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An Investigative, Cooperative Learning Approach for General Chemistry Laboratories

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To assess our results, students completed questionnaires, evaluated their peers and themselves. Instructors evaluated students through written reports, oral presentations, pre- and post test, a practical exam and a final exam. Assessments of the learning outcomes were performed to determine the level of research skills development, the improvement in laboratory techniques, and depth in analysis of concepts. The experimental designs, implementation of results, and comparisons of student performances using traditional approaches are presented.

Keywords

Cooperative learning, General chemistry laboratory, Peer-review, Research experience

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Abstract

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Introduction

During the last decades science educators have tried to integrate the practice of “doing science” in an effective way in laboratories to facilitate student learning, retention, and effective use of scientific information. Integrating research and education has long been a part of the philosophy of the faculty of Natural Sciences at the University of Puerto Rico, Rio Piedras Campus. Exposing students to research-type activities is considered a vital part of any course of studies within the natural sciences. Undergraduate research experiences help retain students, increase graduation rates, and prepare the future workforce for increasingly competitive jobs. According to Lackey, Baltman & Bentley (1993) and Adami (2006), undergraduate research experiences increase student interest in science careers and sustain and confirm plans for graduate education in science. Drapper (2004) and Arnold (2003) have shown various positive aspects that research experiences bring to undergraduate student development. For example, after participating in a research experience, students report an increased confidence in their ability to design and carry out research plans.

However, at our campus undergraduate research experiences were limited to either research in a scientific laboratory in the graduate program or few upper level laboratories. As a result, most of the students that participated in the available research experiences are students in their third or fourth year, when most of the participants had already decided on pursuing a science major and already determined post-college educational and/or employment plan. In addition, junior students often have problems locating a suitable research group because researchers frequently prefer more senior level and experienced students. Also, frequently only the students with the best performance in college coursework are selected because they often have fellowship support. This further limits the development of students who do not do well in the classical course and test type setting. In addition, these research experiences are limited to the number of students that research faculty can accept in their laboratories (in our department we have around 20 research faculties that would be available for roughly 300 chemistry majors). Finally, the quality of undergraduate education within research laboratories can differ significantly depending on how much care is given to further their development in the research group environment. As one result, the traditional model of undergraduate research used at our university is not easily accessible for the majority of students in their first and second year of study and the research experiences differed substantially in quality. To increase the number of undergraduate students with suitable research exposure, we incorporated appropriate guided research experiences in laboratory courses at different levels of our undergraduate curriculum.

In this article we present the results of one of our approaches to revise our General Chemistry Course curriculum in order to provide research experiences to beginning undergraduate science students. Specifically we will describe a research experience that was introduced in the second part of the General Chemistry Laboratory course.

A challenge in these endeavors was the largely inadequate equipment situation in key laboratories preventing necessary conceptual and curricular changes from being implemented. Recently, the Department of Chemistry received a grant from the U.S. Department of Education MSEIP Program which drastically changed this situation by allowing upgrading the equipment in all (four) General Chemistry Laboratories. Since the

new equipment (MeasureNet® systems) allows for fast data acquisition and analysis, we were able to start increasing the content and complexity of experiences in the laboratory. It enabled us to transform the General Chemistry Laboratory from a quite classical format to one that prepares students for requirements and skills commonly encountered in chemical or other research. To accomplish this goal we trained the faculty and graduate students in the use of this equipment, developed and optimized new experiments, supported tutoring and mentoring measures, and installed a rigorous system to measure learning outcomes.

In our curricular revision it was important to acknowledge that General Chemistry students constitute a quite heterogeneous group. General Chemistry students are enrolled in various academic programs and interested in a variety of fields, such as, biology, physics, mathematics, engineering, and medicine. At this early stage of their education they often lack understanding of the importance of chemistry and research skills within their respective fields of interest. In response to this problem and taking advantage of the new technology, we included inquiry-based interdisciplinary laboratory experiences and a research project in our General Chemistry Laboratory Curriculum. These experiences were designed to further student understanding of the importance of molecular sciences in various areas and at the same time teach fundamental concepts that previously were being taught in a more traditional “follow the recipe” manner. In each of these new experiences, components and skills of experimental methodologies, design and theoretical concepts were introduced in order to prepare the students for the final guided-inquiry research project. In this last experience of the laboratory, the undergraduate students are required to contribute their own ideas to the selection of a suitable research project. They executed the experimental design and data analysis to test scientific hypotheses.

Our expectation was that interdisciplinary laboratory experiences and a research project would provide the students with the opportunity to draw connections between technical disciplines thus allowing them to experience science as a continuum rather than a set of discrete disciplines. The inclusion of inquiry-based interdisciplinary experiences and the research project in the General Chemistry Laboratory allowed more than 200 first year science students to acquire a common set of laboratory skills and techniques, practice experimental design, and participate in a team experience.

Participants

General Chemistry has a total enrollment of about 800 students per semester divided into 32 laboratory sections of 25 students each. Ten sections were used as experimental sections. In order to compare the performance of the different sections, a sample of 400 randomly selected General Chemistry students was taken, 200 from the experimental sections and the remaining 200 from selected control sections. Of these students, 17% were chemistry majors, 47.75% were biology majors, and the other 35.25% consisted of students with majors in general sciences, science education, and nutrition, among others. A 90.5% of the students were taking the course for the first time, and 9.5% took it for the second or more times. A 59% of the students were freshmen, 20.25% were sophomore, and the remaining 20.75% were junior or higher. In our sample, 70% of the students came from private high schools and 30% from public schools. In the experimental section, the students performed the new inquiry based experiments and the research project. The control sections were taught in the traditional (non inquiry) way.

Overview of the Experiences

The experiences were developed in order to allow the students to be more actively involved in the construction of their knowledge and practice science using investigative, discovery-based, open-ended processes, with opportunities for designing experiments built on previous observations. Cooperative and peer-review teaching/learning strategies were used to encourage students to work together to achieve a common goal. In addition, by engaging students in cooperative learning we expected that the research experience would lead to the development of higher level thinking skills, greater intrinsic motivation, improved interpersonal skills, positive attitudes towards learning, and heightened self-esteem as documented by Dornyei (1997) and Slavin (1995). We were seeking to provide the five conditions to promote effective cooperative learning according to Johnson, Johnson, & Smith (1998): positive interdependence, promotive interaction, exchange of necessary resources as well as challenge assumptions and encourage one another to achieve their goals, use relevant interpersonal and small group skills (development of social skills), and regular group processing.

The second part of the General Chemistry laboratory is a course in which the students meet three hours weekly during eleven weeks. At the beginning of the semester each experimental section was divided into groups of four students who worked together during the whole semester. In the experimental section during the first six weeks new laboratory experiences were included to prepare the students for the research project. These experiences ranged in the level of difficulty from initially guided inquiry experiences to an open inquiry experience with a minimum of faculty guidance, the research project, as the last experience of the course. During the initial experiences different teaching strategies were used to facilitate the learning process of the students. In each of the laboratory experiences students were introduced to scientific process, research and team skills, and required as homework to work this component of their research project. Table 1 shows laboratory experiences used during the semester.

Table 1. Newly Developed Laboratory Experiences

Experience	Scientific concepts introduced
EXCEL/Data Analysis Workshop, Introduction of the Scientific Method	Data analysis tools, interpretation, statistics, scientific procedures at a glance.
Dissolution Process	Observation, problem identification, hypothesis development, analysis of qualitative data.
Liquid Crystals	Literature revision, method development, analysis of qualitative data.
Colligative Properties	Hypothesis development, analysis of quantitative data.
Enzymatic Kinetics	Experimental design, data analysis (quantitative and qualitative), discussion of results.
Titration	Literature revision, analysis of quantitative data.
Redox Reaction/Cells	Hypothesis, analysis of qualitative data.
Research Project	Use of the scientific concepts and process to propose and prove a research experiment. (Literature revision, observation, problem identification, hypothesis

	development, experimental design, collection and analysis of qualitative and quantitative data, discussion of results).
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Slavin's (1995) six-stage model of group investigation was adapted to perform the cooperative research project in the General Chemistry Laboratory. Each group of students chose a research topic and used the tools and techniques learned throughout the semester to perform it. At various times throughout the semester, progress reports were due for instructor feedback. After the regular laboratory experiences the students worked four laboratory periods (3 hours each) exclusively on the research project. Each of the stages of the six stage model was implemented as follows:

Stage 1: Identify the Topics, Form Groups, and Plan the Learning Task

Students were organized into cooperative learning groups of four students based on their selection of partners during the first day of class. The class was instructed on different possible projects to carry out during the semester and the students selected the topic they wanted to work with. They also had the option to provide their own topic for the research project which around half of the groups did.

Stage 2: Research Plan

The background search was given as an assignment to each student to be completed individually. The topics were discussed using primary literature (journal articles found and read by the students) and different possible methods were identified. During the discussion of the methodology, students were encouraged to identify potential problems or difficulties with the selected research topic and the procedure that they proposed to perform. After those considerations, they were required to design a work plan for their research project.

Stage 3: Carry out the Research

In each of the laboratory periods assigned to conduct research, the students performed specific tasks and were guided by cooperative learning strategies. They were provided with some guidelines, evaluated and at the end shared their results. After the discussion of the procedure, the experiment was performed. The data analysis was discussed throughout the next week with short presentations from each group. This exercise allowed the students to develop analytical thinking skills and establish relationships with concepts taught previously in class. It also made it possible to identify weaknesses and failures in the chosen methods and optimize it or provide alternatives to it.

Stages 4 and 5: Prepare the Groups for the Written Report and the Final Oral Class Presentation

The final report was required to be written in a scientific article format. An introduction and methodology was turned in advance to be revised by the instructor. After the short oral presentation had taken place, the written reports were distributed to other groups to be evaluated. After that, they were finally graded by the instructor. The best works were selected for presentation in a final symposium.

Stage 6: Evaluation of the Group Components and Written Report

Since according to Lanigan (2008) individual accountability and group goals are factors that contribute to the achievement effects of cooperative learning, several measures were used in evaluating student success. Therefore, students were given a combination of individual and group grades.

Individual Grades

Peer- and Instructor-Review on Student Role Performance

As part of the research project, each member received a specific role for the facilitation of the team work. At the end of the semester, students received a rubric to evaluate the performance of their peers and themselves accounting for 10% of the final report grade. Each student had the opportunity to evaluate each other student in the group according to a set of different criteria on a scale from 1 to 10. These rubrics evaluate student contributions to the progress of the research project, laboratory report, and overall participation for the entire semester. It assigns scores for criteria, such as, responsibility, punctuality, motivation, among others. These peer reviews were confidential and submitted directly to the instructor. The maximum amount that could be awarded to each member of the group was 120 points.

The written report was also evaluated using peer-review strategies. This exercise exposed the students to the critique from their peers and required them to analyze data obtained by other groups in order to make suggestions about how to present, interpret, and carry out the necessary calculations. After the peer-review process the instructor evaluated the written report and student performance during the research laboratory periods using developed rubrics.

Oral Test and Laboratory Report

An oral test was performed to assess the involvement of each member of the research groups. This test evaluated how much the students knew about the procedure they followed, the theory behind the experiment, and the interpretation of the results obtained. Despite the requirement of one report per group, the final grade was assigned individually depending on the evaluation of the performance previously done by their peers. The research project report was one of the three reports that the students had to submit during the semester.

Practical Exam

At the end of the semester each student was required to take a practical exam to evaluate their laboratory skills. In it they have to perform basic procedures that are use in the laboratory: preparation of solutions, titrations, use adequately the routine instrumentation and calibrated glassware, In addition they are evaluated by their data collection, analysis and interpretation skills.

Group Grades

Oral Presentation and Final Laboratory Report

By the end of the project, the students performed an oral presentation in front of their fellow students and faculty members. This presentation covered the methodology they used to do the experiment and their results. At the beginning of the semester, each student received a guideline for the final written and oral report and the rubric that was later used for grading their work. The group grade obtained contributed 20% to the final laboratory grade. Finally, a selected number of groups exposed orally their work in a symposium and the chemistry department faculty evaluated them. At least three faculty members evaluated each research presentation and time for questions was provided after the presentations. This prepared students in a friendly way for participation in scientific conferences which are a common method of scientific discussion and exchange.

Questionnaires

Questionnaires, assessing student perceived knowledge or “confidence” with the process of investigation and communication while performing scientific inquiry, were given to them during the first week of class and at the end of the laboratory course. This self-reporting tool was used to assess their level of comfort with a selection of criteria. Students were asked to evaluate their level of comfort. A total of 200 students completed the pre- and 150 students the post-questionnaire. Statistical analysis was performed using SPSS software (SPSS, Chicago, IL) and the Chi-square test. Additionally, at the end of the semester, 154 students evaluated how the research project helped them to improve selected areas. Participation in all questionnaires was voluntary but participation was above 75% in all cases. Finally, students were given an opportunity to provide more detailed comments about the course. We were in particular interested in what they felt worked or not within the new laboratory experiences. Students also provided suggestions for future improvements. In addition, a focal group was performed with 5 students from each new laboratory experience.

The teaching assistants and professors of the laboratory course also answered a brief questionnaire about their perception of the impact of the research project in the students learning process and their teaching experience.

Results and Discussion

In this study, we used an investigative approach together with different teaching strategies to enhance the learning process of science, technology, engineering, and mathematics students during the General Chemistry Laboratory course. The new laboratory design, in which a research project experience was included, allowed us to meet an extensive range of learning outcomes. Students gained experience in fundamental laboratory skills, such as, experiment design, preparing solutions, performing measurements, weighing, constructing and interpreting results, and graph construction and interpretation. They also got experience in using standard laboratory equipment, such as, pH meter, spectrophotometers, selective electrodes, chromatographic techniques, and volumetric glassware. At the same time the inquiry based nature of the laboratory experiences also allowed the students to discover on their own. Students in the research experience had to assume responsibility for their project and make a number of decisions on how to set up and carry out the experiment. Informal surveys of students and the practical examination results showed that after the course students felt well prepared with respect to fundamental laboratory skills expected in upper-level chemistry courses.

Table 2. Average Student Confidence Levels in Various Areas at the Beginning and End of the Semester on a Scale from 1 to 5 (Lowest to Highest Confidence Level, Respectively).

Topic	Pre-Questionnaire	Post-Questionnaire	Net Change
Scientific method Experimental design	4.40	4.70	0.30*
Understanding chemistry concepts	3.44	4.59	1.15
Designing a method using the literature	3.89	4.70	0.81
	3.95	4.70	0.75

Analytical and data interpretation skills	4.00	4.67	0.67
Formulation of conclusions based on the data	3.94	4.67	0.73
Communicating scientific information to peers	4.00	4.50	0.50
Literature searching and comprehension	3.59	4.42	0.83
Public speaking	3.77	4.14	0.37
Scientific writing	3.83	4.42	0.59
Commitment with research	3.95	4.18	0.23*
Motivation to do undergraduate research	3.33	4.16	0.83
Mastering of laboratory techniques	2.67	4.83	2.16
Use of instruments (e.g. spectrophotometer, pH meter ect.)	2.76	4.76	2.00

* Net change statistically not significant.

The results of the first questionnaire demonstrate improvements in the level of confidence of the students with respect to all of the evaluated criteria at the beginning and at the end of the laboratory course (Table 2). Except for the two topics a statistically significant increase was found ($p < 0.05$). The biggest improvements were in areas directly related to chemistry. Smaller increases were noted in more general areas. This indicated that the students felt that they had a considerably better understanding of research after completing this laboratory experience. Increases in confidence were measured for all topics, most of them considerable, even though most of the pre-questionnaire values were already larger than three on average and some of them were even larger than four. With five being the maximum score, recording significant increases in almost every area was unanticipated. The highest increase was achieved in topics that require high order thinking and manipulative skills, such as, experimental design and mastering of laboratory techniques.

The second questionnaire revealed that the research experience promoted student confidence in their work and also reduced some of the frustrations associated with experiments that did not provide the expected results. Students also experienced a sense of ownership of the experiment knowing that they had a role in deciding how the experiment would be carried out. The survey further revealed that students felt that the experience helped them to improve their thinking, research, and team work skills (Figure 1).

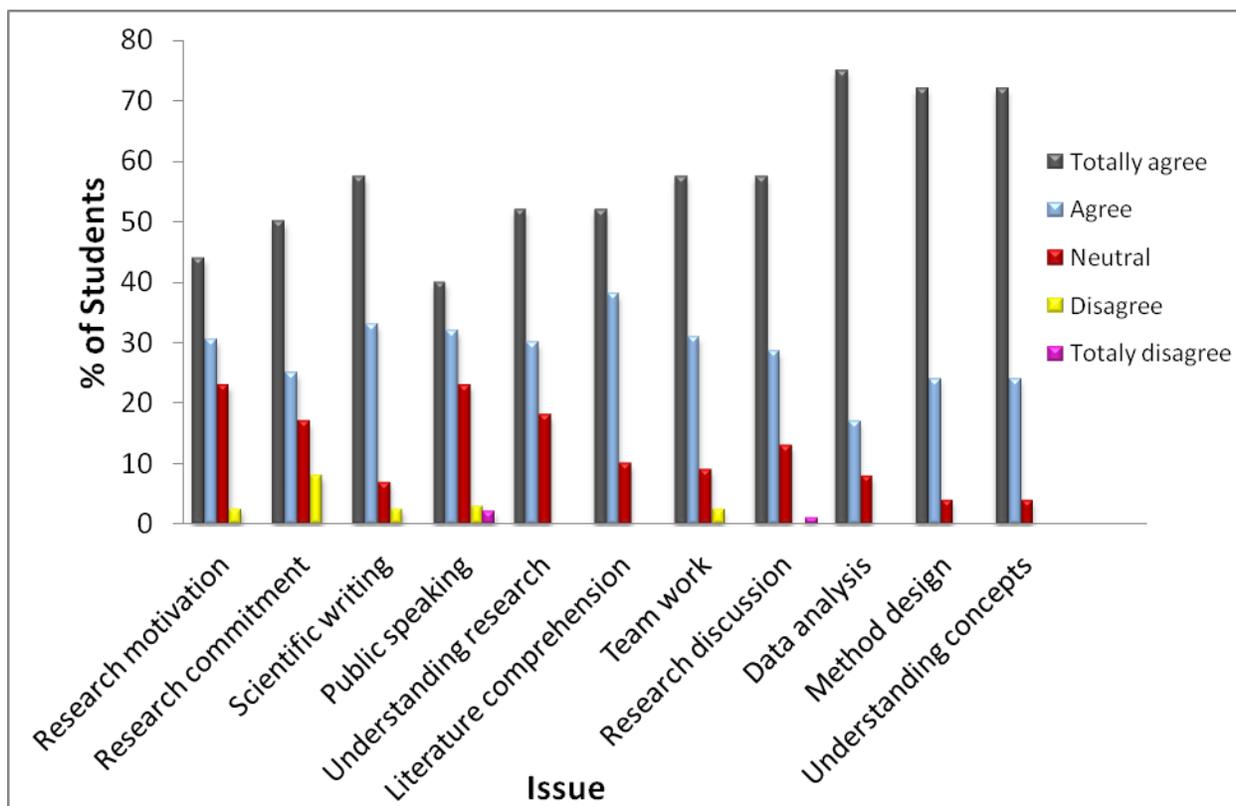


Figure 1. Results of the Student Evaluation of the Research Experiences

It was noticed through student comments and answers to the questionnaire that the experience provided them with the opportunity to learn critical thinking skills, improve their communication skills, develop self-respect and respect for others, change or solidify their views on ethical scientific practices, and acquired improved skills for collaborating within a team. It is important to note that questionnaires were self-reporting instruments and not true indicators of actual proficiency in any specific area. Alternative methods, such as, student grades in oral and written reports, practical exam and team work evaluations were used to determine the learning outcomes of the laboratory experience.

Students were required to prepare different reports during the laboratory course in order to improve their scientific writing, chemistry and data analysis skills. The reports allowed the students to gain experience in writing following the format of a scientific publication. The scores obtained by the students in the written reports were used to assess the impact of the new laboratory set up in the improvement of students’ scientific writing and data analysis skills. Table 3 shows a comparison of the scores obtained by the students in their first and last written report in the experimental and control laboratory sections.

Table 3. Comparison of the Results for the First and Last Written Report for the Experimental and Control Laboratory Sections

Item	Experimental Sections	Control Sections
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	First Report	Last Report	Net Change	First Report	Last Report	Net Change
	Average Score (4pts)	Average Score (4pts)		Average Score (4pts)	Average Score (4pts)	
Title	3.8	3.8	0.0	3.7	3.7	0.0
Abstract	2.5	3.5	1.0	2.5	2.6	0.1
Introduction	2.6	3.7	1.1	2.7	2.9	0.2
Hypothesis Formulation	2.9	3.1	0.2	2.8	2.9	0.1
Materials	3.6	3.8	0.2	3.7	3.7	0.0
Methodology	3.1	3.8	0.7	2.9	2.9	0.0
Tabulated Data	2.9	3.4	0.6	3.1	3.2	0.1
Graphical Analysis	2.4	2.8	0.4	2.5	2.5	0.0
Calculations	2.7	3.3	0.6	2.5	2.5	0.0
Results	2.5	3.4	0.9	2.8	3.0	0.2
Discussion of Results	2.8	3.2	0.4	2.9	3.0	0.1
Conclusion	2.8	3.7	0.9	2.7	2.9	0.2
References	3.6	3.7	0.1	3.7	3.9	0.2
Grammar / Orthography	3.3	3.7	0.4	3.5	3.8	0.3
Average Final Grade %	74 ± 10	87±7	13	75 ± 4	77 ± 3	2

The comparison of the average grades for the first and last written report shows a significant improvement by 13% in the experimental sections. In the control sections there was a lower improvement by 2%. These results validate the data obtained in the student questionnaire; students not only feel more confident with themselves, they actually are achieving better thinking skills and mastering of laboratory skills as demonstrated by their grades. The best improvements were obtained in the redaction of an abstract and introduction, presentation of the results, and formulation of conclusions. Interpretation of the data requires critical thought and quantitative analysis. We noticed an improvement in those skills throughout the laboratory. The nature of the research project allows students to adapt aspects of the final report to their particular interests. The nature of most of the research projects provides the students with the opportunity to better grasp connections among sciences disciplines (e.g. chemistry, biology, mathematics, and environmental science among others). An improvement in the students' ability to connect concepts among discipline was noticed in the discussion of results and formulation of conclusions presented in the final reports.

A comparison of the average scores in the practical examinations and the final grade in the laboratory for the experimental and control sections was performed to evaluate students' improvement in laboratory skills. Table 4 shows the average scores in the practical examination and final percentage obtained by the students in both groups under study.

Table 4. Comparison of Experimental and Control Sections Practical Examination Results and Final Laboratory Scores.

Group	Average Practical Examination Result (%)	Average Final Laboratory Score (140pts)	Average Final Grade (%)
Experimental	85± 15	115 ± 26	82
Control	70 ± 25	108 ± 23	77

The comparison of the experimental and control sections showed that the higher impact was observed in the practical skills gained by the students. The average scores obtained in the practical examinations reveal that students in the experimental sections achieve a better performance in their practical laboratory skills. In terms of the final scores obtained in the whole laboratory the difference between both groups' scores was less drastic, although the experimental section also showed higher scores in that parameter.

Students also experienced working as part of a team in which they depended on and communicated with each other. The research project provides them with the opportunity to assume a leadership role within their group and to develop self-respect and respect for others. We introduced a peer- and self-evaluation process as a summative assessment at the end of the laboratory course (Table 5). The results of these evaluations indicated that the majority of the groups worked properly and most of the students were full and equal contributors to the research project. However, the results of the evaluation also indicated that some groups experienced problems in which an individual or two failed to contribute equitably to the execution of the project. In the future we will use the peer- and self-evaluation as a formative process at the middle point of the semester to identify and intervene with students who are not full contributors. In summary, the peer- and self-evaluations indicated that the students valued the cooperative environment that characterized the project.

Table 5. Average Results of Peer-evaluation

Categories	Average Score (10 points each)
Student Role	8.9± 0.5
Subject Knowledge	8.0 ± 0.4

Work Quality	8.3 ± 0.4
Contribution	9.1 ± 0.4
Group Integration	7.2 ± 0.2
Attendance	8.9 ± 0.3
Punctuality	8.8 ± 0.5
Responsibility	9.0 ± 0.3
Social Skills	8.8 ± 0.2
Criticism Attitude	9.0 ± 0.2
Communication Attitude	9.4 ± 0.3
Motivation	9.1 ± 0.4
Total Score Average (120 points)	105

When comparing the research project laboratory experience with others during the semester, students rated it as the better and a more complete experience. They felt that they are part of and responsible for their learning process. They also felt independence to follow lines of inquiry as needed and believe that this type of laboratory experience helped them to acquire a better mastering of laboratory skills. The students preferred the new laboratory design, they expressed that not knowing the expected results was more like being a authentic scientist, and valued the opportunity to repeat tests. A majority of participants described the experience as challenging and demanding by having the responsibility of being in charge, rather than simply following instructions. Some suggestions for improvement from the students included having more interactions between groups and provide more time to perform the project.

Ten teaching assistants and professors, that previously taught the laboratory in the traditional way and also taught the experimental section during our research, answered a short questionnaire about the impact of the research project on the teaching and learning process (Table 6). The results of the questionnaire, evidence that instructors favor the new research experience. They considered that bigger impact of the research project is the improvement of students' learning of practical skills and mastering of laboratory techniques. Almost all the instructors mentioned that the research experience is an excellent teaching strategy that generated a challenge in terms of preparation and time.

Table 6. Impact of the Research Project on Student Skills as Judged by Professors and Teaching Assistants on a 1 (Minimum) to 10 (Maximum) Scale.

Question	Average score (10 pts maximum)
1. Does the research project improve the teaching and learning of	
<i>Practical skills and mastering of laboratory techniques</i>	10.0
<i>Chemical concepts</i>	8.0
<i>Literature searching and comprehension</i>	9.0
<i>Scientific method</i>	9.5
<i>Experimental design</i>	8.5
<i>Analytical and data interpretation skills</i>	8.5
<i>Formulation of conclusions based on the data</i>	8.0
<i>Communicating scientific information</i>	9.0
<i>Scientific writing</i>	9.0
2. Do you prefer the research project over traditional experience?	8.0
<i>Motivation to do undergraduate research and interest in STEM careers</i>	9.0
<i>Student learning of the science process</i>	8.5

Conclusions

The results revealed that the new laboratory experiences and teaching strategies helped the students to better understand the chemical concepts involved in the laboratory course. In addition, the students presented better perception and mastering of technical skills, data analysis, and interpretation. It also seems that the laboratory experience increased the interest of the students in research. The research experience allowed the students to practice "higher order thinking skills". The specific objectives of our curricular revision, to teach the basic techniques used in the chemistry laboratory and to use these techniques in the research project in a cooperative learning group environment, were accomplished. The laboratory design, which includes a research experience, emphasizes the process associated with scientific discovery and ensures student engagement by offering ownership of the project. Furthermore, students learn to communicate scientific data effectively through both written and oral presentations. This laboratory experience allowed us to improve the learning of chemistry by STEM students through the combination of active and cooperative learning. It was found that this experience was preferred by students and instructors and improved the teaching and learning environment as revealed by the offered questionnaires.

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