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Effect of Cooperative Problem-Based Lab Instruction on Metacognition and Problem-Solving Skills

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ABSTRACT: While most scientists agree that laboratory work is an important part of introductory science courses, there is scant evidence for the relationship between laboratory work and student learning, particularly at the college level. This work reports the quantitative component of a mixed-methods study of the effect of cooperative problem-based laboratory instruction on problem-solving ability and regulatory metacognitive activity. For this purpose, a previously reported assessment, IMMEX, was used. Mixed-methods evidence suggests that students in such an environment showed improved problem-solving skills and strategies, and showed increased regulation of metacognitive skills, despite a lack of explicit instruction. This work puts forth the proposal that providing an environment that is conducive to social interaction and reflection allows students to develop these desirable skills.

KEYWORDS: *General Public, Chemical Education Research, Laboratory Instruction, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making*

FEATURE: Chemical Education Research

Most science educators would agree that teaching laboratory is an important component of introductory college science courses.[1−3] Unfortunately, another aspect on which consensus seems to have been reached is that there is little evidence that the traditionally structured laboratory is accomplishing those learning objectives that are often designated as desirable and significant outcomes for science literacy,[1,4,5] such as problem-solving skills, critical thinking, experiment design and implementation.[6−8] Furthermore, literature suggests that little more is gained through use of traditional laboratories when compared to learning experiences such as demonstrations and group discussions.[9] This lack of sound evidence to show how laboratory instruction affects student learning outcomes or supports increased cognitive development challenges the assumed "inherent merit of laboratory instruction".[10] Paradoxically, traditional laboratory instruction prevails and is, in fact, typical in most chemistry departments.[11] In response to these problems with traditional laboratory instruction, an array of novel instructional techniques have been developed and implemented. Despite strong theoretical and anecdotal support in most cases, these alternatives lack solid evidence for their efficacy. However, evidence available suggests that, under appropriate conditions, laboratory instruction can contribute positively to students' development of science practices. According to Hofstein and Lunetta,[12] creating more opportunities for students to develop and use metacognitive skills during lab instruction can enhance understanding.

METACOGNITION AND THE CHEMISTRY LABORATORY

Little evidence exists about the effectiveness of laboratory learning at the college level, either to show improved content understanding, or on science practices such as open-ended problem solving, or critical thinking. We believe that metacognitive skillfulness is an intrinsic part of science practices, and we propose the use of a range of assessments that we have developed in this area to investigate laboratory experiences.

Metacognition is usually defined using descriptions such as thinking about one's own thinking,[13] the capacity to reflect upon one's actions and thoughts,[14] or knowledge and regulation of one's own cognitive system.[15] Theoretical models support two main components of metacognition: metacognitive knowledge or knowledge of cognition, and metacognitive skillfulness or regulation of cognition.[14,16] Knowledge of cognition refers to the explicit awareness of the individuals about their cognition; that is, knowing about things (declarative knowledge), knowing how to do things (procedural knowledge), and knowing why and when to do things (conditional knowledge). Metacognitive skillfulness or regulatory metacognition is the executive component that comprises the repertoire of activities used by individuals to control their cognition while performing a task.[14,17] It is the regulatory aspect of metacognition with which we are concerned here, as regulatory activities are believed to be integral to the development of problem-solving skills.

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A number of different metacognitive regulatory activities have been identified that can be grouped into three categories: planning, monitoring, and evaluating. These regulatory skills guide the problem-solving process and their refinement is believed to bring improved efficiency and learning.[18] We believe that a laboratory environment that promotes the use of metacognition should help students develop those science practice skills that have typically been so hard to assess. In general, findings suggest that metacognitive strategy instruction can promote increased problem solving in the classroom.[19] However, to the best of our knowledge, little evidence has been collected that directly probes the role of metacognition in chemistry laboratory instruction.

One significant exception is found in the reports that use the model−observe−reflect−explain (MORE) framework to explicitly activate chemistry laboratory students' reflection about models.[13,20−22] Rickey,[22] for example, presented evidence that suggests that students enrolled in a MORE laboratory program exhibited higher levels of metacognition use when compared to students in a standard laboratory course. In a more recent study, Kipnis and Hofstein[23] concluded that "an inquiry-type laboratory that is properly planned and performed can give students an opportunity to practice metacognitive skills" at the secondary education level.

The purpose of this study was to examine the effectiveness of cooperative, problem-based, project instruction in developing problem-solving skills and ability in college general chemistry laboratory students. Assessment of these parameters—problem solving-skills and ability—was conducted through the online Interactive Multi-Media Exercises software (IMMEX) described below. This report aims at contributing to fill a void in science education, that is, the lack of research showing "simple relationships between experiences in the laboratory and student learning" as evidenced by previous reviews.[1]

■ COOPERATIVE, PROJECT-BASED LABORATORY INSTRUCTION AS PEDAGOGICAL INTERVENTION

Cooperative learning is a student-centered, active-learning approach that uses structured situations in which a fixed small group interacts in a noncompetitive manner to accomplish a common goal. This paradigm engages students cognitively, physically, and emotionally in constructing their own knowledge and "it is an important step in changing the passive and impersonal character of many college classrooms".[24] Cooperative, project-based laboratory instruction is one of the many possible ways to operationalize cooperative learning. For the present study, it serves as the pedagogical intervention that is to be assessed.

This investigation was situated in a two-semester general chemistry laboratory sequence fully converted to the cooperative format more than 15 years ago.[25] Four participants are assigned to each lab team and remain together for the extent of the semester. Laboratory sections meet weekly for 3 h; there are four to six teams per section. The course usually includes four to five laboratory projects each semester, with a typical project spanning a period of four weeks during which the team is posed a problem. In that period, the team analyzes the problem, sets goals, plans strategies, designs and implements experiments, learns necessary lab techniques, discusses and evaluates processes and outcomes, answers guiding and planning questions, and prepares a report. The project culminates with a session of team oral presentations for which the use of a poster as visual support is required. Teams communicate their procedure and the rationales behind their decisions and conclusions, as well as their findings, and respond to questions from the teaching assistant (TA) and peers. In addition, participants submit individual written reports. In summary, the project not only facilitates, but actually requires students to exercise an array of varied regulatory metacognitive skills that fall in the fundamental categories of planning, monitoring, and evaluating. In addition, it promotes social interaction to encourage and reinforce these metacognitive processes. Details about the laboratory characteristics and dynamics can be found in the student's laboratory manual and the instructor's manual to the course.[25,26]

■ METHODS

The work reported here is part of a larger research endeavor that investigates learning in the academic chemistry laboratory and it is framed within a sequential explanatory quantitatively driven design. In this approach, quantitative evidence is collected first to explore changes that might have occurred as consequence of the intervention (i.e., what occurred) and then confirmatory qualitative data are collected in an attempt to explain how those changes came about (i.e., how and why they occurred).[27] The qualitative findings have been reported in a separate paper[28] and the present article extends that report by introducing the quantitative component. Quantitative data collection used the IMMEX software previously described.[29−31] This instrument was used to quantify changes in strategy and problem-solving ability that may be associated with the intervention. It is important to emphasize that this study is not comparative in nature; its intention is not to examine the use of two different instructional approaches but to collect evidence on the effectiveness of the one chosen as treatment as opposed to no instruction. Participants were students enrolled in General Chemistry 1 Laboratory at a research-intensive institution in the southeastern United States where the entire first-year program is cooperative project based. Therefore, taking part in the study did not impose any additional burden on the students. Only data from participants who signed informed consent forms were included in the study (typically >95%); identification numbers were assigned to ensure confidentiality. Neither the instructor nor the TAs were part of the research team, and even though they were aware of the data collection, they were unaware of the scope and nature of the research questions. Researchers did not have any instructional contact with participants; neither did they supervise the graduate students serving as TAs. In addition to a TA-training program developed at the beginning of the year, weekly meetings held by the laboratory coordinator were used to support adequate adherence to the guidelines of cooperative work.[25] The laboratory project used for this study was the identification of an unknown substance.[26]

Interactive Multi-Media Exercises

IMMEX is a Web-based platform that has been described in depth elsewhere[29,32−34] and that was extensively used to gather student performance and problem-solving strategy information.[29,35] Typically, an ill-defined problem was presented by using a real-life type scenario. Each problem set contained multiple cases. For example, the problem set used for this study (Hazmat) asked students to identify an unknown. There were 38 different cases (or unknowns) within the problem set. Students were able to design their own problem-solving strategy as they navigated through the problem by requesting information about the unknown (running "virtual tests") and analyzing and processing the results of those tests. Ideally students used that information to decide what to do next. The problem also provided necessary background, as well as information specific to the problem.

IMMEX used an HTML tracking feature to create a record of the items selected, the items' sequence, and the time each item was under consideration. All work done on a case by an individual participant is referred to as a single performance. Because there was no one right way to solve such a problem, a large number of pathways to the solution are possible. To reduce the raw data to a manageable set of information about the student problem-solving activities, artificial neural networks (ANN) and hidden Markov models (HMM) were used to cluster the large number of performances to a reduced number of strategies, also called states.[36] This allowed a partial reconstruction of the strategy used by the student as they attempted to solve the problem. Evidence indicates that for a given problem type, individuals stabilized on one state by the time they had worked on five cases;[33,35] therefore, for research purposes, participants were asked to solve at least five cases of one problem set.

Through ANN and HMM modeling based on thousands of performances, five strategies states were identified for Hazmat. (For a more detailed description of the modeling process see Steven et al.[30] and Cooper et al.[29]) In our prior work, we characterized these states in terms of the implied use of metacognition.[29,35] (See Table 1.) For example, strategy state 1 represented participants who moved rapidly to an answer with little consideration of the background information and without running tests thought to be crucial by experts. These participants used a limited number of items with no noticeable consistency in how they were chosen, suggesting a random selection of information. HMM modeling showed that students in this strategy state had a high probability (p = 0.99) of remaining in it in consecutive cases, despite the fact that they were informed their responses were incorrect and that they had access to a summary of their work. This strategy was associated with lack of planning skills, poor ability to sort out items based on their relevance, and poor monitoring and evaluating skills. Therefore, it was characterized as the lowest in metacognition. It should be noted that IMMEX detected a behavior that might have had multiple causes, perhaps even apathy or lack of interest, but whatever the cause, the strategy detected was low in metacognition.

Table 1. State Characterization for Hazmat

Strategy State	Description	Metacognition Descriptor[a]
1	Limited, few items used	L
2	Equal use of background and test items	I
3	Prolific use of problem space items	L
4	Many tests, little use of background information	I
5	Efficient, relatively few items including relevant ones	H

[a] L, Low; I, Intermediate; H, High.

On the other extreme, participants in strategy state 5 used an adequate number of items to solve the problem, invariably chose those items of high relevance to the problem, consulted the background information, and had a high probability (p = 0.95) of remaining in this strategy having realized it was effective and efficient. Strategy state 3 was prolific, meaning that students chose to view an excessive amount of items, apparently jumping from one to the next without taking the time to analyze the information conveyed in each one. Strategy states 1 and 3 were classified under low metacognition, L (Table 1). These strategies were more prevalent in the solution of the first case attempted, while the students were framing the problem. Those participants who did not transition away from these states are less metacognitive. States 2 and 4 are intermediate, I. Initially (i.e., for the first case that students encounter), these states were not common but were populated later on by students transitioning especially from state 3. The main difference between these two intermediate states was the nature of the information used; strategy state 2 used about the same proportion of tests and background items, whereas strategy state 4 was data driven, with less use of background. State 5 is considered high, H; as pointed out above, this strategy was the most efficient.

The IMMEX performance data were also modeled using item response theory, IRT, to obtain a second piece of valuable information: student ability.[36] This parameter was a measure of the level of case difficulty that a given student could solve. Because not all Hazmat cases were of the same difficulty level (e.g., determining the identity of sodium chloride was considerably different from determining the identity of nitric acid), a simple comparison of correctness might be misleading. Ability calculation considered the different difficulty of the items, hence, enabling reliable comparisons of students' performance; it used an interval scale in which higher values correspond to higher student ability. We have provided evidence that supports a significant association between ability in solving ill-structured problems and metacognition level (L, I, H) as assessed using IMMEX.[29] That is, students who used a high metacognition strategy typically had a higher ability than those students who used strategies that were designated as low metacognition.

Study Design and Data Collection

This field investigation was conducted over a period of three semesters to allow for the replication study. Although randomized control–treatment studies with tight control of variables are the "gold standard" of educational experiments, in practice the constraints imposed when studying unaltered learning experiences make this level of control rarely possible to achieve. Given the open nature of the educational systems, achieving the level of repeatability more common in physical sciences should not truly be expected. By replication, we imply the general principle that, when conducting the study under similar conditions, one should obtain similar findings. Replication is an appropriate means to increase confidence in that observed differences are not a product of random factors, they are real. Therefore, we decided to use the same measurement and analysis and different student groups. Data collection was completed using condition groups as described in Table 2.

Comparison groups prelab 1 and postlab 1 (sequential semesters) comprise the first study; the replication study consisted of comparison groups prelab 2 and postlab 2 (concurrent groups). By using this experimental design, we eliminate the effect of the pretest. The sections in the concurrent study were assigned to a condition so that:

- There were about the same number of sections from all three scheduling blocks (morning, noon, and afternoon)

Table 2. Description of Condition Groups Used during the Three-Semester Study

Semester	N	Group Identifier	Description
1	234	Prelab 1	IMMEX assignment performed before any laboratory work
2	410	Postlab 1	IMMEX assignment performed after completion of laboratory project
3	145	Prelab 2	Replication of Prelab 1: IMMEX assignment performed before any laboratory work
3	114	Postlab 2	Replication of Postlab 1: IMMEX assignment performed after completion of laboratory project

- There was at least one section from each teaching assistant (TA) in each condition (typically TAs teach three laboratory sections)
- The initial number of students in the two conditions was similar

Table 3 summarizes the study design. The prelab conditions were tested using IMMEX during the first week that laboratory sections met, that is, preceding the laboratory experience. The postlab groups were assessed using IMMEX after the fifth week of laboratory instruction once the first project had been completed. These control and treatment group studies address the effect of the cooperative lab project on problem-solving strategy and performance by using IMMEX as the assessment tool.

Table 3. Study Design with Elements by Semester

Semester	Condition	Test	Treatment	Test
1	Prelab 1 (control)	IMMEX	Lab Project	—
2	Postlab 1 (treatment)	—	Lab Project	IMMEX
3	Prelab 2 (control)	IMMEX	Lab Project	—
3	Postlab 2 (treatment)	—	Lab Project	IMMEX

Participants were instructed to solve six cases of the IMMEX Hazmat problem set (six different unknown substances randomly assigned by the system) and were given a full week to complete the online assignment. Only students who completed six or more cases were included in the analysis to allow for strategy stabilization. Hazmat data were modeled by the IMMEX Project as described previously, thereby obtaining state and ability reports for each participant.

The first case in the assignment is typically not used in any of our studies, because the students are exploring the problem space. However, we consider the comparison of postlab and prelab groups' strategy distributions for this first case a relevant indicator of whether the groups are different. We found no significant difference, suggesting the groups were homogeneous in terms of their initial ability and initial strategy use. The state strategy and ability used for our analyses correspond to those attained once the participants had stabilized (sixth case).

SPSS 15.0 was employed for means comparisons (analyses of variance and t-tests), as well as association tests (χ^2) and other descriptive statistics. Table 4 shows the two parameters used to assess the effectiveness of the lab cooperative project.

RESULTS

Figure 1 shows the distribution of IMMEX strategy by study condition. The percentage of participants in the treatment group (postlab 1) who used strategies of the highest metacognitive characteristics more than doubled the corresponding percentage for the control or prelab 1 group. The difference in distribution is statistically significant as indicated by the χ^2 test results.

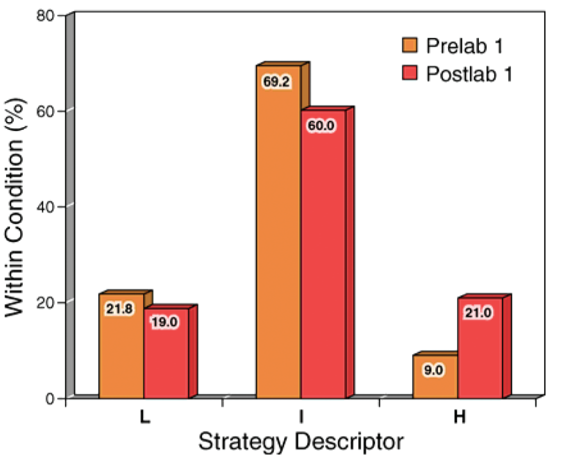

Figure 1. Strategy distribution by study condition (χ^2 = 15.5, p < 0.000).

Table 5 shows a summary of the comparisons between the pre- and postlab groups for both studies. A t-test showed that the difference in mean ability between the prelab 1 and postlab 1 groups in the first study was statistically significant. The trend for the replicate was similar, with the only difference occurring in the p-value being a little higher. This may be due to the smaller sample size available for this study. The calculated effect size on the ability was "moderate" based on Cohen's guidelines (Table 5). Calculations of Cohen's d in this study used the mean scores for the treatment and control conditions and the pooled standard deviation. Neither for the control nor for the treatment groups did we observe significant gender differences in strategy or ability.

A Note about the Methods

This study explored the outcomes when students were immersed in an environment that implicitly required the use of metacognitive skills. A strength of this study is that its effectiveness assessment did not rely on student evaluations or other surveys that directly addressed the intervention. Subjective aspects such as engagement, morale, or participation were not included as measures of effectiveness. As part of their general chemistry course, students worked on several different IMMEX assignments, and from the students' perspective,

Table 4. Study Parameters

Parameter	Description	Representation	Source
Strategy	Metacognitive characterization of solution of qualitative inorganic unknowns	States: High, H; Intermediate, I; and Low, L	Hazmat (IMMEX ANN and HMM modeling)
Ability	Maximum difficulty level of a case that a participant can solve	20−80 range, dimensionless	Hazmat (IMMEX performance IRT modeling)

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Table 5. Summary of the Comparison for Postlab and Prelab Groups

Study	Group (n)	Mean Ability (SD)	Mean Ability t-Test p-Values (Cohen's d)	Percentage Classified as High Strategy	Strategy Distribution χ^2 p-Value
First Study	Postlab 1 (410)	48.9 (12.7)	<0.000 (0.37)	21.0	<0.000
First Study	Prelab 1 (234)	44.6 (10.5)	<0.000 (0.37)	9.0	<0.000
Replicate	Postlab 2 (114)	46.6 (12.5)	0.07 (0.23)	14.4	0.005
Replicate	Prelab 2 (145)	44.0 (10.5)	0.07 (0.23)	7.0	0.005

Hazmat was just one more. Another important aspect is the distance placed between researchers and participants; we tried to actively avoid direct instruction of any kind that might have biased either the students' responses and performance, and the researchers' data interpretation, or both. The nature of the quantitative assessment made it unique for the application presented. Large cohorts of students were assessed in a short time and gathering and modeling of data were fully automated.

■ DISCUSSION

There are three frequently employed approaches for teaching metacognition:[19,37]

1. Strategy training (or direct instruction)
2. Creation of social environments to support reflective discourse
3. Modeling and prompting

The intervention proposed in this study, a laboratory cooperative problem-based project, is a combination of the latter two but, at the same time, very distinct in its contextual characteristics from other interventions. Even though student teams are presented with an overall project objective, numerous smaller problems and challenges have to be uncovered and defined by the students as they advance: there is no single well-defined problem. Challenges emerge naturally from the lab practice, with no single optimal solution existing for the entire collection of problems. The learning environment is therefore not stable in itself. Failure is a reasonable occurrence, especially for peripheral or intermediate tasks and it is not uncommon for teams to be faced with the decision about whether they need to abort their plans. There is no emphasis on a single component of regulatory metacognition. Commonly, the project requires teams to meet out of the lab or interact via email. Members are assigned randomly to the teams, creating an opportunity for environments in which participants have to negotiate regarding their beliefs, values, and goals. We hypothesized that these particular contextual characteristics would enhance the development of metacognitive skills and their transfer to diverse situations.

As a whole, the quantitative findings support this hypothesis and in conjunction with the qualitative report,[28] the results contribute evidence that supports the positive effect of the cooperative project-based laboratory instruction on problem-solving strategy (Figure 1), and ability (Table 5). The Cohen's effect size values are moderate for problem-solving ability. We support the use of effect size measures to interpret differences between condition groups, as opposed to solely relying on statistical significance. However, we insist:[38]

> *[C]aution must be exercised in interpreting effect size values since its practical importance needs to be judged in relation to other interventions seeking to have a similar effect, the nature of the outcome, and intervention characteristics such as duration, cost, and inherent ease of implementation.*

Replication of results, Table 5, suggests these are the effect of the intrinsic nature of the laboratory learning environment, because for each study the students and the teaching assistants were different in each instantiation. These results are in close agreement with previous reports that used IMMEX to investigate the effect of short-term collaborative problem-solving interventions,[39] and group use of concept mapping.[35,40]

As explained in the preceding sections, the most efficient strategy for solving the online problem Hazmat is also characterized as the most metacognitive. The increased use of the high metacognitive strategy by the treatment condition (Figure 1) can be interpreted as evidence of this group performing more metacognitively. Findings from this quantitative component of the larger mixed-methods study suggest that these are the result of engaging in this kind of laboratory work. Although the trend in strategy distribution is consistent in both studies, we observed a considerably smaller percentage of students in the second treatment group classified as high strategy users. We do not have any evidence to support an explanation for this difference; however, it is worth emphasizing that the ability measures are consistent with the strategy trend. To investigate the possibility of the content of the project affecting the results of the IMMEX problem-solving activity, we performed a separate study using a different laboratory project based on the spectrophotometric determination of phosphate in cola drinks.[26] In this case, the trend was similar and students who had the laboratory experience prior to solving the IMMEX problem showed more metacognitive strategies and higher abilities than students without the laboratory experience. These findings will be reported separately.

Given that the IMMEX measures were not concurrent for both conditions but there was a lapse of weeks between the assessment of the control and treatment groups, an alternate interpretation may be possible. It could be argued that the observed results were the consequence of the general college experience. We will not contest that college, and perhaps especially the first-year experience, has an impact at multiple levels of an individual's life. Nevertheless, we consider unlikely that a few weeks in college would spontaneously enhance students' use of metacognitive strategies in solving chemistry problems. We wondered, just like any reader may, how the outcomes observed in this report can be linked to the treatment. That moved us to conduct the replication study first, and then to recruit the collaboration of an expert to conduct qualitative inquiry to complement the quantitative investigation.[28] Additionally, Gatlin carried out a qualitative study that directly investigated the effect of this laboratory experience on IMMEX problem solving.[41] The results from this separate study support the proposal presented here.

The positive effect on metacognition and problem solving that we postulate in this study is supported by investigations on the effects of social interaction on learning.[42] Okita and collaborators[42] reported that the mere belief that one is interacting with another person led to increased learning outcomes; they hypothesized that it is the participation in socially relevant actions that promotes this favorable effect.

These findings are in accordance with those from other researchers who have used qualitative inquiry methods to probe metacognition development in environments rich in social interaction.[43,44] The intervention employed in this study creates an environment that not only promotes social interaction, but also facilitates the participation in group actions that are relevant for the accomplishment of the common goals.[28] We postulate that by emphasizing the use of social interaction, cooperative problem-based project laboratory instruction supports the effective development of metacognitive skills through activities such as reflective discussion, verbalization, thinking aloud, group planning, monitoring and evaluating, that is, those activities that contribute to metacognitive skillfulness. The preparation of written reports gives individual students the opportunity to consolidate these skills. The second phase of the larger mixed-methods study took a phenomenological approach to generate a description of the laboratory course experienced by the general chemistry students[28] and pursued an explanation for the quantitative observations. We believe our mixed-methods findings are support for our contention that it is the cooperative, project-based laboratory experience itself that is causing the increases in problem-solving ability and metacognitive strategies.

We believe this work has yielded insights into learning in a cooperative, problem-based laboratory program. Although field research contributes to the generalizability of findings, the complexity of the learning environment studied here and especially the fact that extraneous factors are not controllable constitute a call for careful and modest interpretation of findings. The idea of establishing quick causal relationships and finding what is sought are constant threats in chemistry educational research. We believe no one should expect the open systems of educational research to be subject to the strict falsification principles associated with traditions in physical sciences; on the other hand, this should not serve as an excuse to permit shallow analysis of results or lead to unwarranted generalizations. Moreover, we maintain that educators should be wary of implementing changes based on the findings of one-off studies and we applaud the scrutinizing of the multiple roles researchers sometimes play in their studies. The purpose of scientific research is to put forward a possible cause for the investigated effect and not the quest for the absolute truth. We present this work to be considered within the frame of the larger mixed-methods investigation in which it is nested.

Furthermore, we want to reiterate that findings from this work are consistent with independent studies that have investigated similar learning environments and used different methodological approaches.[23,43] We are aware that we are addressing a "tough question" and in doing so we have used a multi-methods, mixed-methods, multi-studies design because we think tough questions do not lend themselves to easy solutions. This report is part of that research program. In 1968, referring to the role of replication in educational research, Bauernfeind[45] asserted that "burden of proof begins to shift to those who would attack" a generalization when the investigators conduct a variety of replication studies given that these studies provided similar conclusions. We would like to extend this idea to the use of multiple studies.

■ IMPLICATIONS FOR TEACHING

It has been very difficult to justify the time and expense typically spent on laboratory experiences, particularly in large-scale introductory classes. As previously noted, there is almost no evidence that these laboratories provide any positive outcomes for students. According to Hofstein and Lunetta,[12] this is due partially to "insufficient data to confirm or reject convincingly many of the statements that have been made about the importance and the effects of laboratory teaching" and due partially to an inability to assess less tangible outcomes—science practices such as asking scientific questions, critical thinking, and metacognition. This work suggests that placing students in an environment in which they are forced to use and practice these skills produces measurable changes in problem-solving ability and metacognition.

In addition, we believe that the findings drawn from this work do not refer only to the applicability and usefulness of this laboratory project. Their replication and consistency with other reports[23,35,43,44,46] shed light about the possibilities of instruction in the science laboratory. We believe that the findings presented evidence for the relationship between experiences in the laboratory and the development of metacognitive skillfulness, and can positively inform curricular development based on sound research. It is possible to envision the development of metacognition across a variety of social learning and teaching tasks,[47] many of which can take place in the science laboratory, not necessarily as isolated interventions but as an underlying constant.

It is our profound hope that work such as this will provide sufficient evidence to catalyze curricular change across the whole undergraduate (and graduate) experience, so that students will be provided with experiences in which they are able to further expand and develop the skills that we believe are so important.

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