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Impact of Guided-Inquiry-Based Instruction with a Writing and Reflection Emphasis on Chemistry Students' Critical Thinking Abilities

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S Supporting Information

ABSTRACT: The Science Writing Heuristic (SWH) laboratory instruction approach has been used successfully over a decade to engage students in laboratory activities. SWH-based instruction emphasizes knowledge construction through individual writing and reflection, and collaborative learning as a group. In the SWH approach, writing is a core component of learning. Previous studies on the SWH approach have reported effective implementation of the SWH approach leads to an improvement in overall student academic performance and content knowledge. Using a rubric developed by Maria Oliver-Hoyo, we compared the critical thinking (CT) skills of students across three groups, based on their written laboratory reports for various traits of CT, and the cognitive skills embedded in the rubric. Participants in this study were first-year general chemistry students who received traditional laboratory instruction, first-year general chemistry students who were instructed using the SWH approach, and fourth-year chemistry students who received traditional laboratory instruction. First-year students and fourth-year chemistry students who received traditional laboratory instruction scored statistically significantly lower on various CT traits, suggesting the SWH-based laboratory instruction is valuable in promoting CT thinking skills of students.

KEYWORDS: *First-Year Undergraduate/General, Chemical Education Research, Problem Solving/Decision Making, Inquiry-Based/Discovery Learning, Learning Theories, Student-Centered Learning*

FEATURE: Chemical Education Research

■ INTRODUCTION

An important goal of inquiry-based instruction is to foster the critical thinking skills of students as well as promote an understanding of scientific concepts and principles.[1−3] Critical thinking (CT) is defined as an "*intellectually disciplined process of actively and skillfully conceptualizing, applying, analyzing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication, as a guide to belief and action. In its exemplary form, it is based on universal intellectual values that transcend subject matter divisions: clarity, accuracy, precision, consistency, relevance, sound evidence, good reasons, depth, breadth, and fairness*".[4,5] While the goal of encouraging CT is embedded in instructional materials and, in particular, in classroom materials geared toward providing inquiry-based instruction, it is an ongoing challenge for instructors to assess CT abilities of students using traditional assessments such as multiple-choice exams.[6] In a laboratory environment, discussions among students and the instructor can provide an opportunity to foster CT skills. Therefore, we set out to investigate whether an inquiry-based laboratory approach known as the Science Writing Heuristic (SWH) promotes CT skills in students.

■ LITERATURE REVIEW

Educational opportunities at any age or grade level should foster the development of the critical capacities of learners.[7,8] A literature review of CT revealed an emphasis on the evaluation and assessment of CT skills integrated in a specific course focusing on the learning/teaching strategies used in the classroom. For example, Caramel and Yezierski[9] assessed pre- and post-CT skills of nonscience chemistry students using Lawson's Classroom Test of Scientific Reasoning (LCTSR). The LCTSR data was further supplemented with qualitative interviews of students to explore reasoning patterns measured by Lawson's test. Their findings indicate a modest improvement in students' critical thinking after completing the course. On the basis of their findings, Caramel and Yezierski suggested use of more student-centered classroom teaching practices to promote CT.

A variety of approaches have been used to uncover whether CT skills are promoted in the classroom or not based upon pedagogical approaches. For example, Moll and Allen[10] incorporated teaching of CT strategies using video clips in an introductory biology course. In another study, Terry[11] developed a rubric using articles from popular science press in conjunction with a case study instructional approach and showed the effectiveness of using relevant science articles for formative assessment of student CT skills. Noblitt et al.[12] reported that students' CT improved with the use of a case study teaching approach. In a study on various teaching methods designed to promote CT, in-class mini investigations through questions, robust multiple-choice assessments, review quizzes, and cooperative learning played an important role in advancing thinking skills of students.

Table 1. Difference between Traditional Laboratory Instruction and the SWH Approach[24]

Segment of the Lab-Class Session	Traditional Laboratory	SWH-Based Laboratory Instruction
Prelaboratory session	a. Teacher-centered: TA/instructor gives step-by-step directions and asks for questions related to verification of procedure.	a. Student-centered lab: Students write beginning questions (BQs) on chalkboard.
		b. Together the class discusses which BQs to investigate.
		c. Students talk about what data needs to be collected and how to divide the tasks among groups.
		d. Students prepare a class data table on the chalkboard and an Excel spreadsheet on the computer.
Students perform experimental work	a. Students follow the procedure outlined in the laboratory manual or by the TA/instructor.	a. Students perform laboratory work necessary to answer their own questions.
	b. Students remain at their own experimental station and talk mainly with their partner (unless they ask a question of the TA or instructor).	b. Students talk with their other group members and with other groups to compare and discuss their findings.
Data Collection	a. Lab partners check with one another to be certain that both have all the experimental data and then leave after completion of data and observations.	a. Each group enters data in the class data table on the chalkboard and in the Excel database.
		b. Groups, who have finished their part, move around the laboratory to check with other groups to determine whether other groups need help in completing their task(s) or with calculations.
Discussion	Students may ask questions of their partners or of the instructor and then leave the laboratory.	As soon as more than half of the data has been entered in the table, students begin to look for trends to answer their BQs. If data are inconsistent with an apparent trend, students may repeat their work.
		a. When all the data are on the board, students critically evaluate the information.
		b. Students work together to negotiate the meaning, construct a concept, and answer BQs.
		c. Students write and discuss an appropriate claim and provide supporting evidence.
		d. A short discussion of topics for reflection on the overall experimental investigation, errors, and applications may also occur.

Statkiewicz and Allen[13] evaluated the effectiveness of CT-based problems introduced in a general biology course. Skills developed by students while solving CT-based problems were transferrable to other science-based courses. In a longitudinal study, the use of new strategies for critical thinking required students to pose and answer their own questions during final course exams. Using the California Critical Thinking Skills Test (CCTST) and a mixed-methods research approach, Quitadimo et al.[14] examined factors influencing CT skills of students enrolled simultaneously in a biology and a chemistry course. Quitadimo et al. concluded that nonmajor chemistry students had better critical thinking skills as compared to students in the biology class, and a background in high school physics was an important factor leading to better CT skills for chemistry students.

Open-ended surveys have also been used by researchers to assess the critical thinking skills of a diverse group of students, ranging from undergraduate students to postdoctoral researchers in the sciences.[15] The surveys were used to score the CT skills of participants in terms of their ability to address the complexity of conflicting information. The results revealed a relationship between CT skills and academic level.

Researchers have emphasized the importance of writing for promoting CT skills. For example, VanOrden[16,17] stressed the importance of writing assignments for promoting critical thinking and conceptual understanding in chemistry. Kogut[18] suggests that the analysis of student work is a rich source for insight into student thought process and consequently may reveal CT skills of students. There is empirical research published on the evaluation of various traits of critical thinking of students based on the writing component of their laboratory work. Oliver-Hoyo[19] studied critical thinking skills of students based on the evaluation of 18 written reports. In another study, Kim et al.[20] studied change in the CT levels of undergraduate general science students as demonstrated in their individual reports. On the basis of their study Kim et al.[20] reported the use of active learning strategies in classroom increased CT skills of students.

THE SCIENCE WRITING HEURISTIC AND CRITICAL THINKING

Compelling evidence from the literature indicates using an inquiry-based instructional approach in the laboratory promotes CT skills by providing opportunities to develop, discuss, debate, reflect and refine their ideas. Studies involving the Science Writing Heuristic (SWH) approach have shown a positive impact on students' academic performance.[21−23] Instructional elements within the SWH approach have the potential to promote CT skills. The SWH is an inquiry-based instructional approach serving two purposes: as a format for students to write their laboratory reports and as an instructional technique to guide the flow of activities during laboratory activities.[24−28] The predominant role of writing in this approach is to enable students to reflect on their laboratory investigations and to effectively articulate their understanding of scientific concepts and scientific reasoning by encouraging students to pose questions, make claims and provide evidence to support their claims.[28]

To provide evidence on whether the SWH approach promotes CT skills in students, a rubric developed by Oliver-Hoyo[19] was used to assess students' CT skills as found in written laboratory reports. This Oliver-Hoyo Rubric for Critical Thinking incorporates cognitive traits that define critical thinking skills and will be referred to throughout this manuscript with the acronym OHRCT. The OHRCT evaluates specific components of written reports such as the abstract, sources of information used by students, relevance of ideas, content of the report, and clarity of presentation. Each

Table 2. A Brief Summary of the Context of the Study, the Courses, and the Participants

Parameters	Characteristics of the Study Groups for Comparison		
Groups in the Study	CHEM 177 L, $N = 10$	CHEM 167 L, $N = 10$	CHEM 401 L, $N = 10$
Chemistry Class	General Chemistry I	General Chemistry	Advanced Inorganic Chemistry
Student Standing	First-Year	First-Year	Fourth-Year
Majors	Science and Chemical Engineering majors	Engineering majors	Chemistry and Biochemistry majors
Method of Instruction	SWH based-1 TA per lab section meeting. One lab meeting per week for a duration of 3 h	Traditional-1 TA per lab section meeting. One lab meeting per week for a duration of 3 h	Traditional-2 TAs and an instructor per lab meeting. One lab meeting per week for a duration of 4 h
Student Group Size	Students worked in small groups of 3−4 students per group	Students worked in a pair	Students worked individually

component is related to various cognitive skills outlined in Bloom's taxonomy.[29,30] For example, the "analyzing" level is based on the cognitive ability of students to design experiments, examine data, question results, and test hypotheses. The "evaluating" level requires the use of various sources of information and to argue, defend, and judge. According to the OHRCT, each cognitive trait has prescriptive levels associated with scores using a scale of 1 to 3, with 1 being lowest and 3 being the highest level of CT. The OHRCT was slightly modified to evaluate the traditional and guided-inquiry based SWH laboratory reports (Appendix 1-OHRCT in the Supporting Information). Intellectual standards of clarity, accuracy, precision, consistency, relevance, reasoning, fairness and depth and breadth of argument are rooted in the various traits measured by the OHRCT.[19]

■ STUDY

Since writing is an essential component of the SWH approach, we chose to evaluate written laboratory reports of chemistry students at opposite ends of the academic spectrum because critical thinking skills should improve as a result of continued exposure of students to increasing difficulty of course material. There were three groups of students in this study: two groups of first-year or freshmen chemistry students and one group of students enrolled in the fourth-year or senior-level inorganic laboratory. The first group received traditional instruction during the first year of general chemistry. The second group of students received guided-inquiry based instruction involving the SWH approach during a first-year general chemistry course. The third group included fourth-year chemistry students in a traditional advanced chemistry laboratory course. The key differences between the traditional and the SWH approaches are summarized in Table 1.

The sample of students in this study consisted of different chemistry students at different levels of coursework studying similar content in a laboratory setting. OHRCT scores, based on the analysis of written laboratory reports across the three groups, were used to assess various traits of critical thinking skills. This is a limitation of the study. We analyzed the laboratory reports based on content themes incorporating the same fundamental concepts treated at the first year and fourth year of chemistry. These included basic synthesis, calculating percent yield, stoichiometry, and heat transfer. It is important to note the objective of this study is not to compare content knowledge, as it is unfair to compare the chemistry knowledge of fourth-year students to students in the first-year level. In this exploratory study, our aim is to rate the critical thinking skills of first-year and fourth-year chemistry students, and compare related CT skills scores in order to infer whether differences in the instructional approaches practiced in the laboratory (traditional versus SWH) are reflected in the OHRCT scores.

From the two chemistry courses incorporating traditional laboratory instruction, one course (Chemistry 167L) consisted of first-year engineering students while the other (Chemistry 401L) was an advanced inorganic chemistry laboratory course for fourth-year chemistry and biochemistry majors. The laboratory course in which the SWH approach was used (Chemistry 177L), was comprised primarily of first-year general chemistry students, who were science and chemical engineering majors. The advanced Chemistry 401L course had an enrollment of 11 students, the general chemistry course Chemistry167L had 158 students, and the general chemistry course for science and chemical engineering majors (Chemistry 177L) had 562 students who completed the course. Table 2 provides a brief overview of the three chemistry courses from which the written report samples were drawn.

For specific details on the differences in the SWH laboratory report format and traditional report format, please refer to Appendix 2 in the Supporting Information.

■ RESEARCH QUESTION(S) AND METHODS

On the basis of the literature review about CT, and the potential of the SWH approach to promote such skills, the following research questions were posed for this study:

1. What is the relationship between the instructional approach used in the laboratory and the change in OHRCT scores over the period of study?
2. Is there a difference among the OHRCT mean rank scores for the three different groups under study?

This study was considered quasi-experimental[31] due to its empirical nature, its aim at finding whether the SWH can be considered an effective intervention, and preselection (not by chance) of students into each of the sections. Students who participated in this study signed up for a course of study during a given semester based on their program structure. In general, all the laboratory students in Chemistry 177L received SWH-based instruction, and the students in chemistry 167L and 401L laboratory courses received traditional laboratory instruction.

Data Collection and Analysis

The data collected from this study were primarily student-written laboratory reports. Three laboratory activities were scored per student for each of the three chemistry courses (167L, 177L and 401L). In addition, the first laboratory activity in each course was analyzed and considered to be the baseline for each course.

For scoring the reports, the raters looked at specific components of the traditional and SWH-based laboratory

Table 3. Group Total Score Distributions of Critical Thinking Traits for Three Successive Student Laboratory Reports during the Semester

		Score Distribution of Critical Thinking Traits					
Parameters	Lab Report No.	Abstract/ Synthesis	Sources of Information/ Knowledge and Evaluation	Organization/ Analysis	Relevance/Knowledge and Application	Content/ Comprehension	Presentation/ Evaluation
177L-SWH	1	10	15	16	15	18	18
First-Year Students	2	17	22	23	22	23	21
	3	20	20	23	23	26	19
(N = 10)	**Mean**	15.66	19.00	20.66	20.66	22.33	19.33
167L-Trad.	1	14	13	13	13	10	11
First-Year Students	2	16	13	15	12	12	13
	3	14	14	13	16	14	12
(N = 10)	**Mean**	14.66	13.33	13.66	13.66	12.00	12.00
401L-Trad. Fourth-Year Students	1	16	16	14	13	14	14
	2	19	14	14	12	13	12
	3	11	13	14	16	12	11
(N = 10)	**Mean**	15.33	14.33	14.00	13.66	13.00	12.33

reports with respect to the rubric and discussed in detail the various components of the rubric for each of the CT traits to ascertain the scoring criteria. For example, the SWH report format has a title and beginning questions as the first two components and traditional written reports have a title and a purpose. The expectation for both report formats was the title of the experiment should be clearly stated. Further, the beginning question in the case of an SWH report should clearly articulate the actual question being pursued by the student. In the case of a traditional report, the purpose should be clearly stated. Following this discussion, copies were made of three selected laboratory reports (for each participant from the three groups) and coded to remove all identifiers. These codes were generated as random numbers using an Excel spreadsheet for students in each of the three groups. The written reports were then typed into a rich text document and scored for cognitive traits using the OHRCT. A total of 90 blind-coded student laboratory reports were scored. Examples of OHRCT lab-report scoring are provided in Appendix 3 in the Supporting Information.

To establish inter-rater reliability, two independent raters were trained to use the OHRCT[19] and then coded 18 out of the total 90 reports (20%) selected for the study. Each independent rater was assigned six laboratory reports per group. Ratings for various traits of critical thinking were found to be in 98.8% agreement between the two independent raters. One of the independent raters scored the remainder of the 72 reports. The scores were then entered in SPSS software to run nonparametric tests. Due to a small number of participants per group in this study (N = 10), we used nonparametric statistical methods of comparison among groups.[32,33]

RESULTS

To establish the equivalence of the three student groups in this study, the Kruskal–Wallis test[32] was used. A baseline comparison of the laboratory report scores among the three student groups (167L students, traditional instruction, N = 10; 177L students, inquiry-based SWH instruction, N = 10; and 401L students, traditional instruction, N = 10) showed no statistically significant differences among the mean rankings ($H_{(2)} = 1.031$, $p = 0.597$ at $\alpha = 0.05$) for their first report of the semester.

As discussed, using the OHRCT, a student can achieve a maximum score of 3 and a minimum score of 1 for any one of the six traits of critical thinking. The maximum value for each trait for 10 students per group is 30 points (10 students in each group with 3 points per trait). Table 3 summarizes the group total score distributions for the six traits in the OHRCT. The results indicate the 177L students in the SWH group scored higher on each trait of the OHRCT as compared to both general chemistry and advanced students (167L and 401L) who experienced a traditional instructional format.

A summary of the change in total OHRCT scores for each group by instructional approach used is provided in Figure 1. A

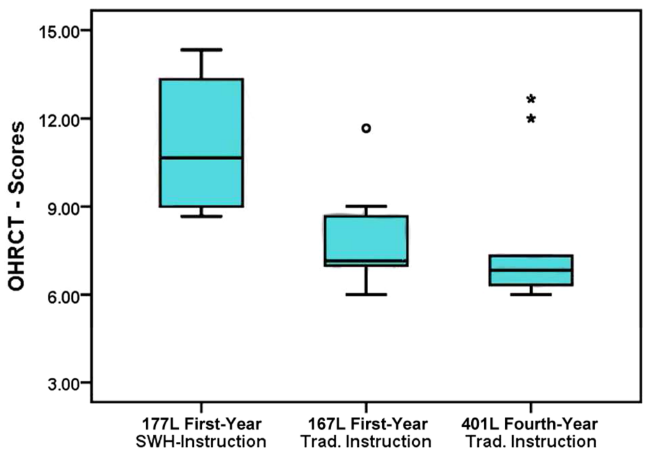

Figure 1. Distribution of OHRCT scores by group. Boxes are bounded by first and third quartiles and banded at the median. Whiskers in the box-plot indicate the maximum and minimum scores for each group's data set. The open circles indicate outliers. The asterisks indicate statistically significant differences among the groups.

box plot for OHRCT scores for the 3 groups included in this study illustrates a wide distribution of scores across the three groups and shows the median OHRCT score for two of the three groups is close to 50%.

A Kruskal–Wallis test[32] was performed to compare the three groups of students on the median change in the total OHRCT scores. On correcting the test for tied ranks, statistically significant differences were found, χ^2 (2, N = 30) = 11.59, p = 0.003; η^2 = 0.40) among the three groups. There appears to be a fairly strong relationship between the instructional approach used and the OHRCT scores as indicated by the effect size of 0.40. Mann−Whitney U tests[32] were conducted for post-hoc pairwise comparisons among the three groups, while controlling for Type I error using Bonferroni's method.[32] The results indicated statistically significant differences for the total OHRCT scores between the 177L first-year students who received SWH based laboratory instruction, and both the 167L first-year students and 401L fourth-year students who received traditional laboratory instruction (see Table 4). There was no statistically significant difference between the first-year 167L and fourth-year 401L students (both of which received traditional instruction).

Table 4. Chi-Square Values for Pairwise Mann−Whitney U Test Comparisons

Parameters, $N = 30$	Chi-Square Values		
Pairwise Comparisons	χ^2	df	p-value
167L First-Year Trad. and 401L Fourth-Year Trad.	0.701	1	0.402
167L First-Year Trad. and 177L First-Year SWH	7.430	1	0.006
177L First-Year SWH and 401L Fourth-Year Trad.	9.450	1	0.002

A two-way contingency table analysis was also performed, relating the instructional approach used. The two-way contingency analysis showed statistically significant differences, χ^2 (2, N = 30) = 15.20, p = 0.001. Follow-up tests were conducted to evaluate the pairwise differences among the three groups using Bonferroni's method to control for Type I error. On the basis of the tests, two of the three pairwise comparisons of groups were statistically significant: the difference between the 167L first-year students who received traditional instruction and 177L first-year students who received SWH-based instruction, and the difference between the 401L fourth-year students who received traditional instruction and 177L first-year students who received SWH-based instruction. This dichotomized response to the instructional approach variable indicates a strong relationship between the instructional approach used in the laboratory and the OHRCT scores. The Cramer's V and p-values for the pairwise comparisons are summarized in Table 5.

Table 5. Cramer's V Values for Correlation between OHRCT Group Total Score and the Instructional Approach Used in Each Group

Parameters, $N = 30$	Correlation between OHRCT Group Total Score and Instructional Approach Used in Each Group	
Pairwise comparisons	Cramer's V	p-value
167L First-Year Trad. and 401L Fourth-Year Trad.	0.115	0.606
167L First-Year Trad. and 177L First-Year SWH	0.816	0.000
177L First-Year SWH and 401L Fourth-Year Trad.	0.734	0.001

■ DISCUSSIONS AND CONCLUSIONS

The results obtained for the 30 students in this study who were exposed to either a guided-inquiry based SWH laboratory instruction approach or a traditional laboratory approach showed statistically significant differences on the scores for various traits of CT in the student laboratory reports as evaluated using the OHRCT rubric. These results suggest that students who experience guided-inquiry based SWH instruction show an improvement in their use of CT in their written component of the laboratory. No statistically significant differences were found on comparing the students at different levels (first-year and fourth-year) who were exposed to a traditional laboratory instruction. The mean group scores on six different traits of critical thinking are very much similar in the case of 167L first-year chemistry students, and 401L chemistry fourth-year students who received traditional instruction (Table 3).

Students instructed using the SWH approach obtained a statistically significantly higher mean score for cognitive traits of knowledge, organization, comprehension, and evaluation. The difference in student mean scores on different traits of CT can be attributed to the difference in the laboratory report formats. For example, the SWH format requires students to prepare in advance a prelaboratory component consisting of three categories, namely, the beginning questions, a safety summary, and a procedure outline. This demands students read the activity, think through it, and develop a tentative action plan.[34] Equally important for the preparation of the laboratory report of the activity was the "reading and reflection" section, which was completed by the students individually outside the laboratory. This SWH component required metacognitive reflection on the part of students about the laboratory activity and their findings, making connections between the activity and topics being studied during class, as well as any real world application of the concepts and skills learned while performing the experiment. In addition, students in the SWH-based laboratories answered postlaboratory questions addressing findings and evidentiary data as well as application of the concepts explored during the laboratory.

Another aspect to be considered with respect to the differences between the traditional and SWH approach was the emphasis on collaborative working groups in the SWH-based laboratories. Students were required to work in collaborative groups (3−4 students per group) using the SWH approach, while in the traditional sections, students worked individually or only with their lab partners. The 167L students worked with laboratory partners, and the fourth-year students worked individually. In addition, SWH groups worked with their entire class during a laboratory activity.[35] At the beginning of each laboratory session, as a group, students shared their beginning questions, safety concerns, and procedure outline. The entire class was involved in refining the questions and planning for replication of the experiment. During the laboratory, students shared their data with the entire class on the chalkboard as well as using an Excel spreadsheet. This particular step helped students compare their data and observations, observe trends, and identify any anomalies present in their data, especially in the case of groups who replicated experiments.

This study was limited in sample size and number of laboratory reports analyzed. For further quantitative studies of the SWH format used as an intervention, a larger sample size is suggested. In addition, instruments such as the Test of Logical Thinking (TOLT) may be used to correlate the findings across samples. An additional recommendation is to conduct in-depth qualitative analysis of student reports, in particular focusing on the sections that promote discussion, such as the evidence and analysis sections.

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When properly implemented by an instructor and a group of students, inquiry-based laboratory instruction attempts to promote students' critical thinking skills. Students conduct laboratory activities in teams, generate and analyze data as a class, and negotiate their understanding of a concept as a group.[36] From a social constructivist standpoint,[37−40] critical thinking develops in students through interactions with the teacher and among students. Writing and interaction with peers have been shown to promote critical thinking.[41−45] From the Unified Learning Model, critical thinking involves identifying or creating pattern matches, the search for new sensory input, provided by data generated in laboratory experiments, and restructuring and transforming sensory input into different understanding of a process or content.[46] All of these elements are present in the SWH laboratory format. By pooling class data, graphing the data, having a group discussion about what patterns are present, and writing about how the laboratory data answers the beginning questions, students using the SWH approach are engaged in critical thinking.[43,47]

This study is useful in providing insight into student CT abilities through student written work. An important implication of this study is to emphasize scientific writing and reflection. Both are essential skills for learning and communicating science. It should be worthwhile to provide opportunities for students to acquire and practice CT skills during laboratory sessions starting from first year to advanced level undergraduate chemistry courses.[48,49]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

A table describing a modified Oliver-Hoyo Rubric for Critical Thinking (OHRCT) used for the evaluation of students' written laboratory reports is provided in Appendix 1. A table describing a comparison of the traditional laboratory report format and the Science Writing Heuristic (SWH) based laboratory report format is provided in Appendix 2. A table describing sample scoring criteria for attaining levels of the OHRCT rubric for individual SWH and traditional laboratory reports with examples of student work is provided in Appendix 3. This material is available via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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