab or project in which the students know the expected outcome, a lab or project where no one knows the outcome, work individually, work in small groups, become responsible for part of a project, read primary scientific literature, write a research proposal, collect data, analyze data, and present posters. While overall response patterns were shown to be different between CURE-1 and SI students, items read in the primary literature and present posters showed no significant differences in any specific response group according to post hoc comparison tests. Work individually, showed significant differences in "large gain" responses with SI students reporting more "large gain" responses in reference to working individually. Significantly more CURE-1 students reported "small gain" responses in reference to a scripted lab or project in which the students know the expected outcome. CURE-1 students reported significantly higher "very large gain" responses on, a lab or project where no one knows the outcome, work in small groups, become responsible for a port of the project, write a research proposal, collect data, analyzes data. These reported gains support the research-based focus of the CURE.

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Table 6. Scoring Rubric Example:

Prompt	Target Response
The student claims the experiment was successful. Do you agree or disagree? Explain your decision detailing any claim you make with sufficient evidence.	• Experiment was not successful. • Unknown absorbance is outside of calibration curve. • Unknown concentration does not consider dilutions. • Calculated correct unknown value. • Correction for blank.
What assumptions or flaws are there in the experiment as carried out by the student?	• Assumes that extraction is 100% efficient. • Assumes that calibration is linear. • Correction: dilute unknown by a factor of 2 • Improvement: extend calibration region • Improvement: do extraction on standards

Table 7. Results of χ^2 Comparison for SI Comparison Group and CURE Enrollments

Student Data	CURE-1 N = 24 (%)	SI Organic N = 35 (%)	CURE-2 N = 21 (%)	SI Analytical N = 30 (%)
Gender				
Female	17 (70.8)	24 (68.6)	12 (57.1)	22 (73.3)
Male	7 (29.2)	11 (31.4)	9 (42.9)	8 (26.7)
	χ^2 = 0.034, π > 0.05		**χ^2 = 1.46, π > 0.05**	
Race/Ethnicity				
Non-URM[a]	14 (58.3)	27 (77.1)	15 (71.4)	21 (70.0)
URM	10 (41.7)	8 (22.9)	4 (19.0)	9 (30.0)
Not listed	0 (0.0)	0 (0.0)	2 (9.5)	0 (0.0)
	χ^2 = 2.38, π > 0.05		**χ^2 = 3.44, π > 0.05**	
Major				
STEM[b]	16 (66.7)	24 (68.6)	19 (90.5)	30 (100.0)
Non-STEM	8 (33.3)	11 (31.4)	1 (4.8)	0 (0.0)
Not listed	0 (0.0)	0 (0.0)	1 (4.8)	0 (0.0
	χ^2 = 0.024, π > 0.05		**χ^2 = 2.97, π > 0.05**	
Prereq Grade				
A	8 (33.3)	8 (22.9)	9 (42.9)	7 (23.3)
B	11 (31.4)	7 (29.2)	6 (28.6)	6 (20.0)
C	6 (25.0)	15 (42.9)	5 (23.8)	14 (46.7)
D	3 (12.5)	1 (2.86)	1 (4.8)	3 (10.0)
	χ^2 = 3.83, π > 5		**χ^2 = 4.05, π > 0.05**	

[a]URM is defined as students that identified as Black, Hispanic, Native American, or two or more races. [b]STEM majors were biology, chemistry, biochemistry, mathematics, engineering.

Ten perceived course benefit items showed significant differences in responses between CURE-1 and SI students (Figure 2). Students answered differently when reporting their perceived gains for the following course benefits: skill in the interpretation of results, tolerance for obstacles faced in the research process, readiness for more demanding research, understanding of the research process in your field, ability to integrate theory and practice, understanding of how scientists work on real problems, understanding that scientific assertions require supporting evidence, ability to analyze data and other information, learning laboratory techniques, and skill in science writing. While overall response patterns were shown to be different between CURE-1 and SI students, two items, understand the research process in your field and skill in science writing, showed no significant differences in any specific response group according to post hoc comparison tests. SI students reported significantly higher "small gain" responses in reference to ability to integrate theory and practice. This is likely due to the decoupling of the CURE from the lecture pacing. Students in the SI laboratory course are, for example, learning about reduction reactions as they are conducting reduction reactions. CURE-1 students reported significantly more "very large gain" responses on the remaining items, skill in the interpretation of results, tolerance for obstacles faced in the research process, readiness for more demanding research, understanding how scientists work on real problems, understanding the scientific assertions require supporting evidence, ability to analyze data and other information, and learning laboratory techniques. All of the gains are consistent with the strong research focus in the CURE.

Two overall evaluation items showed significant differences in responses between CURE-1 and SI students: this course was a good way of learning about the process of scientific research, and this course had a positive effect on my interest in science (Figure 3). Significantly more CURE-1 students reported "strongly agree" on both of these items.

RQ2. How Does Student Content Understanding on an End-of-Course Exam in an Organic CURE Compare to a SI Laboratory Course?

Table 8 presents the means and standard deviations for total and subcategory exam scores for CURE-1 and the comparison group from the SI Organic Chemistry Laboratory II course. Mann−Whitney U tests were performed due to the non-normality within a majority of the variables. Resulting Mann−Whitney U statistics and their significance are reported in Table 8. There was not a significant difference in the total scores on the laboratory practical exam between the students in CURE-1 and the SI comparison group. This was important given the departure of the CURE section from a long-established laboratory curriculum that steps students through syntheses using simplified laboratory methods. The area that did show a significant difference, proficiency with chemical apparatus, is explained by the CURE students repeated use of equipment and the need to make informed decisions for each iteration of their synthesis.

RQ3. What Are Student Perceptions of Course Design Elements, Collaboration, Iteration, and Discovery and Relevance in the Analytical CURE Compared to SI?

The complete results of the LCAS are available as Supporting Information. Means, standard deviations, and the results from Mann−Whitney U tests on each dimension are provided in Table 9. Three CURE students and five SI students were left out of this analysis because they did not complete the LCAS survey.

Mann−Whitney U tests were performed for all comparisons due to non-normality in the collaboration, discovery, and iteration variables. The comparison of *collaboration* between

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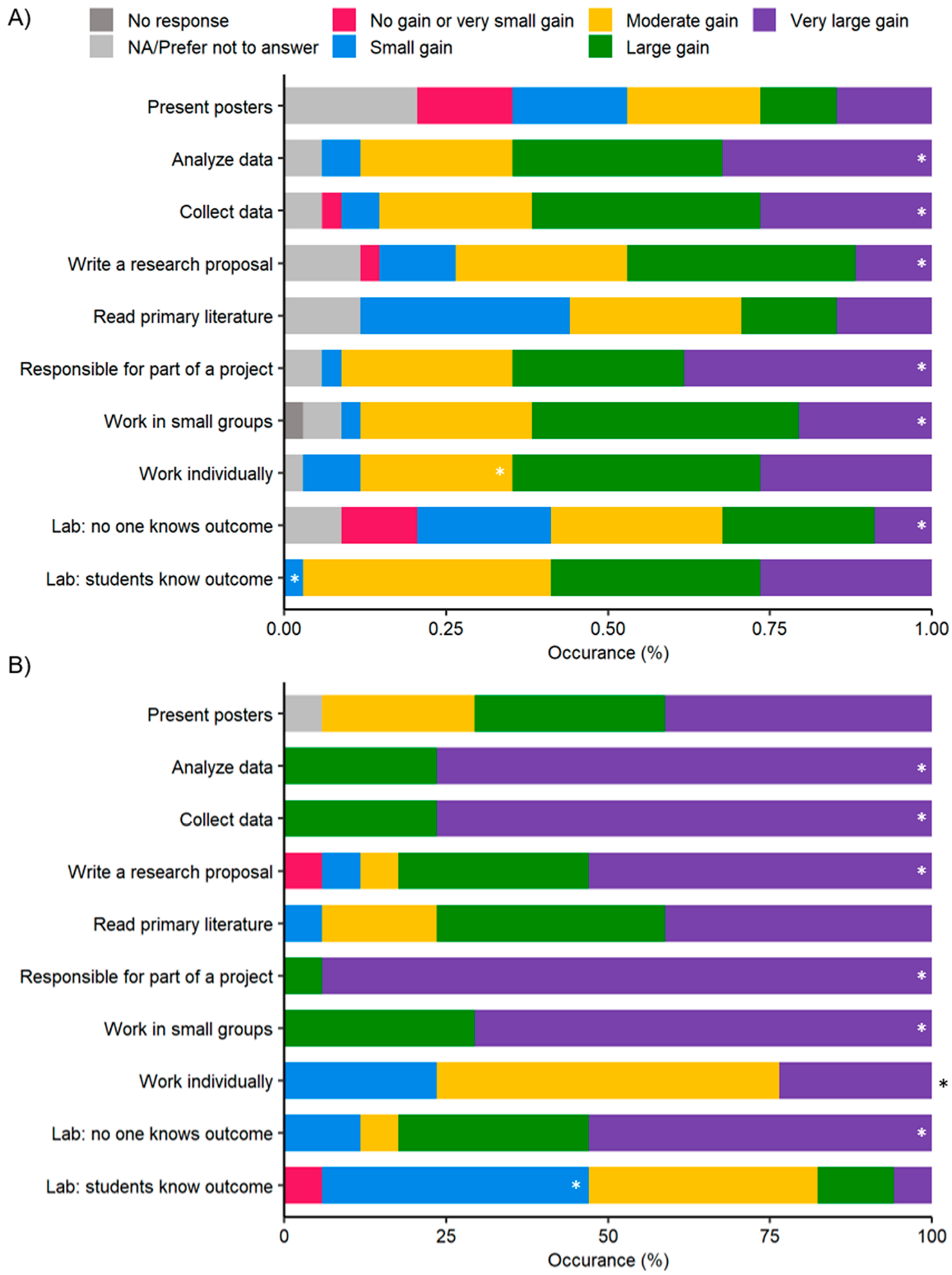

Figure 1. Perceived learning gains reported by (A) SI and (B) CURE-1 students. Only items that showed a significant difference between groups according to Fisher's Exact Test are reported. Asterisks within a certain response group indicate significant differences of that group between CURE-1 and SI students as indicated by post hoc comparison tests (*$p < 0.05$).

CURE-2 and SI students resulted in a nonsignificant result, or no difference between groups. The comparison of the *discovery* construct between groups resulted in a significant result, $U = 4.21$, $p < 0.001$. The effect size was large, at $r = 0.59$. The comparison of the *iteration* construct between groups resulted in a significant result, $U = 5.04$, $p < 0.001$. The r effect size was large, at 0.71.

Most notable in the LCAS analysis is the large effect for discovery as well as for iteration. Figure 4 illustrates these findings. Both constructs are noted features of a CURE and would be expected to strongly differ from a SI laboratory experience.[28] The CURE-2 students spent the semester repeating the analytical methods, with each iteration thoughtfully designed by the students to address results from a previous analysis.

RQ4. How Does Student Ability to Analyze Familiar and Unfamiliar Experimental Information in an Analytical CURE Compare to a SI Laboratory Course?

Table 10 presents the exam scores for CURE-2 and the comparison group from the SI Analytical Laboratory course. Mann−Whitney U tests were performed due to the non-normality in the subcategory and total exam score data. There was a significant difference in the total scores on the laboratory practical exam between the students in CURE-2 and the SI comparison group (Table 10) due to the underperformance of CURE-2 students on the Analysis and Reasoning section. This part of the exam assesses student ability to interpret calibration curve data and identify potential flaws in the way the data was collected or plotted. The SI comparison students were regularly

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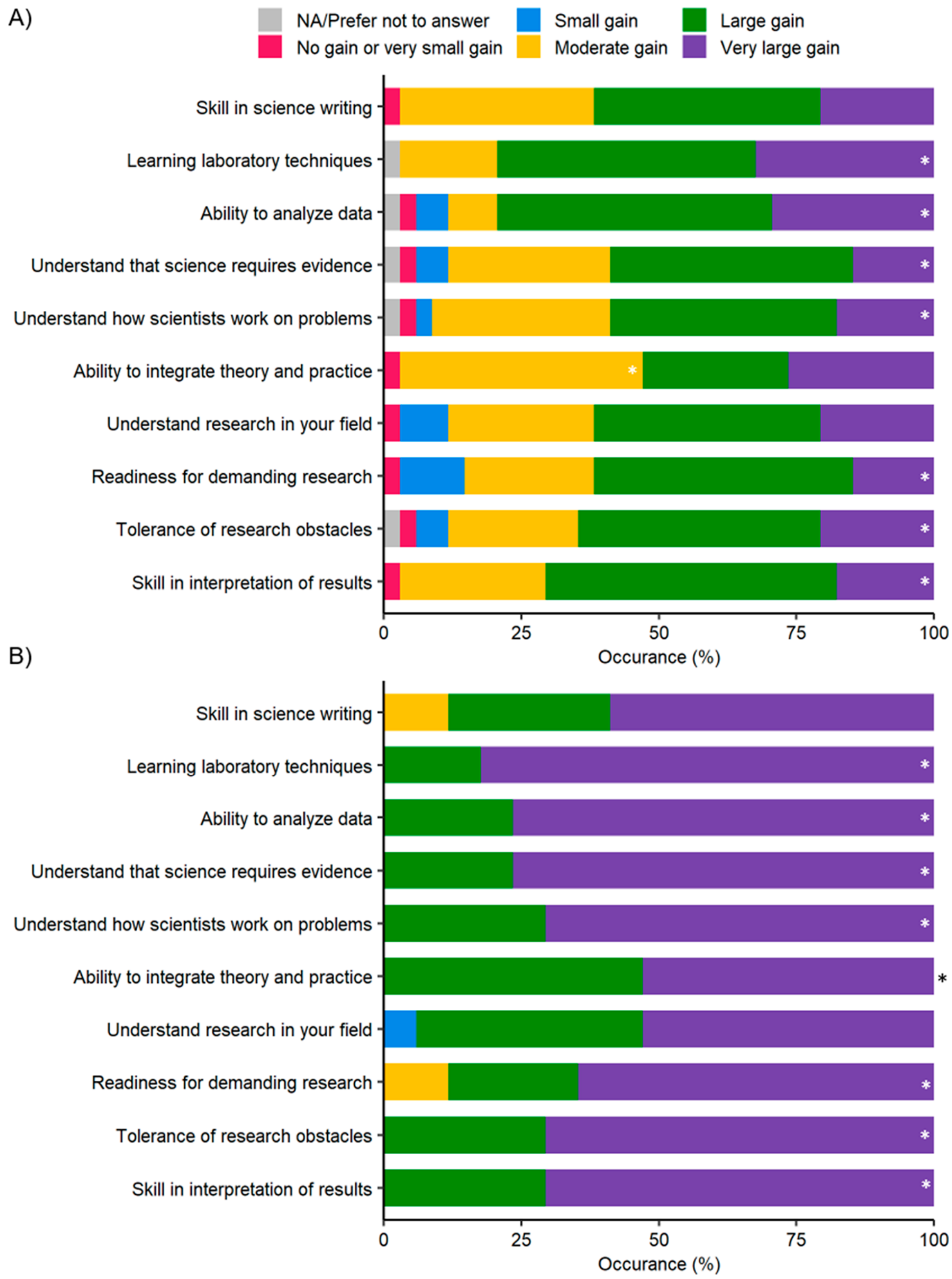

Figure 2. Perceived course benefits reported by (A) SI and (B) CURE-1 students. Only items that showed a significant difference between groups according to Fisher's Exact Test are reported. Asterisks within a certain response group indicate significant differences of that group between CURE-1 and SI students as indicated by post hoc comparison tests (* $p < 0.05$).

exposed to calibration curves in the analytical lab, whereas the CURE students were not. The exam scores demonstrated this distinction in the course content.

■ LIMITATIONS AND IMPLICATIONS

The results are limited by the number of students enrolled in the CURE sections and by the self-report survey data. While the CURE survey and LCAS have been shown to provide valid and reliable data in other samples,[5,20,22,28] with the small sample size, validity and reliability evidence of the CURE survey and LCAS in this specific context was not possible. While this implies caution, it is important to note that the CURE survey has been used nationally in a wide range of educational contexts and the results in this research are aligned with other CUREs. Williams and Reddish[20] reported results from the CURE Survey that indicated a positive effect of integrating research into the second semester of a physical chemistry laboratory in both student understanding of research and confidence in conducting research. Their results were similar to those found by other researchers in terms of student self-reported gains from survey data and interviews. Likewise, the LCAS scores obtained were in close alignment with those reported other researchers, specifically in the chemistry laboratory context. Although we made a significant effort to remove barriers to participation in research, the students did self-select into applicant pool. Over the course of the semester, individual students in the analytical CURE took turns preparing liposomes which required an

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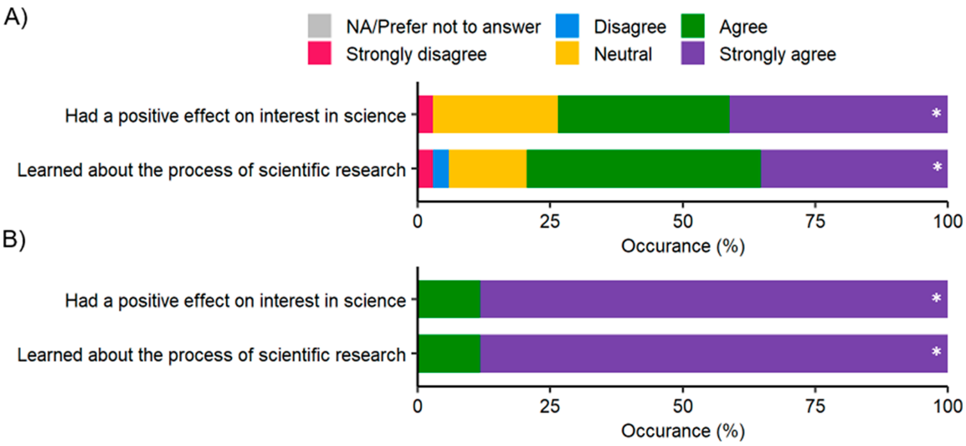

Figure 3. Perceived overall evaluation of the courses reported by (A) SI and (B) CURE-1 students. Only items that showed a significant difference between groups according to Fisher's Exact Test are reported. Asterisks within a certain response group indicate significant differences of that group between CURE-1 and SI students as indicated by post hoc comparison tests (* $p < 0.05$).

Table 8. Organic Laboratory Practical Exam Scores

	CURE-1		SI			
	N = 24		*N* = 35			
Topic	Mean	Sd	Mean	SD	*U*	*r*
Spectroscopy Interpretation (20 pts)	15.2	3.24	15.2	3.56	0.251	NA
Synthetic Scheme and Experimental Design (15 pts)	10.9	3.41	11.6	4.24	1.34	NA
Proficiency with Chemical Apparatus (10 pts)	8.25	1.87	7.00	2.14	2.38[a]	0.307
Interpretation of Experimental Data (15 pts)	11.9	2.57	11.6	3.35	0.386	NA
Total Score (60 pts)	54.5	8.79	56.2	10.2	0.914	NA

[a]Significant at $p < 0.05$.

Table 9. LCAS Means and SD for the Course Design Constructs

	CURE-2		SI			
	(*N* = 21)		(*N* = 30)			
Course Design Constructs (Range of Scores Possible)	*M*	SD	*M*	SD	*U*	*r*
Collaboration (6–24)	21.62	2.46	20.47	3.92	0.515	NA
Discovery and Relevance (5–30)	25.05	4.65	17.20	6.27	4.21[a]	0.590
Iteration (6–36)	29.57	5.23	20.47	3.92	5.04[a]	0.706

[a]Significant at $p < 0.05$.

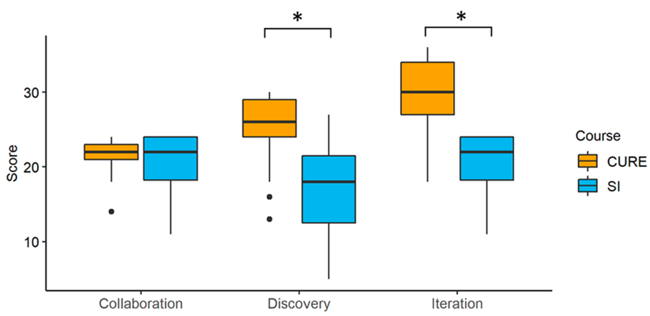

Figure 4. LCAS constructs for CURE vs SI students.

Table 10. Analytical Exam Scores

	CURE-2		SI			
	N = 24		*N* = 35			
question	*M*	SD	*M*	SD	*U*	*d*
Analysis and Reasoning (10 pts)	2.35	2.50	5.16	3.26	3.52[a]	0.454
Knowledge Application (10 pts)	4.00	2.02	5.86	3.53	1.92	NA
Total Score	6.35	3.69	9.03	3.94	2.51[a]	0.342

[a]Significant at $p < 0.05$ level.

additional 90 min of lab time. This occasional additional time was not replicated in the comparison group.

This work does provide direct comparison of traditional laboratory experiences with CUREs in two disciplines. The surveys are self-report but from both contexts and illustrate the value added in moving from the long-established model of laboratory instruction to a CURE. There is a need for powerful and generalizable assessments that can document student progress, help distinguish effective and ineffective aspects of the experiences, and illustrate how students interpret the research experiences they encounter.[31,32] The organic laboratory practical exam and analytical exam did provide empirical data that distinguished the CURE experience from the SI. The organic lab practical did suggest that CURE participants developed greater proficiency with laboratory glassware, but this would need to be substantiated with additional research. The analytical exam did suggest that students in CURE were less proficient with calibration curve methods.

CUREs are typically limited to a single semester experience, whereas independent research experiences may evolve over multiple academic semesters or even years. Previous research suggests the greatest benefit is seen with at least three semesters of research experience.[16] Research collaboration between faculty provides opportunities to develop multidisciplinary research experiences that students could access in multiple courses as they progress in their program of study. A multicourse CURE which allows students to continue the research project within their course of study provides the opportunity for more students to have the extended experience of this high-impact practice. Our results suggest that replacing long-established instructional methods with course-based research experiences provides the benefits of research without forfeiting development of knowledge, skills, and ability attendant with the laboratory course.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.0c01263.

Course activities and expected outcomes (PDF)
Course activities and expected outcomes (DOCX)
CURE survey items (PDF)
CURE survey items (DOCX)
LCAS item descriptives (PDF)
LCAS item descriptives (DOCX)

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Notes

The authors declare no competing financial interest.

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