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Precision and Accuracy: Knowledge Transformation through Conceptual Learning and Inquiry-Based Practices in Introductory and Advanced Chemistry Laboratories

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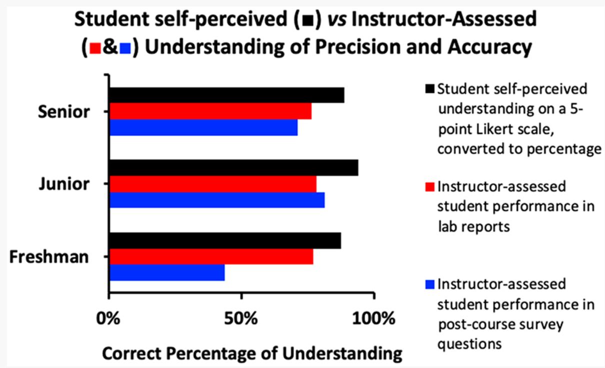
ABSTRACT: Whereas extensive studies have examined the effectiveness of inquiry-based learning in chemistry education, few have tracked undergraduate performance throughout the college chemistry curricula. In this study, we describe an instructional model of conceptual learning and inquiry-based practices (CLIP) and assess students' transformation of knowledge about precision and accuracy in the laboratory components of Introductory Chemistry, Analytical Chemistry, Instrumental Analysis, and Physical Chemistry. Student performance in written laboratory reports reveals that repetition of concepts and specific feedback from instructors are essential in constructing knowledge about precision and accuracy. We observed a distinct gap between students' perception of their understanding and their ability to determine precision and accuracy in data sets. This gap decreases as students move from introductory to advanced chemistry laboratories, but loss of student participants throughout the study increases the uncertainty in the significance. In contrast to traditional teaching, enhanced learning was observed in Introductory Chemistry I Laboratories thought CLIP, with the support of concept/skill training, specific feedback, and student-centered activities. This study benefits members of the community who are engaged in supporting students' mastery of theory with practice.



KEYWORDS: *First-Year Undergraduate/General, Upper-Division Undergraduate, Analytical Chemistry, Laboratory Instruction, Communication/Writing, Inquiry-Based/Discovery Learning, Testing/Assessment, Chemometrics*

■ INTRODUCTION

Student learning is greatly affected by instructors' methodology. Over the past decade, increasing evidence has shown that learning can be improved through the frameworks of learning progressions (LPs) and teaching-learning sequences (TLSs). LPs emphasize cognitive development through purposeful sequences of teaching and learning expectations,[1] in which students' understanding of scientific concepts and the applications of those concepts are advanced. TLSs aim to reduce the gap between proposed teaching and expected learning.[2] These two frameworks are similar in aiming to understand teaching and learning from both teachers' and students' viewpoints. Their advancement has been promoted[3] in scientific conceptual learning through teaching sequences;[4] in development of argumentative ability using simple instructional context for K-12;[5] and in acquisition of procedural knowledge in medical school by clinical experience.[6] However, insufficient research is available to understand knowledge development and transformation over timespans longer than a lecture or a course.[3] This deficiency is partially due to the difficulty of implementing activities focused on a single set of concepts throughout the college years.

Precision and accuracy are two of the most important analytical figures of merit. They are introduced in first-year chemistry as well as in analytical chemistry courses. Undergraduates learn the difference between random and systematic error, between precision and accuracy, between data variation and deviation from a theoretical value, and how to propagate significant figures in their calculations. Extensive research has shown that inquiry-based teaching is an effective method for students to increase content knowledge and problem-solving skills.[7−9] The concept of inquiry lies in using self-generated data to explain scientific observations, rather than simply testing knowledge.[10] Research has shown that incorporation of scientific practices into a learning environment promotes the development of expert-like thinking in students,[11] and the chemistry laboratory is the ideal place for students to practice and evaluate their own data. Several laboratory exercises have

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Table 1. Distribution of Conceptual Learning and Inquiry-Based Practices for Precision and Accuracy

Laboratory Courses	Laboratory Components	Teaching Lab by Course: CLIP, 2016–2019	Teaching Lab by Course: Chem. I 2015–2016
Density training lab for Introductory Chem. I and Analytical Chem.	Prelab assignment on significant figures	CL[d]	CL[d]
	Guiding question 1: Which is more precise and accurate, a beaker or a transfer pipet (or volumetric flask)?	IP[e]	N/A
	Exp.: $\bar{x}$, S.D., R.S.D., bias, relative bias	CL[d]	CL[d]
	Error analysis in lab report	CLIP[f]	CLIP[f]
	Postlab activities[b]	CLIP[f]	N/A
Practices in measurement laboratories[a] for all participating courses	Prelab assignments (for Intro. Chem. I and II laboratories only)	CL[d]	CL[d]
	Guiding question 2: What may be the reason for a considerable SD and/or bias? Be specific with your answer.	IP[e]	N/A
	Guiding question 3: Design a procedure for solution preparation and/or analyte determination.	IP[e]	N/A
	Exp.: $\bar{x}$, S.D., R.S.D., bias, relative bias	CL[d]	CL[d]
	Error analysis in lab report	CLIP[f]	CLIP[f]
	Postlab activities[b]	CLIP[f]	N/A
	Self-designed experiments or projects[c]	IP[e]	N/A

[a]Measurement laboratories refer to any experiments involving replicate measurements and/or comparison of experimental values to a true value. [b]Postlaboratory activities include instructor's feedback and discussions on laboratory reports, revision, and resubmission. [c]Self-designed experiments include calculations and self-designed procedures for solution preparation and analyte determination. Juniors and seniors are required to do one self-designed project independently at the end of the semester going though literature survey, experimental design and execution, data analysis, and result report and presentation. [d]CL indicates conceptual learning. [e]IP indicates inquiry-based practices. [f]CLIP indicates both conceptual learning and inquiry-based practices.

been developed for exploring the correct use of significant figures through length measurements[12] and for understanding experimental errors through density[13,14] and mass[15] determination. Nevertheless, many students struggle to explicate experimental errors in their own data. They may point out potential sources of error in general but fail to make connections between theory and experimental observations. A recent review by Stone summarized assessment practices used for precision and accuracy, pointing out that students need more specific feedback rather than mere numeric grades to develop a particular skill.[16] This appears to be an area where students experience a gap in learning between the expression of experimental errors and transformation of what they have learned into practice. Given the importance of precision and accuracy in evaluating any measurements involving replicate tests and/or comparison of experimental values to theoretically known quantities, we use these two concepts to explore how students' abilities are developed in acquiring and applying knowledge. The specific questions to be answered by this paper are (1) How do years of conceptual learning (CL) and inquiry-based practices (IP) (CLIP) help students master theory and practice? (2) How well do students' perceptions of knowledge match their performance? In this study, it is not our intention to confirm advantages of inquiry over traditional teaching in all chemistry laboratories, but rather, to provide a picture of student progress in understanding precision and accuracy throughout college years with the aid of CLIP exercises. The work presented herein reflects five years of data on our laboratory teaching focusing on analytical measurements and evaluations. We have introduced a number of changes into our chemistry laboratory experiences to address the issues discussed here. Because of the small size of our institution and newness of the project, the number of students impacted is small in all but the introductory-level chemistry laboratory course. About 70–80% of students completed the pre- and postcourse surveys. It has been our practice to keep all data anonymous; therefore, evaluating individual students' progress from the lower to the upper division was not possible in this study. In addition, we relied on students to complete surveys on a voluntary basis, which limited the number of responses, and may have skewed the results toward stronger students. These factors must be considered when interpreting the findings.

■ PEDAGOGICAL METHODOLOGY

Teaching Sequences and Activities of CLIP

CLIP is best described as guided inquiry because student learning takes place under the instructor's guidance with the aid of training and student-centered activities. A density training laboratory for conceptual learning is held early semester in the laboratories of Introductory Chemistry I and Analytical Chemistry (see Table 1 and student handout in Supporting Information.). In this lab, students use the known density and measured mass of water to calibrate micropipettes and laboratory glassware, such as beakers, volumetric flasks, and transfer pipettes. This activity helps students understand the meaning of random and systematic errors as well as how to evaluate them, thus providing them with a general means for quantitative error analysis which can be used in other similar situations. During the prelaboratory lecture, students are instructed on the principles of liquid volumetric calibration, the meaning of random and systematic error, how to calculate significant figures, mean (x_i and $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$), standard deviation (SD $= \sqrt{\frac{\sum_i^n (x_i - \bar{x})^2}{n-1}}$), relative SD (RSD $= \frac{\text{SD}}{\bar{x}} \times 100$), bias ($= \bar{x} - \mu$, μ = true value or theoretical value), and relative bias ($= \frac{|\text{bias}|}{\mu} \times 100$). They are also encouraged to answer questions about how to dry glassware, whether it is necessary, and why. Freshmen can normally finish calibrating three different types of glassware within the 3-h laboratory, while students in analytical chemistry laboratories can calibrate two pieces of volumetric glassware plus a micropipette. Various measurement laboratories, for example, 2 in Introductory Chemistry I Lab, 4 in

Introductory Chemistry II Lab with 1 self-designed experiment, 5 in Analytical Chemistry Lab with 4 self-designed experiments, 6 in Instrumental Analysis Lab with 3 self-designed experiments, and 4 in Physical Chemistry Lab with 1 self-designed experiment, are also scheduled during the semester (Table 1 and Table S1 in Supporting Information), which will enhance their learning through various analytical measurements. Students work individually or in groups of 2−4 on both experiments and laboratory report writing. The inquiry levels of the measurement experiments, evaluated by the quantitative rubric,[17] were found to be a mix of structured, guided, and open for freshmen, and a mix of guided and open for juniors and seniors. The density training laboratory and self-designed projects (described in Table 1 footnote) were designated as confirmational exercises and authentic research, respectively. Depending on course levels, it may be necessary to show students how to use micropipettes and Excel, go over rules for significant figures, and review statistical methods for testing outliers. Information on CLIP teaching sequences and activities is summarized in Table 1. The differences between guided inquiry teaching and traditional teaching for each component are indicated in the last two columns.

Guiding Question-Initiated Goal-Driven Activities

One aspect distinguishing CLIP laboratories from traditional ones is the use of guiding questions to highlight objectives and make experimental goals explicit. Guiding question 1 probes the precision and accuracy of different types of glassware and the explanation for observed errors in the density training laboratory (Table 1 footnote). Students are asked to comment on which is more precise and accurate, a beaker or a transfer pipet (or volumetric flask). They generally notice that the beaker is neither precise due to the larger scatter in measurements (S.D.) nor accurate because of the poor agreement with the true value (bias) when compared to the transfer pipet or volumetric flask. However, they often fail to see the importance of percent error (RSD and/or relative bias). For example, the RSD in a 50 mL volumetric flask is small and comparable to that from 10 mL transfer pipet although there is a big difference in SD between these two types of glassware, an observation that should encourage students to think about the effect of glassware size on the errors in measurements (see Excel file produced by instructor using students' data in Supporting Information and Post-Laboratory Activities below). The sign of bias and relative bias might be confusing. The density training laboratory clarifies that bias is positive if the experimental value is larger than the true value but negative if smaller, while the relative bias is always positive when calculated by dividing the absolute value of bias by the true value. It is worth pointing out that accuracy or systematic error can only be determined when the theoretical value is known. A theoretical value is often an accurate, known quantity in chemical measurements, such as molecular mass, molar volume at STP, melting point and boiling point. In the density training laboratory, it is given by etched ring marking or numbers shown on micropipettes. As student performance greatly depends on their prior knowledge, this activity equips them with necessary concepts for constructing their own error analysis in future measurement laboratories.

Guiding questions 2 and 3 can be used in any measurement laboratories. For guiding question 2, students must explain their observed SD and/or bias, thus making connections between experimental errors and theoretical analysis. For instance, a significant SD caused by random error might be attributed to the limited number of trials, while each trial should be done exactly the same way. A substantial bias caused by systematic error could be associated with various factors, such as solution spillage, blank interference, reactant or product evaporation, etc. Students need to figure out what made their results higher or lower, thus leading to a positive or negative bias, respectively; rather than simply stating there were human errors in reading balance or buret, or in controlling temperature, etc. Guiding question 2 reinforces deep thinking and encourages careful observations. Guiding question 3 presents the goal for a self-designed experiment, that is, asking students to design an experimental protocol. For example, after learning about Beer's law and limiting reagents, students in an introductory chemistry lab successfully determined the molar absorptivity of $FeSCN^{2+}$ with Fe^{3+} as a limiting reagent. Juniors and seniors prepared standards and/or unknown solutions in measurement laboratories independently. They calculated the masses to be weighed, chose a proper balance and volumetric tools, and prepared calibration solutions with external or internal standards. Juniors and seniors also perform self-designed projects at the end of the semester. They experience the entire research process from the literature search, problem identification, procedure design, experimental execution, to scientific laboratory report writing, submission, revision, and resubmission.[18] These practices provide them with opportunities to apply what they have learned to a real-world problem.

Postlaboratory Activities

Students spend a week to write and submit their laboratory reports, followed by instructor's feedback, discussion, revision, and resubmission. The discussions involve more than simply correcting calculation mistakes after density training laboratories were done in Introductory Chemistry I Lab and Analytical Chemistry Lab. Students are asked to comment on better ways to present errors. Figure 1 is constructed by the instructor using

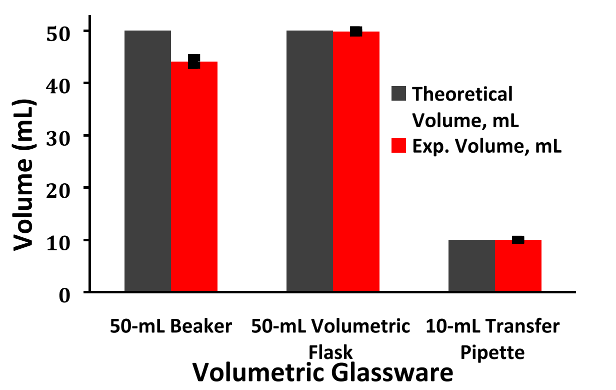

Figure 1. Glassware calibration ($n = 3$). Precision is indicated by the SD error bars on experimental values (red columns); accuracy or bias is indicated by comparing the experimental volume (red bars) and true value (black bars).

student data obtained from the density training laboratories (See Excel file in Supporting Information.); similar graphs may be created with data from any measurement experiments as needed. Precision is elucidated by the error bars. Accuracy is indicated by comparing the black column (theoretical volume) to the red one (experimental value) for each piece of volumetric glassware (Figure 1), or by the changes in bias as a function of volume delivered by a micropipette (Excel file in Supporting Information). These graphs, posted on our Blackboard Class-

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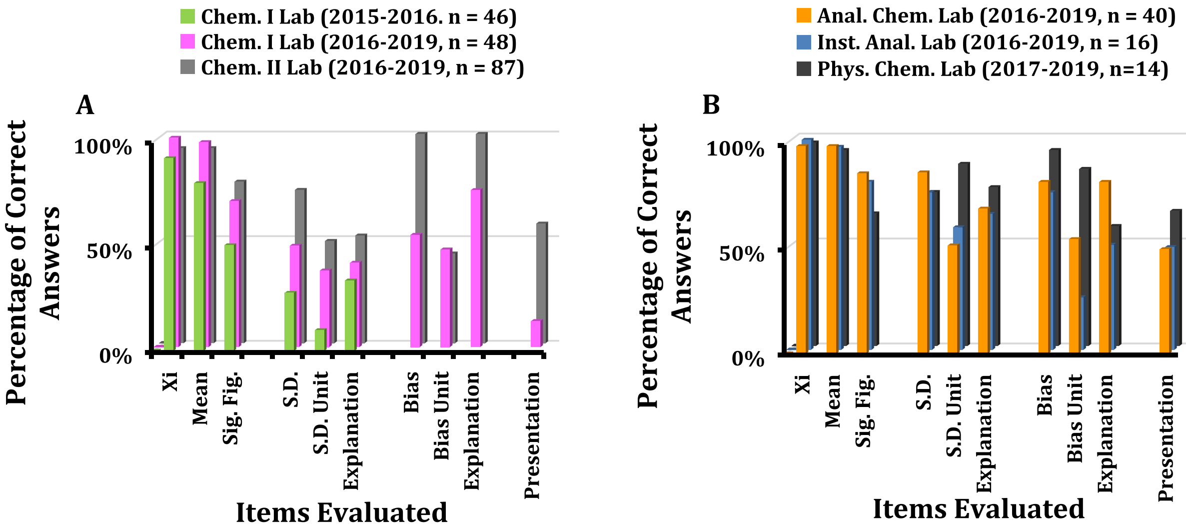

Figure 2. (A) Students' performance in introductory chemistry laboratories: green columns, 2015−2016, $n = 46$ under traditional teaching of Chem. I Laboratories; pink columns, 2017−2018, $n = 48$ under CLIP teaching of Chem. I Laboratories; gray columns, 2017−2019, $n = 87$ under CLIP teaching of Chem. II Laboratories. (B) Students' performance in advanced chemistry laboratories with CLIP teaching: orange columns, 2016−2018, $n = 40$ in Anal. Chem. Laboratories; blue columns, 2017−2019, $n = 16$ in Inst. Anal. Laboratories; black columns, 2017−2019, $n = 14$ in Phys. Chem. Laboratories.

room Management System, also show relative errors by comparison of the error bar to the mean (RSD) or the bias to the theoretical value (relative bias), thus providing students with good examples of how to present their findings in a concise way, in which both random error and systematic error are observable and fluctuate. By conducting these activities early in the semester, students develop skills that can be used for error analysis in all subsequent measurements.

FINDINGS AND ASSESSMENTS

How Do Years of CLIP Teaching Help Students Master Theory and Practice?

We examined student performance on error analysis in terms of calculations of mean, SD, and bias as well as relevant explanations. The results in Figure 2 were extracted from the laboratory reports, graded by the same group of instructors, under CLIP teaching between 2016 and 2019 for Introductory Chemistry I Lab (pink columns), Introductory Chemistry II Lab (gray columns), Analytical Chemistry Lab (orange columns), Instrumental Analysis Lab (blue columns), and Physical Chemistry Lab (black columns), as well as between 2015 and 2016 for traditional teaching laboratories of Introductory Chemistry I Lab (green columns). An example of the rubric is provided in the Supporting Information (Table S2). Approximately 75% of students in Introductory Chemistry I Laboratories continue to Introductory Chemistry II Laboratories, 30% from Introductory Chemistry Laboratories to Analytical Chemistry Laboratories, and ∼60% from Analytical Chemistry Laboratories to Instrumental Analysis Laboratories and Physical Chemistry Laboratories. There were various reasons for students to discontinue their participation: higher level courses may not be required for their major, they may fail the course, transfer out, or simply attend other laboratory sections that were not part of this educational research. All of these factors may add uncertainty to this study.

We see enhanced learning through CLIP teaching, compared to traditional teaching in Introductory Chemistry I lab, with correct percentages increased from 92% to 100% for x_i, 80% to 98% for $\bar{x}$, 50% to 70% for significant figures, 28% to 48% for showing SD with a unit (10% to 37%) and relevant explanation (34% to 40%), respectively (Figure 2, pink and green columns). On average, the overall percent correct improved significantly from 49% for traditional teaching to 65.5% for CLIP teaching in Introductory Chemistry I Laboratories, as analyzed by Student's t test (Supporting Information Excel).

Figure 2 also shows that, on average, CLIP approaches (pink, gray, orange, blue and black columns) results in approximately 90% correct performance in calculating results (x_i and $\bar{x}$) with correct significant figures. An improvement in random error analysis with CLIP teaching is seen in Introductory Chemistry II Lab (gray columns) when compared to Introductory Chemistry I Lab (pink columns) with correct percentages increasing from 70% to 77% on the correct use of significant figures, 48% to 73% on reporting SD with a proper unit (37% to 49%), and relevant explanation (40% to 51%). Similar observations are obtained for systematic error analysis, for which all students in Introductory Chemistry II Lab (gray columns) correctly calculate bias and give relevant error explanations, while these percentages for Introductory Chemistry I Lab (pink columns) are only 54% and 75%, respectively. Presentation of their results improves dramatically in Introductory Chemistry II Laboratories (57% on last gray column) compared to Introductory Chemistry I Laboratories (12% on last pink column). We believe this progress is associated with postlaboratory discussions and good examples provided by the instructors (Figure 1 and Excel file in Supporting Information). Our observation emphasizes the importance of inquiry-teaching, specific feedback, and more opportunities to evaluate measurements when students continue from Introductory Chemistry I Lab to Chemistry II Lab. Overall the correct percentage improved significantly when comparing Introductory Chemistry II (73.7%) to I (58.1%) Laboratories (Supporting Information Excel).

Over years of CLIP training for precision and accuracy in measurement laboratories, our data in Figure 2 show that juniors and seniors better understood random errors than freshmen did (Supporting Information Excel), indicating that more opportunities for students to be engaged in measurement experiments

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Table 2. Comparison of Correct Performance in Postlaboratory Surveys and in Written Laboratory Reports over Time in the Chemistry Laboratories

	Students Correctly Responding, Av. %, by Lab Course and Performance Measure							
	Chemistry II, n = 52−56 (Freshmen)		Analytical Chemistry, n = 8−10 (Juniors)		Instrumental Analysis, n = 5−11 (Seniors)		Physical Chemistry, n = 7 (Seniors)	
Assessment Areas	Survey[a]	Lab Report[b]	Survey[a]	Lab Report[b]	Survey[a]	Lab Report[b]	Survey[a]	Lab Report[b]
Density/conc. measurements	59	93	100	98	70	97	NA	95
Significant figures	24	77	63	82	50	90	NA	63
Precision	39	58	NA	61	67	59	100	79
Accuracy	53	81	NA	73	66	50	75	78
Average	44	77	82	79	63	74	88	79

[a]Solving problems in postlab survey questions. [b]Performance in lab reports.

enhance learning. On average for presenting SD with unit and explanations, the correct percentages are 42% for Introductory Chemistry I Lab (pink columns in Figure 2), 58% for Chemistry II Lab (gray columns in Figure 2), 69% for Analytical Chemistry Lab (orange columns in Figure 2), 66% for Instrumental Analysis Lab (blue columns in Figure 2), and 79% for Physical Chemistry Lab (black columns in Figure 2). A noticeable deficiency is that students did not pay enough attention to the details of their calculations. They often ignore units of SD and bias, which should be the same unit as that for the mean. Only a minority of laboratory reports include correct units for SD and/or bias in traditional (10% for SD unit, green column in Figure 2) and CLIP Introductory Chemistry I Lab (37% for SD unit and 47% for bias unit, pink columns in Figure 2), Introductory Chemistry II Lab (49% for SD unit and 43% for bias unit, gray columns in Figure 2), and Instrumental Analysis Lab (25% for bias unit, blue column in Figure 2). Several factors may contribute to this lower performance. It is our perception that specific feedback on units, explanation of the rubric, frequent review, and question−answer sessions during prelaboratory lectures and postlaboratory activities help students focus on details, thus improving their ability to apply what they had learned about accuracy and precision to other measurements.

How Well Do Students' Perceptions of Knowledge Match Their Performance?

Both instructors' direct evaluations (e.g., exams, classroom observations, and feedback) and student perceptions are commonly used to assess learning. An accurate self-assessment of one's knowledge leads to more effective use of feedback, improved time management, and appropriate goal setting.[19] To demonstrate pedagogical effectiveness from instructors' and students' views, students completed postcourse survey questions designed to track their perception as well as the reality of mastering knowledge. Students were asked to self-report, on a scale of 1 to 5, their confidence in their understanding of measurement techniques for density or concentrations, significant figures, precision and accuracy (Tables S3 and S4 in Supporting Information). Although the surveys mostly addressed student perception of their abilities, we were able to add numerical problems for them to solve. Their performance on solving these problems was compared to their self-reported understanding and their performance in written laboratory reports. For each assessment area, we have students' average self-reported understanding on the 1−5 Likert scale (Table S3, converted to percentages in the graphical abstract), average percent who correctly solved problems in postlaboratory surveys (Table S4, Table 2 and graphical abstract), and percent of students who correctly calculated these quantities in their lab reports (Table 2 and graphical abstract), which was extracted from Figures 2A and 2B.

Our data show that students generally overestimate their mastery of knowledge. For instance, students from introductory Chemistry II Lab rated their understanding of knowledge 4.2−4.7/5 with an average of 4.4/5 (Table S4), while the correct percentages on analytical figures of merit varies from 24% to 59% with an average of 44% in surveys and 58% to 93% with an average of 77% in written laboratory reports (Table 2). Similar observations are seen in advanced courses when comparing the averages of self-reported understanding (4.7/5 for Analytical Chemistry Lab and 4.6/5 for Instrumental Analysis Lab) to correct percentages in survey (82% for Analytical Chemistry Lab and 63% for Instrumental Analysis Lab) and in written laboratory reports (79% for Analytical Chemistry Lab and 74% for Instrumental Analysis Lab), respectively (Table S4, Table 2 and graphical abstract). In general, students did a better job in written laboratory reports, which implies that learning is enhanced though explicit experimental goal, specific feedback, and laboratory report revision. In addition, the good performance by juniors in Analytical Chemistry Laboratories could be associated with more practice in density training laboratories, which was not part of the curriculum design in Instrumental Analysis Lab. There is a distinct gap between students' self-reported understanding and their performance in both surveys and laboratory reports. This gap or Dunning-Kruger effect[20] is, however, smaller in advanced courses as indicated by the increased correct percentages. As precision and accuracy are specific terms associated with analytical measurements only, student progress in mastering these concepts, relies, to some extent, on the training they received throughout the college years. It is worth noting that students in general focus their attention more on graded work than surveys, which could bias our interpretation of their academic performance. Our data suggest that students' perceptions of content mastery may not accurately reflect the knowledge necessary for solving problems, thus should not be used as primary indication for validating instructional achievement. Evidence for learning should include instructors' direct measure addressing course competencies under specific goals.

■ CONCLUSIONS

By incorporating CLIP into chemistry laboratory teaching, such as a density training laboratory for preparing students with necessary skills, and guiding questions for reviewing knowledge, specifying goals, and reinforcing deep thinking and careful observation, we found that students were able to master knowledge and apply it in their own experimental error analysis.

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Again, we note that our conclusions are based on small numbers in many cases, have not followed individuals as they progressed through the curriculum, and were based on voluntary surveys. These claims should be considered tentative until our future studies can track students with the assistance of campus IT, and offer incentives for student participation in the surveys.

More effective learning was achieved in guided inquiry laboratories rather than traditional ones. More practices resulted in enhanced performance. With explicit goals and clear instructions, undergraduates were able to construct their own knowledge and apply it in multiple activities.

Our data show that freshmen overestimated their mastery of precision and accuracy; there is a gap between their perception of understanding and what they are really able to do. Juniors and seniors were better able to monitor their progress toward content understanding. The fact that students did a better job in written laboratory reports rather than in solving problems given in surveys implies the importance of explicit goals and feedback for learning. Further study is required to reduce the gap between perception and reality so that students are aware of their weaknesses and motivated to make necessary adjustments in their efforts.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b00563.

- Handouts of density training laboratory for students (PDF)
- List of measurement laboratories, rubric survey questions and results (PDF)
- Calculations for statistic tests and presentations of precision and accuracy (XLSX)

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Notes

The authors declare no competing financial interest.

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