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Laboratory Instrumentation: An Exploration of the Impact of Instrumentation on Student Learning

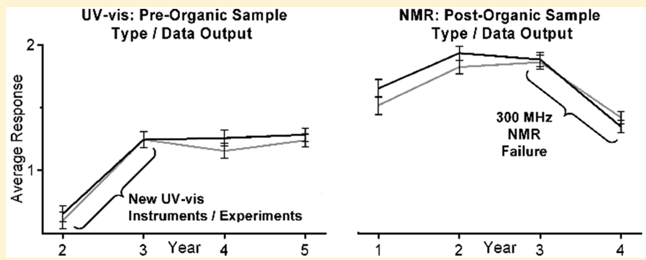
Don L. Warner,[†] Eric C. Brown,[†] and Susan E. Shadle*[,†,‡]

[†]Department of Chemistry, Boise State University, MS 1520, 1910 University Drive, Boise, Idaho 83725, United States

[‡]Center for Teaching and Learning, Boise State University, MS 1005, 1910 University Drive, Boise, Idaho 83725, United States

Supporting Information

ABSTRACT: Academic programs generally work to make their laboratory curriculum both as instrumentation rich and up to date as possible. However, little is known about the relationship between the use of instrumentation in the curriculum and student learning. As part of our department's ongoing assessment efforts, a project was designed to probe this relationship. Two aspects of the laboratory curriculum, explicitly tied to instrumentation, were the focus: technical competence with instrumentation and the ability of students to use instrumentation to solve chemical problems. Student survey responses and their scores on a practicum task were used to explore the relationship between instrument use and these outcomes. Results suggest that hands-on use of instruments matters. While emphasis on instrumentation in the lecture appears to increase perceived familiarity, more direct use in the laboratory translates into more technical knowledge. However, more exposure to instruments in the laboratory does not necessarily result in better problem solving skills. The introduction of new (to the students) instruments, combined with a guided inquiry approach, seem to improve this outcome. If educators want students to use instruments to problem solve like chemists, then it is important to explicitly support the development of this skill.



KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Curriculum, Laboratory Instruction, Laboratory Equipment/Apparatus, Problem Solving/Decision Making, Inquiry-Based/Discovery Learning*

INTRODUCTION

The use of instrumentation by chemists is ubiquitous in research and other professional contexts. The integration of instrumentation into the laboratory curriculum has therefore been a cornerstone of undergraduate degree programs for many years.[1] Academic programs generally work to make their laboratory curriculum both as instrumentation rich and up to date as possible. An underlying assumption is that students who work with a breadth of instruments and instruments that are similar to those they will find in research laboratories and professional contexts will be better prepared for careers or further study in chemistry. However, we found no prior literature reports that describe the relationship between the presence of instrumentation in the curriculum and student learning. Given the significant budgets spent on instrumentation, this is an important question.

The range of student learning goals that exist for the laboratory context have been identified:[2] skills related to learning chemistry, practical skills, scientific skills, and general skills. Their relative emphasis and how these categories of goals are operationalized has been shown to vary with course context.[2,3] While many of the possible laboratory goals are connected in some way to instrumentation, none of the previously reported goals are explicitly connected to the presence of instrumentation in the laboratory. For example, "Preparing students for research experiences" or "Understanding the need for proper data collection techniques"[2] may be connected to chemical instrumentation, but are not explicitly so. Likewise, the importance that academicians[4] and industrial chemists[5] place on specific organic chemistry instrumentation and techniques has been reported. However, the extent to which student learning is impacted by the explicit use of instrumentation is not well understood.

As part of our department's ongoing efforts to assess the effectiveness of our curriculum, we designed an assessment project to probe the impact on student learning of instruments that were being used in our undergraduate teaching laboratories. In our exploration, we chose to focus on two aspects of the laboratory curriculum explicitly tied to instrumentation.[2] The first is that (1) students should gain knowledge of and facility with chemical instrumentation. This goal might be associated with the skills required for a good instrument technician. The second goal, most closely aligned with critical thinking or problem solving goals, is (2) students should be able to make intentional choices about instruments that could be used to help solve particular chemical problems. We wanted to determine if we could see a relationship between

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Table 1. Timeline for Curricular Changes and Assessments

Pre-organic Assessment[a]	Academic Year Instrument and Curricular events	Post-organic Assessment[b]
Year 1		
None	• ***Gen Chem Lab*** instrumentation use: UV-vis (2 expts) • ***Organic Lab*** instrumentation use: IR (3 expts), NMR (4 expts), GC (2 expts),GC/MS (3 expts)	Survey & Practicum, $N = 52$
Year 2		
Survey & Practicum, $N = 116$	• Vernier SpectroVis UV-vis instruments replaced old Spec 20s • ***Gen Chem Lab*** now has 4 UV-vis experiments (through remainder of project) • ***Organic Lab*** now has IR (5 expts), NMR (6 expts), GC (3 expts), GC/MS (3 expts)	Survey, $N = 91$
Year 3		
Survey, $N = 125$	• 600 MHz NMR installed (not used in teaching laboratories, but prompted increase of NMR content in courses) • ATR FT-IRs installed in January (two new FT-IRs replaced a single older instrument, Attenuated Total Reflectance accessory increased sampling capacity) • GC and GC/MS instruments with autosampling capability installed (January), replaced models without autosamplers • 300 MHz NMR, used in organic labs, experienced intermittent downtime (spring)	Survey, $N = 87$
Summer Between Years 3 and 4		
None	• Vernier mini-GCs purchased • IR and GC Guided Inquiry Laboratories introduced in general chemistry (GC experiment used Vernier mini-GCs) • 300 MHz NMR failed completely (was not available during Year 4)	None
Year 4		
Survey, $N = 129$	• IR and GC Guided Inquiry Laboratories used in regular Gen Chem sequence	Survey, $N = 115$; Practicum, $N = 112$
Year 5		
Survey, $N = 180$; Practicum, $N = 176$	• New 300 MHz NMR installed	None

[a]Pre-organic assessments were administered during the first week of the fall semester. [b]Post-organic assessments were administered during the last week of the spring semester.

the inclusion of instruments in the curriculum and one or both of these outcomes.

Although students at all levels of the undergraduate curriculum were surveyed as part of our departmental assessment of these outcomes, this report focuses on pre- and post-organic chemistry students for two reasons: (1) organic chemistry is the first instrument-intensive laboratory course students take after limited use of instrumentation in general chemistry; and (2) the organic sequence has enough students in it to make statistical measurements meaningful.

This exploration was conducted over a period of eight semesters spanning five academic years (see Table 1). Students were surveyed about their knowledge and experience with instrumentation. Students' ability to solve chemical problems involving instrumentation was also tested using a problem-solving instrument previously developed for this task, which has been shown to differentiate students at different stages of the curriculum.[6] The intention was to see if the results of these measures was at all sensitive to the inclusion of instrument-focused experiments in the laboratory curriculum.

■ METHODOLOGY

Data Collection and Analysis

The data collected in this study came from (a) an instrumentation survey and (b) student responses to practicum questions. Collection and use of student data was approved by the Boise State University Human Subjects Institutional Review Board.

Assessment Overview. The broader purpose of collecting the data reported here was an assessment of the department's entire laboratory curriculum with respect to instrumentation, with the idea that gaps in student exposure and proficiency throughout the program could be identified. The survey administered to students contained questions about instruments that a student might encounter in laboratory courses or undergraduate research. Here, we focus solely on the primary instruments encountered in general and organic chemistry. In addition to the surveys, our practicum questions (described below) were designed to test competency and understanding across the curriculum. The questions were not tied to a specific lab course and some questions were challenging to address for students at the beginning of the curriculum.

Survey Data Collection and Analysis. A survey was developed to gauge a student's perception of their exposure to and knowledge of selected instrumentation in use in the chemistry curriculum. Specifically, we were interested in seeing whether that perception changed upon (a) exposure to hands-on use of instrumentation and (b) by completing a year of organic chemistry. Although student responses for an exhaustive list of instruments were collected, the focus of this manuscript is on the balance, GC, GC/MS, IR, NMR, polarimeter, and UV−vis, since these instruments are in standard use in general and organic chemistry. The instrument survey data was collected from pre-organic and post-organic students over an eight-semester period. Table 1 indicates the number of students who completed the survey in each cohort. In the spring of Year 1 (Yr1) and fall of Year 2 (Yr2), the survey was administered via paper/pencil during class. After that, the survey was administered online.

The following questions were asked for each instrument type:

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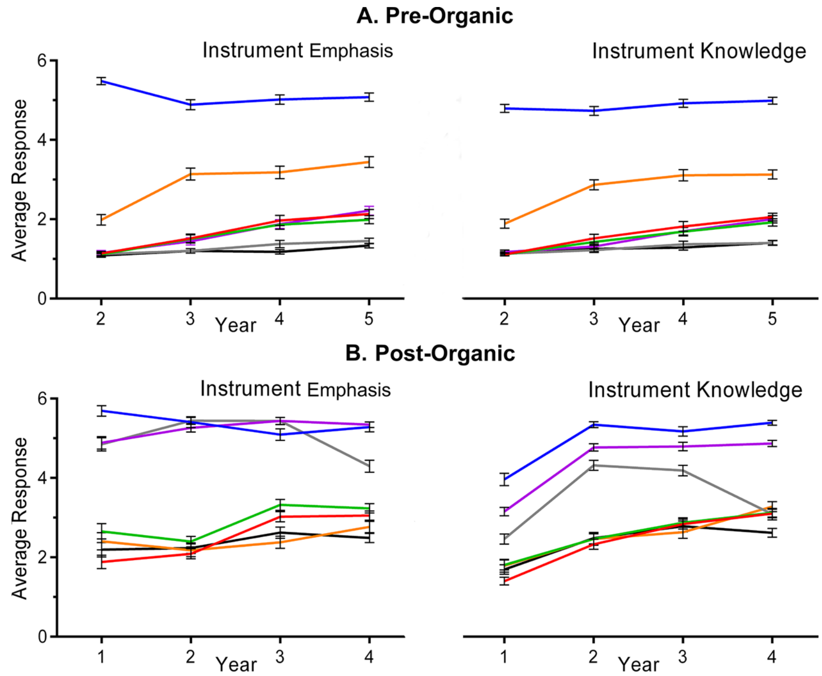

Figure 1. Average student responses to survey questions about specific chemical instrumentation as a function of year in the study (blue = balance, orange = UV–vis, red = GC, green = GC/MS, purple = IR, gray = NMR, black = polarimeter). Error bars show standard error of the mean. Panels A (pre-organic) and B (post-organic) show student perceptions of how much each instrument has been **emphasized** in their chemistry coursework to date (1 = minimal emphasis/used infrequently or not in-depth; 6 = strong emphasis/used multiple times and/or experience was in-depth) and student perceptions of their **instrument knowledge** (1 = I am unfamiliar with this instrument, 2 = I can operate this instrument with prompting and thorough guidance (e.g., demonstration) from an instructor, 3 = I can successfully operate this instrument independently by following explicitly written instructions, 4 = I know how to operate this instrument using only an operational checklist or an occasional reference to operating instructions, 5 = I am able to optimize procedures for this instrument and/or adapt my use of the instrument to improve the quality of data collected with this instrument, 6 = I can use this instrument for new applications and/or am able to repair the equipment. I am comfortable enough with the use of this instrument that I can teach someone else to use it properly).

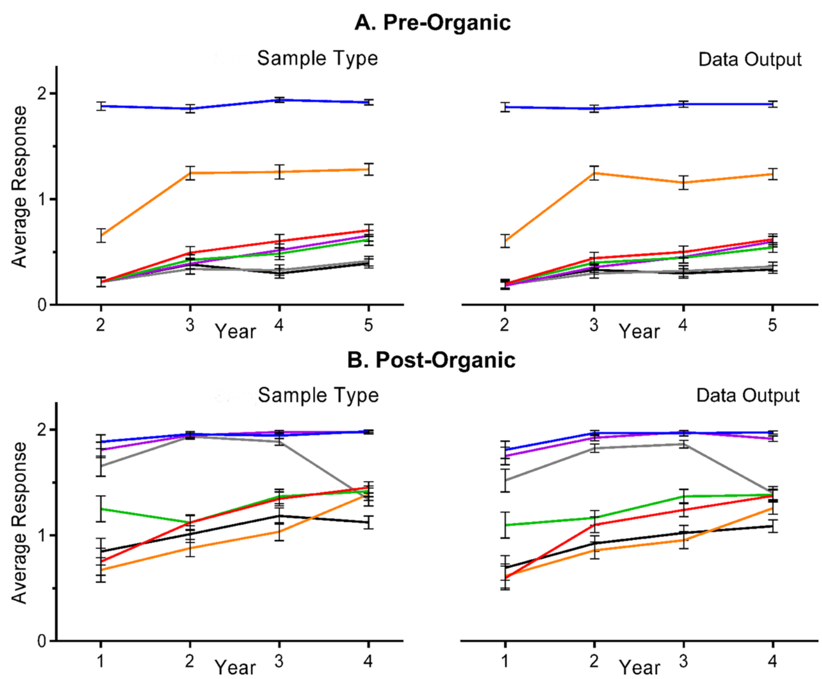

Figure 2. Average student responses to questions about their ability to answer questions about aspects of instrumentation use (blue = balance, orange = UV–vis, red = GC, green = GC/MS, purple = IR, gray = NMR, black = polarimeter). Panels A (pre-organic) and B (post-organic) show student responses regarding the question "What type of sample is used in this instrument (solid, liquid, gas)?" and "What does the data output look like (e.g. what is observed)?". Student responses were chosen from 2 = you can address the question for the instrument without looking at reference materials; 1 = you know you could find the information to answer the question within 20 min using appropriate reference materials; 0 = If neither of the above statements describes your knowledge.

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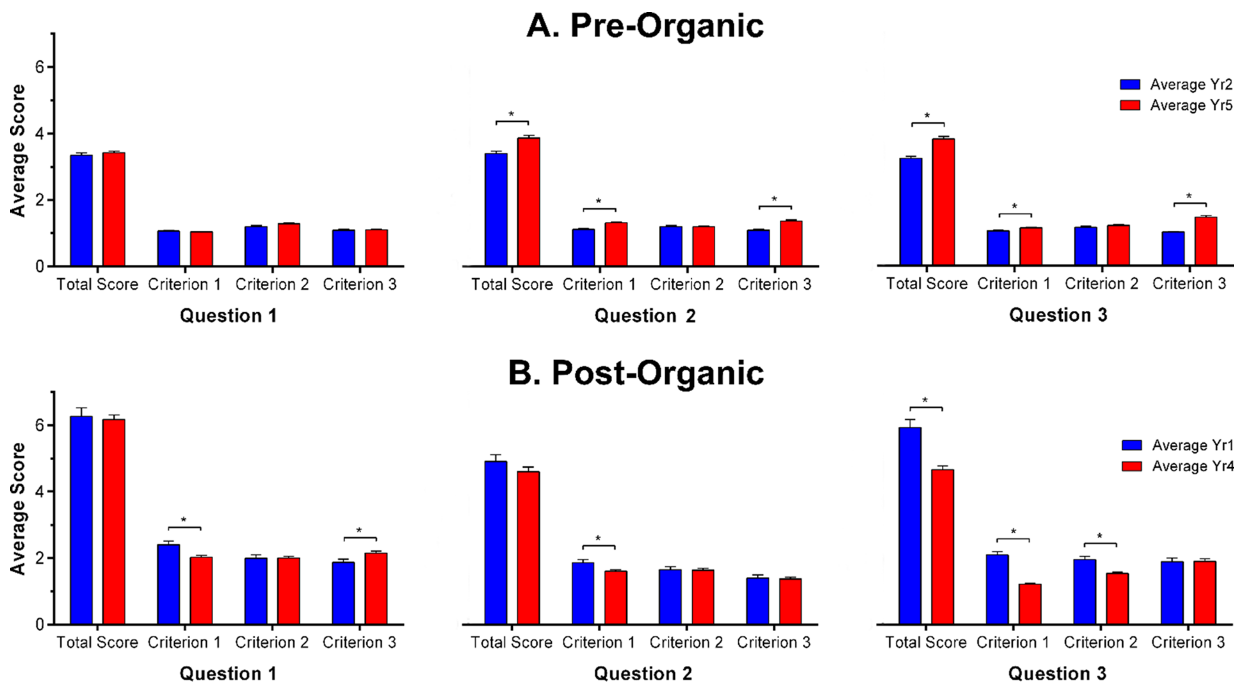

Figure 3. Average ± SEM (standard error of the mean) practicum scores obtained by students pre-organic in years 2 and 5 (A) and post-organic in years 1 and 4 (B). The total score for each question is the sum of the scores for the three individual criteria, which each have a minimum of one point and a maximum of four points. All statistically significant differences ($p < 0.05$) are indicated with an asterisk (*) and were determined using an unpaired t test with unequal variances.

1. *Indicate to what extent the "insert instrument type" was emphasized in your chemistry course work to date.*
2. *What is your experience with the "insert instrument type"?*
3. *What type of sample is used in the "insert instrument type" (solid, liquid, gas)?*
4. *What does the data output look like (e.g., what is observed) for the "insert instrument type"?*

Questions 1 and 2 used a six-point Likert scale and focused on a student's perception of instrumentation emphasis in their coursework and their resulting instrument knowledge, respectively. For question 1, a score of 1 = minimal emphasis (used infrequently or not in-depth), while a score of 6 = strong emphasis (used multiple times and/or experience was in-depth). Likewise, for question 2, a score of 1 = "I am unfamiliar with this instrument", while a score of 6 = "I can use this instrument for new applications and/or am able to repair the equipment. I am comfortable enough with the use of this instrument that I can teach someone to use it properly."

Questions 3 and 4 were used to gauge student understanding of specific aspects of laboratory instrumentation. In particular, can the student identify the type of sample the instrument requires and what the data output looks like? These questions used a three-point knowledge survey scale.[7] The possible student responses were 2 = "you can address the question for the instrument without looking at reference materials", 1 = "you know you could find the information to answer the question within 20 min using appropriate reference materials", or 0 = "neither of the above statements describes your knowledge".

Survey Data Statistical Analysis. A one-way ANOVA analysis was used to determine statistically significant differences in multiple population means. Figures 1 and 2 provide the student perception means for questions 1−4. Confidence intervals are represented by vertical lines. Statistical differences between groups are indicated by the lack of overlap between the confidence intervals.

Practicum Questions Data Collection. Practicum questions were designed as previously described[4] to assess a student's ability to address a chemical question using instrumentation. Each practicum was given as a "take home" assignment. Students were instructed not to consult outside sources, but to complete the assignment based on what they already knew. The study sample size for each administration is summarized in Table 1. Post-organic students in Yr1 and Yr4 and pre-organic students in Yr2 and Yr5 were administered the same practicum questions; students in other semesters were given different questions. Even though all the practicums shared a similar format and theme (transition metal-catalyzed reactions), the focus in this report is on the data drawn from practicums using the same questions, to eliminate variability that may arise from administering different questions.

Post-organic students in Yr1 and Yr4 and pre-organic students in Yr2 and Yr5 were asked to answer a set of three practicum questions related to the ring-opening of epoxides using the Jacobsen catalyst (see Supporting Information).[8] The questions, which were designed to become increasingly complex, asked students how they would characterize the reaction product (question #1), measure the reactions' rate constant (question #2), and study the reaction's mechanism by distinguishing between possible intermediates (question #3). For each question, students were asked to briefly describe the experiment they would perform, indicating what instrument(s) they would use, what results they would expect to see, and what problems they may encounter. Exemplar answers to the practicum questions were obtained from three content experts (see Supporting Information). The exemplar answers were used to determine the scoring criteria for the student responses. On the basis of the exemplar answers, students with knowledge of

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IR (and specialized instruments like FT-IR or reactIR), NMR, polarimetry, GC, and UV−vis would be expected to be able to successfully address the questions.

The scoring of student responses involved applying a "Rubric for Assessing Students' Experimental Problem-Solving Ability" developed by the authors. The details of the rubric and how it was administered to score student responses to the practicum questions has been described.[6] Each question was scored according to three criteria: (a) the student identifies the important or relevant features of the problem, (b) the student presents a complete justification or explanation for the strategy, and (c) the student provides an effective experimental strategy that is likely to work to solve the problem. The three criteria for each problem are scored using a scale from 1 to 4, with 1 being emerging ability (lowest) and 4 being mastering ability (highest). As such, the maximum score for each of the three individual criteria is four points, and the maximum score per question is 12 points. The minimum criteria score and total overall score are 1 point and 3 points, respectively. To ensure inter-rater reliability, three separate graders scored the practicum answers and applied the developed rubric. The inter-rater reliability was 82%.

Practicum Questions Statistical Analysis. Figure 3 shows the student mean by question and criterion for post-organic students in Yr1 and Yr4 and pre-organic students in Yr2 and Yr5. An independent means t test with unequal variances was used as the statistical method of comparison for the practicum questions. Confidence intervals are represented by vertical lines and an asterisk (*) indicates statistical differences. Table 2 reports effect-size calculations (Cohen's d) for responses that were statistically different.

Table 2. Effect Size (Cohen's d) for All Significant Differences between Yr2 and Yr5 for Pre-Organic Students and Yr1 and Yr4 for Post-Organic Students

Question/Criterion	d, Effect Size[a]
Pre-Organic	
Question 2: Total Score	+0.47
Question 2: Criterion 1	+0.50
Question 2: Criterion 3	+0.66
Question 3: Total Score	+0.66
Question 3: Criterion 1	+0.32
Question 3: Criterion 3	+0.87
Post-Organic	
Question 1: Criterion 1	−0.58
Question 1: Criterion 3	+0.47
Question 2: Criterion 1	−0.44
Question 3: Total Score	−0.93
Question 3: Criterion 1	−1.88
Question 3: Criterion 2	−0.86

[a]A positive effect size indicates students scored higher later in the study (i.e., Yr4 or Yr5), and a negative effect size indicates students scored higher early in the study (i.e., Yr1 or Yr2).

Frequency of Instrumentation in Student Responses. To identify the instruments students selected in their answers, a count of the instruments mentioned in student practicum solutions was tallied. For example, each time a student mentioned that NMR could be used to address the question, this was counted. If a student noted NMR in all three questions, this was counted as "3". Once the sum for each instrument was tallied, this was normalized based on the number of total students responding. This process resulted in a rate of selection for all instruments mentioned by students.

Timeline and Description of Curriculum

The assessment described here examined the undergraduate laboratory curriculum over a period of eight semesters. Table 1 provides a timeline for changes to the curriculum, changes to instruments, and the assessment events associated with this study. A more detailed description of the experiments that used instrumentation, as well as students' tasks associated with each instrument, are included in the Supporting Information.

Changes to the curriculum made during this time were independent of the annual assessment efforts and were made primarily because the individuals responsible for the curricula became aware of an intriguing new lab or the department obtained a new piece of equipment. Experiments are a mixture of expository, guided-inquiry, and problem-based laboratory styles (using Domin's classifications).[9] As depicted in Table 1, students primarily used the Vernier SpectroVis UV−vis instruments in general chemistry, which were not used at all in organic chemistry lab. Use of the IR and NMR spectrometers was prevalent in organic chemistry lab, as was use of the GC and GC/MS.

During the timeline of this project, a number of new instruments were introduced in the department. Some of these were entirely new (e.g., Vernier mini-GCs) and others were replacement instruments (e.g., Vernier SpectroVis UV−vis spectrophotometers, NMR), still others were additional instruments (e.g., IR, GC, GC/MS), equipped with accessories (e.g., Attenuated Total Reflectance accessory for the IR, autosamplers for the GC and GC/MS) designed to add capacity and efficiency to laboratory environments. While unplanned, there were also some instrumentation failures that occurred during the period of this project.

Several laboratory curricular changes related to instrumentation were made during this window. In particular, two new laboratories using instruments were added to the general chemistry sequence, using the Vernier mini-GCs and the FT-IRs.[10,11] Each of these new laboratories was designed using an inquiry-based framework. In organic chemistry, the number of experiments using the NMR, IR, GC, and GC/MS was increased.

Students typically had direct exposure to an instrument during a relevant experiment; they prepared their own samples, collected their own data, and analyzed the output either individually or as part of a small group. (The one exception was for a GC experiment in which students were provided with the chromatogram to determine the amount of starting material present in a mixture of isomers). Additionally, the unanticipated failure of the NMR spectrometer during part of Yr3 and all of Yr4 necessitated that students be provided directly with spectra for experiments involving the NMR.

In some experiments, instrument operation and data interpretation were relatively insignificant, as students followed explicit instructions to obtain one key data point. In other cases, the experience was richer, forcing students to critically evaluate the data output to draw conclusions about chemical properties, structural trends, or experimental results.

■ RESULTS

Student Experiences with Instruments

To better understand students' perception of their exposure to and knowledge of selected instrumentation in use in the

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chemistry curriculum, we surveyed students at the beginning of Organic I (pre-organic) and then again at the end of Organic II (post-organic). Figure 1 shows, over the 8 semester period of the project, students' perceptions of the degree to which instruments had been emphasized in their coursework and their perceived knowledge of different instruments (Figure 1A: pre-Organic and Figure 1B: Post-Organic).

In each year of the project, pre-organic students noted most emphasis in their curriculum has been on the balance, compared to other instruments. They similarly indicate greater knowledge of how to use the balance. They have a moderate level of emphasis for and knowledge of the UV−vis. Pre-organic students tend not to know much about other instruments and indicate they have not been emphasized in their coursework at this stage in their undergraduate curriculum.

For post-organic students, two instruments, the NMR and the IR, are perceived to be highly emphasized, such that their emphasis is similar to that of the balance. Other instruments have a moderate level of emphasis, similar to the level of UV−vis for pre-organic students. It is important to note that the survey question asked about emphasis in their coursework (generally), so students are likely answering from the perspective of emphasis in *both* lecture and lab.

While the patterns of pre-organic emphasis and instrument knowledge are very similar, there are differences between emphasis and knowledge for post-organic students. For example, while post-organic students felt the NMR and IR were emphasized as much as the balance, their knowledge of how to run the instrument was somewhat lower than that of the balance. This may reflect a distinction between what students learn *about* (e.g., using IR or NMR data to identify functional groups) and their actual experience with the instrument in a laboratory setting. In general chemistry (the coursework on which the pre-organic responses are based), there is relatively little emphasis on instrumentation and data in the "lecture", so whatever emphasis students experience likely comes through actual experience in the lab, resulting in the similar patterns for emphasis and experience for the pre-organic students.

The data in Figure 1 also allow us to explore the impact of curricular shifts and instrumentation environment over the multiple years of this project. Data show the pre-organic knowledge of the balance is constant over the years of the study. The knowledge of the balance is similarly constant in the post-organic knowledge data, with the exception of the post-organic Yr1 data, which shows the balance (and all other instruments) as lower than in subsequent years. This may reflect a curricular shift between Yr1 and Yr2. The Yr1 post-organic cohort came through the curriculum prior to an intentional effort to use instruments in every organic laboratory.

The pre-organic experience shows a modest increase in knowledge of the UV−vis between Yr2 and Yr3. This change is coincident with the full implementation of new SpectroVis/Labquest instrumentation in general chemistry courses and a doubling of the number of experiments relying on UV−vis (see Table 1). In other words, the students who took the general chemistry course in Yr1 but were surveyed in Yr2 had less exposure to UV−vis than those who took general chemistry in Yr2 and took the pre-organic survey in Yr3. Pre-organic students' knowledge of other instrumentation increases slowly over the eight-semester period, coincident with modest changes to the general chemistry laboratory curriculum. For example, laboratories that used the IR and GC/MS were introduced to summer general chemistry students between Yrs3 and 4, impacting some pre-organic students in Yr4 and nearly all pre-organic students in Yr5.[10,11] The increase in knowledge of the NMR and polarimeter trails the other instruments among pre-organic students, as these are not introduced at all in general chemistry.

In the post-organic data, there is a significant increase in students' reported knowledge of nearly all instruments between Yr1 and Yr2. This is likely a result of changes that, as already noted, intentionally increased the overall use of instruments in the organic laboratory (see Table 1). Over Yrs2−4, the data for balance and the IR are relatively constant. During this time, new IRs were integrated into the organic chemistry laboratory curriculum. While the new IRs added capacity and increased throughput, the introduction of the new instruments did not seem to impact students' perception of emphasis or knowledge of the IR. This may be related to the fact that, while additional laboratory experiments made use of the IR, the new experiments used the IR in the same way as the old ones (e.g., functional group identification).

During Yrs2−4, other instruments (GC/MS, GC, UV−vis, and polarimeter) show a modest increase in students' perception of their knowledge of how to use these instruments, with a larger increase coming between Yr3 and Yr4 for everything but the polarimeter. The increase in UV−vis over time may reflect an indirect effect from the increased use of UV−vis in the general chemistry curriculum. It is unclear why the GC and GC/MS increase, though it is possible that as the NMR was removed from the curriculum (see below), students perceived they gained relatively more experience with these instruments, despite an absence of any curricular changes.

Between Yr3 and Yr4, the perception of emphasis and knowledge of the NMR decreases significantly among post-organic students, with the knowledge of how to use the NMR showing a particularly large decline. This change was coincident with our departmental 300 MHz NMR, the workhorse NMR for the organic labs, first experiencing technical problems (Yr3) and then being out of commission (Yr4). That the perception of emphasis of the NMR did not decrease as much as students' self-reported knowledge of how to use it may be a reflection of the fact that emphasis (at least for NMR) includes a significant component of learning how to interpret NMR data (e.g., in the lecture course). This further suggests that their knowledge of how to use the instrument comes in the laboratory. Without a working NMR, students did not perceive they gained as much knowledge about the NMR as previous cohorts.

In addition to the questions about emphasis and knowledge of instrumentation, the surveys asked questions about students' specific understanding about instrumentation. For example, do students know what type of sample the instrument takes and what the data output looks like? Figure 2 shows these results from the student survey data. Average responses from students were <2, which suggests that generally students felt confident they could look up information about instruments, but they did not have it ready for easy recall. The patterns of responses generally follow students' general knowledge responses (Figure 1), suggesting that when students feel they have knowledge of how to use a particular instrument, they also gain mastery of more specific aspects of using the instrument.

Using Instruments in Problem Solving

The second component of the assessment looked at students' ability to make intentional choices about instruments in chemical problem solving. Figure 3 shows the average scores

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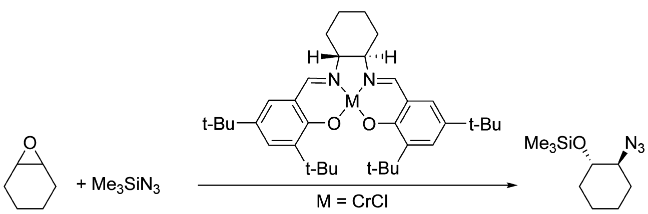
on the problem solving practicum questions for pre-organic students in Yr2 and Yr5 (panel A) and post-organic students in Yr1 and Yr4 (panel B). Since the four different cohorts of students were asked to answer the same set of questions, a comparison of responses between the groups at the start and end of our project is possible. Effect sizes (Cohen's d) for statistically significant differences are shown in Table 2. Effect sizes are considered small, medium, or large if d is 0.2−0.49, 0.5−0.8, or >0.8, respectively.[12] The effect size is reported as a positive number in Table 2 if students' scores improved and as a negative number if scores declined over time.

Pre-Organic to Post-Organic. The data show that pre-organic students (Figure 3A) provided answers that received lower scores than the post-organic students (Figure 3B). In general, the pre-organic students obtained a total score for each question that was just above the minimum possible and the post-organic students were scored approximately 1.5 times higher. This result was expected, given that organic chemistry offers our students the first significant opportunity to use scientific instrumentation to answer chemical questions of the type represented by the practicum questions. This experience is evident in practicum question 1, which asks students how they would characterize the chiral product produced from the reaction depicted in Scheme 1. Typical pre-organic and post-organic responses to this question are depicted in Box 1. The pre-organic student received a 3 out of 12 for this answer, while the post-organic student received a 7.7 out of 12 (refer to ref 6 for scoring rationale and use of the rubric). The increase in overall average score between pre- and post-organic students is clearly indicative of the knowledge and experience that students gain as they progress through an undergraduate chemistry curriculum. Further, these results support our earlier findings that the rubric is effective at differentiating between students who are at different stages in their chemistry program.[6]

Scheme 1. Practicum Question 1 Asked Students To Describe How They Would Characterize the Product of the Epoxide Ring-Opening Reaction



Box 1. Representative answers from pre- and post-organic students asked how they would characterize the product of the reaction depicted in Scheme 1

Pre-Organic Student Response: "You could possibly take a sample and using a balance, find the mass. Then, through stoichiometry you could compute the atomic mass of the sample and compare to the actual atomic mass of the compound."

Post-Organic Student Response: "The first instrument will be the polarimeter. This will give me information as to whether the product is chiral. The second instrument I will use will be IR spectrometer, which will help me determine the functional groups present in the product. The third instrument will be NMR, which will help me determine the structure"

The differences between pre- and post-organic students is further underscored by looking at the most frequently selected instruments in student practicum answers. Pre-organic students in both Yr2 and Yr5 selected UV−vis most frequently, followed by either the balance or an instrument to measure either melting point or boiling point (students were not made aware of a compound's physical state). Beyond the top three, there are no patterns in the selections made by pre-organic students. In both Yr1 and Yr4, post-organic students select NMR most frequently. Yr1 students selected polarimeter, IR, mp/bp, and MS as the next most frequent instruments they would use to solve these problems. Yr4 students selected IR, TLC, polarimeter, and GC/MS. (Students identifying TLC is a reflection of the fact that many in this cohort were more focused on a strategy to address the question than on choosing something an experienced chemist might call an instrument.) The "correctness" of a particular instrument is reflected in the scores on criterion 3 of each question. Perhaps not surprisingly, however, the instruments that students select appear to be strongly influenced by the instruments to which they have been exposed. Both pre and post-organic students select instruments that Figure 1 and 2 indicate they know something about.

Pre-Organic: Year 2 and Year 5. The average scores obtained by pre-organic chemistry students in Yr2 and Yr5 are depicted in Figure 3A. Table 2 reports the effect size (Cohen's d) for all questions/criteria where there was a statistically significant difference in scores between the two years. For question 1, the pre-organic students received scores in Yr2 and in Yr5 for each of the three criteria that were statistically equivalent. However, for the more difficult questions 2 and 3, students demonstrated small, but significant gains. Analysis of each individual criterion using an unpaired t test with unequal variances allowed us to attribute the improved scores to criterion 1 (identifying the features of the problem) and criterion 3 (identify an instrumental strategy that would address the problem). For both questions, the Cohen's effect size values for criterion 1 (small to moderate effect) were less significant than for criterion 3 (moderate to large effect).

While the cause of these shifts cannot be definitively determined, results can be correlated with changes to the general chemistry curriculum. First, the students in Yr5 had greater exposure to instrumentation. As part of their general chemistry labs, all of the pre-organic students assessed in Yr5 used Vernier SpectroVis spectrophotometers, Vernier Mini Gas Chromatographs, and FT-IR spectrometers (this was not the case for pre-organic students in Yr2). The additional tools to which students were exposed likely accounts for the moderate to large increases observed in criterion 3, which evaluates whether students select an instrument(s) that will successfully address each question. The increased exposure to instruments among students in Yr5, which is also reflected in the survey responses presented in Figures 1 and 2, increases the likelihood they will select a correct answer. While it is likely that some students select the correct instrument(s) on the basis of a rich understanding of the instrument, some make a selection based on a shallow analysis of what might work to solve the problem. We believe the latter is frequently the case. If the correct instrument was selected based on more advanced understanding of the instrument, it can be assumed that students would provide better justification of their selection, which is a component of criterion 2. This criterion did not see

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improvements from Yr2 to Yr5, which is consistent with earlier findings that while students at this level of the curriculum are able to put forth answers, they have a harder time justifying their choices.[6]

A second change to the curriculum that correlates with the increased performance of Yr5 pre-organic students is that the mini-GC and the FT-IR labs were of a guided inquiry type,[10,11] where each student obtained individual results that were pooled with the entire class so that they could independently draw conclusions, make predictions, and answer post-lab questions (Level 1−2 inquiry in ref 13). Guided inquiry labs challenge students to "figure things out", rather than walk through a set of steps. It is possible that the opportunity to have had to "figure things out" gave students more confidence to tackle unfamiliar and, indeed, challenging practicum questions. There were fewer "I have no idea" responses in Yr5 than in Yr1.

Third, mini-GC and FT-IR experiments that were added to the general chemistry curriculum relied upon organic molecules to address a general chemistry theme (e.g., electrostatic interactions and bond strength). These laboratories exposed general chemistry students to organic chemistry functional groups. Increased knowledge of organic symbolism may have contributed to Yr5 students being less overwhelmed with the practicum questions. Evidence for lower levels of overwhelm is that answers like this one, which were common in responses from Yr2 pre-organic students, "no idea! ...I cannot understand this notation" were absent from the Yr5 pre-organic responses. The increased familiarity with standard representations of organic molecules may have provided students enough knowledge such that they were able to analyze the various organic drawings in a way that allowed them to compare and contrast the changes occurring over the course of the reactions presented in the practicum questions. The ability to analyze the structures is critical to correctly identify the components of the practicum questions, which may account for the small to moderate increases in criterion 1.

While we cannot tease out the relative importance of the three factors (exposure to new instruments, the guided inquiry format, and the exposure to organic molecule notation), it is likely that these elements of the curricular changes in general chemistry lab contribute to the gains for questions 2 and 3. We did not see a similar effect in practicum question 1, although the total score for this question is also trending upward (the averages have a t test $p = 0.053$).

Post-Organic: Year 1 to Year 4. As shown in Figure 3B, the average scores for the post-organic students vary between Yr1 and Yr4, and, in general, students in Yr4 scored worse than in Yr1. The data show that the overall score for each question tended to be lower for Yr4 than for Yr1. Analysis of the individual criteria demonstrates that only criterion 1, which measures students' ability to identify the important features of a problem, decreased for all three questions and the effect size ranged from small to large, depending on the question. The remaining two criteria did not offer a discernible trend. Only criterion 1 and 2 from question 3 had a significant decline with a large effect size.

For the post-organic students, it appears that there were no significant improvements in student learning over the course of this project. Indeed, the data suggest declines in student learning. Given the nature of the curricular changes, these results are, perhaps, unsurprising. While new instruments replaced older ones and new experiments were added, the additional experiments tended to use the instruments in the same ways as the old one(s). There were no changes to the format of the labs; in other words, there was no new focus on inquiry or problem solving. Finally, as was previously mentioned, the 300 MHz NMR spectrometer reached the end of its lifetime during Yr4. Students clearly felt less confident about their knowledge of the NMR (Figure 1 and 2). This may have contributed to the decrease in post-organic performance.

■ IMPLICATIONS AND CONCLUSIONS

This project was aimed at understanding how the presence of instrumentation in the laboratory curriculum might impact two important outcomes of our curriculum: (1) students should gain knowledge of and facility with chemical instrumentation and (2) students should be able to make intentional choices about instruments that could be used to help solve particular chemical problems. With respect to outcome 1 (knowledge and facility with instrumentation), the results suggest that students are sensitive to changes in the level of exposure to instrumentation in the chemistry lab curriculum. However, simply upgrading old instruments with modern ones (with improved throughput or functionality) does not impact students' knowledge of instrumentation. It does appear to matter whether students are given opportunities for actual hands-on use of instruments, or if they learn about them only through indirect methods without having collected their own data. As would be expected, students are more familiar with sample preparation, instrument operation, and data output if they have actually used an instrument; this knowledge declines in the absence of direct experience with an instrument, even if the instrument had been discussed as part of laboratory and lecture courses. Thus, students' perceived technical competency with respect to instrumentation appears to suffer in the absence of direct exposure. These results argue for providing instrument intensive labs if technical competency is an important goal for students enrolled in laboratory courses.[2]

With respect to outcome 2, the ability to solve problems using instrumentation, the results suggest that this outcome can be improved by increasing opportunities to work with instruments in problem solving contexts. It should be noted, however, that upgrading old instruments with modern ones (with improved throughput or functionality) or adding more experiments that use the same instruments in similar ways does not impact this outcome. In the organic labs, for example, FT-IR, GC, and GC/MS instruments were replaced over the course of this study. However, the nature of instrument use remained relatively unchanged during the same period. The organic students perceived greater emphasis, experience, and knowledge of instrumentation year to year (for most instruments), but this did not translate into greater effectiveness on their part at using the instrumentation to solve problems. However, the addition of new experiments that use new (to the students) instruments does seem to impact outcome 2, especially if the experiments are intentionally formatted to provide useful foundational knowledge and to promote problem solving. When students in general chemistry were introduced to FT-IR and GC through two new guided inquiry labs that also introduced organic notation, a small but statistically significant improvement in problem solving skills was observed. Introducing instrument-intensive guided inquiry labs in the first year general chemistry course provides students with an opportunity to learn something about those specific instruments and they are able to carry this forward into

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improved problem solving with those instruments a semester later.[13]

In response to these assessment results, we are now working to restructure the organic labs, which fall primarily into the expository domain of laboratory instructional style,[9] to provide more authentic inquiry-based learning in the organic laboratory.

What do these results suggest about the importance of instrument-rich laboratory experiences? Our data suggests that hands-on exposure to instrumentation is important for the development of the valuable skill of "how to use" the instruments. At the same time, however, problem solving with instruments is not a skill that just "appears" based on the presence of instruments in the curriculum; more experience with instruments does not necessarily improve problem solving with instruments. Likewise, upgrading instrumentation, but using them in the same way, does not have an impact on this outcome. Rather, intentional curricular choices that increase the breadth of experiences (e.g., using new instruments, or using instruments in new ways) and that explicitly support problem solving are important. This is, perhaps, not surprising—students do not learn problem solving simply by osmosis. If a program's focus is on training students to run instruments (technical aspects), then including labs with an instrumentation focus matters. If educators want students to problem solve like chemists, then it is important to support the development of this skill while they are in the labs.

■ LIMITATIONS

This is an assessment project and, as such, it is rooted in our institutional context. Additional work is needed to determine if similar results would be observed broadly across institutions. Another important limitation is that it focused solely on mostly nonmajor students as they progressed through the year of organic chemistry. We did take measurements from students in upper division majors courses, but the number of students was so small that trends were impossible to discern.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00566.

Description of general and organic chemistry laboratory experiments, practicum questions and exemplar answers used in this study (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: sshadle@boisestate.edu.

Notes

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