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Extending Students' Practice of Metacognitive Regulation Skills with the Science Writing Heuristic

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Extending Students' Practice of Metacognitive Regulation Skills with the Science Writing Heuristic

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Metacognition can be described as an internal conversation that seeks to answer the questions, 'how much do I really know about what I am learning' and, 'how am I monitoring what I am learning?' Metacognitive regulation skills are critical to meaningful learning because they facilitate the abilities to recognize the times when one's current level of understanding is insufficient and to identify the needs for closing the gap in understanding. This research explored how using the Science Writing Heuristic (SWH) as an instructional approach in a laboratory classroom affected students' practice of metacognitive skills while solving open-ended laboratory problems. Within our qualitative research design, results demonstrate that students in the SWH environment, compared to non-SWH students, used metacognitive strategies to a different degree and to a different depth when solving open-ended laboratory problems. As students engaged in higher levels of metacognitive regulation, peer collaboration became a prominent path for supporting the use of metacognitive strategies. Students claimed that the structure of the SWH weekly laboratory experiments improved their ability to solve open-ended lab problems. Results from this study suggest that using instruction that encourages practice of metacognitive strategies can improve students' use of these strategies.

Keywords: *Metacognitive Regulation Skills; Science Writing Heuristic; Qualitative Analysis*

Introduction

Several studies describe that people with greater use of metacognition have significantly improved learning and understanding of content because they are more able to recognize gaps in their knowledge and can better plan and monitor skill development during the learning process (Kuhn, 2000; Mathabathe & Potgieter, 2014; Rickey &

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Stacy, 2000; Schraw, Crippen, & Hartley, 2006). Recently, the Discipline-Based Education Research (DBER) report from the National Research Council (US) (2012) emphasized that metacognitive strategies should be incorporated into the teaching of Science, Technology, Engineering and Mathematics (STEM) disciplines because these strategies are essential for greater learning of science concepts and skills. Determining what types of instruction can support the use of metacognitive strategies and how such instruction actually affects students' use of these strategies is needed in order to further inform discipline-based education.

Metacognition

Metacognition is the knowledge of and ability to understand and to self-monitor the cognitive strategies used while learning (Flavell, 1979; Schraw & Dennison, 1994). In general, metacognition consists of two components: knowledge of cognition and regulation of cognition (Brown, 1987; Georghiades, 2004). Knowledge of cognition (metacognitive knowledge) has three components: (1) declarative, which is knowledge about oneself; (2) procedural, which is knowledge about how to perform a task and (3) conditional knowledge, which is knowledge about when and why to select strategies to perform a task (Schraw & Moshman, 1995). An example that requires conditional knowledge is students working to solve an open-ended lab problem. They might recognize that in order to properly analyze data, they should use graphs because the data on absorbance and concentration of a solution show a directly proportional relationship.

The second branch of metacognitive thought and the focus of this research is the regulation of cognition (metacognitive skillfulness). It is a skill set of planning, monitoring and evaluating of cognitive strategies that allow students to control and monitor their learning to complete a task. Planning is the step in which students think about how they will accomplish a task, what relevant previous knowledge they may have and what gaps in their knowledge may exist (Brown, 1987). Students' abilities to plan may affect their performance on a task. For example, when preparing to run an experiment, a student who does not consider the goals of the experiment or techniques used in lab may not acquire enough data to adequately identify an unknown chemical provided to them. When monitoring, students self-assess their knowledge about the task as well as the strategies they use to perform the task. In running a lab, for example, students may ask themselves questions and compare results with a partner to ensure that their data make sense. Finally, evaluating is the step in which students reflect on the strategies and goals they used to complete the task and whether they could have used different strategies to better complete the task. An example of this step is students' reflections on their procedure for completing an experiment. They might think about what they learned and how they could improve their procedure to take more accurate and precise data.

Metacognitive knowledge and skills are innate in humans; however, they do not fully form inherently. As children, metacognitive processes do increase naturally to a degree, such as knowledge about one's memory abilities (Garner & Alexander, 1989).

However, when moving into adolescence, people will develop further metacognition only if it becomes necessary to do so. For example, adolescent students may be able to perform a task using certain cognitive strategies such as asking questions about a problem in order to learn more information. However, they may lack the ability to monitor that they are actually learning the new information, unless the learning environment requires in some way that they do so. Research supports that as students enter adolescence, they need to be taught how to recognize their memory capabilities and how to monitor their learning to become better problem solvers (Veenman, Elshout, & Meijer, 1997). Often students are not explicitly taught these strategies, which means that they may not recognize these processes even exist. Teaching students that they can know about and regulate their learning by providing an environment that encourages them to do so can be helpful in moving students from thinking like novices to thinking more like experts (Sternberg, 1998). Experts exhibit high levels of metacognitive knowledge and skill use when compared to novices because they have well-organized mental frameworks that recognize when their current level of understanding is insufficient and what they need to do to close that gap in understanding. Through metacognition, experts are also better able to transfer skills and knowledge to new learning situations (National Research Council (US), 2000). The development of metacognitive strategies by learners is essential to their learning because it leads to greater independence and self-regulation of learning, which in turn builds a foundation for efficient and lifelong learning (Veenman, Kok, & Blöte, 2005).

Supporting Metacognitive Skill Use in the General Chemistry Laboratory

Several studies have identified that chemistry students lack metacognitive use and awareness in laboratory classrooms (Georghiades, 2004; Haidar & Al Naqabi, 2008; Rickey & Stacy, 2000). However, other studies show that providing an environment in which metacognitive strategy use is supported improves metacognitive strategy use and awareness in students (Case, Gunstone, & Lewis, 2001; Kipnis & Hofstein, 2008; Sandi-Urena, Cooper, & Stevens, 2011, 2012; White & Frederiksen, 1998). These studies have identified characteristics of instruction that support metacognitive skill use. They include (1) reflective prompting, (2) a supportive social environment and (3) inquiry-based approaches to instruction.

Lin (2001) provides two frameworks for promoting metacognitive skill use in students: strategy training and the social environment. Through strategy training, reflective prompting by the teacher and the structuring of lab activity are common ways to encourage students to self-assess their knowledge and learning. Students can monitor and integrate knowledge more effectively with properly timed and directed prompts (Davis, 2003; Davis & Linn, 2000). Students who are provided with prompts that identify and discuss metacognitive strategies in relationship to their learning might help them better understand why they are using the strategies (Bielaczyc, Pirolli, & Brown, 1995). In the second framework, a social environment where students feel that they can acknowledge what they do not know, have a useful role to their peers and personally reflect on their work helps to support metacognitive skill use (Lin, 2001). Research supports that students in these types of environments demonstrate stronger content knowledge (Hein, 2012) and better problem-solving skills (Ge & Land, 2003; Sandi-Urena et al., 2012) than students in passive learning environments. In addition to the use of reflective prompting, Sandi-Urena et al. (2011) found that the instructional interventions that included peer interactions improved metacognitive awareness and, in turn, improved problem-solving ability and conceptual understanding. In labs that were instructed using the Science Writing Heuristic (SWH) (Rudd, Greenbowe, Hand, & Legg, 2001), an inquiry-based instructional approach, students had the opportunity to collaborate to share knowledge and to use skills to better understand the content. Proper implementation of SWH labs by the instructor has shown significant improvement in students' chemical knowledge understanding (Akkus, Gunel, & Hand, 2007; Greenbowe, Rudd, & Hand, 2007; Kingir, Geban, & Gunel, 2012). In collaborative learning situations, students take part in processes that are socially constructed including the use of cognitive and metacognitive strategies. While developing individually as a chemistry learner, students may be able to internalize the metacognitive strategies they used with their peers in order to strengthen their own learning process (Kuhn, 2000).

Several chemistry education studies support that inquiry-based instruction improves metacognitive skills use (Haidar & Al Naqabi, 2008; Kipnis & Hofstein, 2008; Rickey & Stacy, 2000; Sandi-Urena et al., 2011, 2012). Inquiry labs engage students more than 'verification' style labs, and students demonstrate greater conceptual understanding of subject matter and improved scientific reasoning abilities in inquiry-based learning environments (Hofstein & Lunetta, 2004; Rudd et al., 2001). In inquiry-based pedagogies, students use skills such as observing, predicting, collecting and analyzing data, and formulating conclusions to learn a new concept (Leonard & Penick, 2009). By using such skills, students are likely to use metacognitive processes because they have to plan, monitor and evaluate their skills to make sure that they draw sound conclusions from the data. Inquiry labs provide a strong base for teaching metacognitive strategies because of their structure (Kipnis & Hofstein, 2008) and the guidance by the instructor, who assists students in using metacognitive strategies by asking questions as well as by guiding and promoting peer interactions.

These results emphasize the importance of metacognition for learning chemistry concepts. It is proposed that if teachers want their students to better understand chemistry, it is necessary to teach them metacognitive strategies (Rickey & Stacy, 2000). Several instructional strategies in the chemistry laboratory—the SWH, the Model-Observe-Reflect-Explain (MORE) framework and Argument Driven Inquiry—claim to promote metacognitive strategy use (Hand, Hohenshell, & Prain, 2004; Tien, Teichert, & Rickey, 2007; Walker, Sampson, & Zimmerman, 2011). Further research may elucidate whether these methods of instruction in the lab provide environments for students to practice metacognitive regulation strategies. There is research to support that students use metacognitive strategies in cooperative and inquiry labs (Kipnis & Hofstein, 2008; Sandi-Urena et al., 2012). We explored the types of regulation strategies that students used to solve open-ended problems and how they described their strategy use when engaged in a collaborative, inquiry-based and reflective environment. The SWH is described in detail below because it was the instructional strategy examined in this study with respect to students' use of metacognitive strategies during their laboratory experience.

The SWH as the Environment to Scaffold Metacognitive Skills Use

The SWH provides a supportive environment for promoting metacognitive strategy use because the inquiry-based approach is constructed on a set of questions that prompt thinking in a collaborative, student-centered environment (Akkus et al., 2007). The structure prompts students at each step with questions about what knowledge is necessary to perform the lab, how they will perform the lab and what they learned from the lab (Akkus et al., 2007; Keys, Hand, Prain, & Collins, 1999; Poock, Burke, Greenbowe, & Hand, 2007). It requires a level of problem solving beyond simply verifying concepts by asking students to work together to determine the best path to get good data and to argue how the data collected in lab support the claim(s) they make (Burke, Greenbowe, & Hand, 2006). Through the steps of the SWH, students are encouraged to use metacognitive strategies. The students begin the lab by asking a question that will help them to focus on a goal for the lab. In order to prepare a beginning question and procedure for the lab, they must plan and consider the goals of the lab, as well as the time and resources necessary to complete the experiment. If students do not prepare well before lab, there is an opportunity during the pre-lab class discussion for students to consider strategies and goals with their peers before the experiment begins to plan parts of the procedure.

The SWH structure also supports students' monitoring strategies during data collection and observation because of the consistent questions asked throughout the lab procedure in order to encourage students to review and compare their data with others as the experiment is performed. This step is followed by a post-lab discussion of the data, its trends, patterns and errors. In the post-lab discussion, there is an opportunity for students again to monitor their comprehension of the data and also to evaluate how well they performed the lab. Through writing a lab report structured on the SWH prompts, students are again encouraged to assess their knowledge as they are prompted to write claims that can be supported by data (Keys et al., 1999). The final section of the report prompts students to reflect on and evaluate how they did the experiment as well as what they learned during the experiment that relates to other science content outside the laboratory. The SWH supports opportunities for students to use metacognitive skills through the inquiry nature of lab, the supportive social environment and consistent reflection prompts during lab and report writing. The SWH provides reinforcement of metacognitive strategy use in each experiment which supports the repetition necessary for students to build heuristics into their learning processes as experts do (National Research Council (US), 2000).

Research Questions

How does the process by which students solve and report on open-ended laboratory problems reveal their use of metacognitive regulation strategies?

How does the type of laboratory instructional environment (SWH vs. traditional) that students regularly experience elicit differences in their use of metacognitive regulation strategies while solving open-ended laboratory problems?

Method[1]

Participants

Students who were declared chemistry majors from a second semester general chemistry course at a private, research active university took part in the study. A total of 62 students participated. Thirty-five students received a traditional laboratory experience (Spring 2012) and 27 students received instruction with the SWH (Spring 2013).

Instructional Environment

In the Spring of 2012, students in the comparison group experienced a traditional instructional strategy in their weekly laboratory meetings. Students were provided with a published laboratory manual of experiments (Nelson, Kemp, & Stoltzfus, 2011) with step-by-step procedures. They filled out report sheets in their lab manuals with the data obtained from lab and answered pre- and post-laboratory questions with a lab partner. In this laboratory format, students followed a preset procedure to verify a concept or outcome that they learned in lecture.

In the Spring of 2013, students were instructed using the SWH (Burke & Greenbowe, 2012). Each weekly lab session began with a student discussion about testable questions to be investigated during the experiment. The teaching assistants (TAs) guided the discussion with prompts when students were not sure how to proceed with beginning questions or procedures. After reviewing necessary protocols, students worked in groups of 3–4 and as a whole class to determine how the data would be collected. They ran their experiments. TAs monitored student progress by asking guiding questions when needed and encouraging peer discussion about the data being collected. The lab ended with a student-led and TA guided discussion to compare data results and discuss trends or patterns evident in the data. Each student wrote a lab report using the SWH format (Table 1).

Use of Open-ended Laboratory Problems

Open-ended problems require students to determine their own questions and procedures with the results left open-ended to the student but known to the teacher (Domin, 1999). Open-ended problems require greater use of metacognitive skills as compared to completion of a structured problem (or traditional experiment) (Jonassen, 1997; Shin, Jonassen, & McGee, 2003). Students in both groups performed the same five open-ended laboratory problems in order to establish events in common between the two weekly instructional environments every few weeks during the

Table 1. Comparison of traditional report format to SWH template

Traditional report format	SWH report and lab template
Title, purpose	Beginning questions: What are my questions?
Outline of procedure	Tests—What do I do?
Data and observations	Observations—What can I see?
Discussion	Claims—What can I claim?
	Evidence—How do I know?
Balanced equations, calculations and graphs	Reflections—How do my ideas compare with other ideas? How have my ideas changed?

Source: Burke et al. (2006).

semester. The week previous to each open-ended lab problem, students conducted an experiment that was designed to provide them with base knowledge and techniques (SWH or traditional). Students conducted their approved self-designed experiment to solve the lab problem and wrote a lab report. Neither group was provided with explicit instruction about collaboration or how to prepare the procedure. TA's were available to answer questions and provide guidance while students planned and conducted their experiments. The problems were based on the American Chemical Society (ACS) small-scale experiments that provided a short prompt for the investigation, such as, 'determine the pKa of an unknown weak acid', as well as a list of suggested materials to be used in the experiment (Silberman, 1994). These open-ended problems provided an opportunity for students to plan, to conduct and to report on an experiment. The students' work in completing these problems was the primary source of our data collection.

Data Collection Strategies and Instruments

Assessments: Three surveys were administered to the participating students before the study. A demographic survey was used to obtain students' gender, year in school and chemistry classes taken in high school. The Group Assessment of Logical Thinking (GALT) (Roadrangka, Yeany, & Padilla, 1983) was given as a pre-assessment to assess logical thinking ability, which has shown correlation with academic achievement in chemistry (Bunce & Hutchinson, 1993). Logical thinking ability was categorized on a scale out of 11 as low (<5), medium (6–8) and high (>9) ability based on previous work (Daubenmire, 2004). The Metacognitive Activities Inventory (MCAI) was administered as a baseline for self-report of habitual metacognitive strategy use during problem solving (Cooper & Sandi-Urena, 2009). The assessments were used to establish that the two group populations were similar at the beginning of the semester. To assess chemistry content knowledge, the ACS First- and Second-Term General Chemistry Paired Questions exams were given at the beginning and end of the course (ACS Exams Institute, 2005, 2007). The ACS exam scores were converted to normed percentiles (ACS Examinations Institute, 2013). Previous research from Greenbowe and Hand (2005) has shown that students who participated in a SWH lab and a lecture course had significantly higher scores on the First -Term ACS exam than non-SWH students at the end of the lecture course.

Interviews: Nine students from the non-SWH group and 10 students from the SWH group were interviewed twice during each 15-week spring semester by the primary researcher. The students were chosen using a stratified, random sampling based on the GALT scores. The interview protocol was semi-structured, which provided structured and open-ended questions and also provided opportunities for the interviewer to ask for clarification or further information (Herrington & Daubenmire, 2014). Interview questions were built around the constructs of metacognitive regulation strategies and learning perceptions. The main goal of the interviews was to have students explain the steps and strategies they used to plan, conduct and report on their open-ended lab problem. In addition to students' descriptions of how they solved open-ended lab problems, the protocols allowed students to describe their experience in lab, their perceptions of their learning, and reflections on how their strategies for problem solving changed throughout the semester. The first interview was four weeks into the semester, after students had performed two weekly labs and two open-ended lab problems. Students were asked about how they learned in lab as well as the steps and strategies they used to perform the lab problems and write the lab reports. The second interview occurred one to two weeks before the end of the semester. These interviews focused on how students perceived their progress over the semester as well as how conducting the open-ended experiments and how their weekly lab experiments helped them learn. Students in both groups were asked the same interview questions. Interviews ranged from 15 minutes to 1 hour and averaged about 30–35 minutes. The interview protocol can be found in supplemental information.

Qualitative Data Analysis

Basic qualitative research protocols (Merriam, 2009) were used to study the phenomenon of students' use of metacognitive regulation strategies. Interview transcripts were analyzed using a process of qualitative coding that was inductive and comparative (Merriam, 2009). The qualitative analysis program NVivo 9.2 (QSR International Pty Ltd., 2013) was used in all analyses. Important phrases, themes and patterns were initially parsed from one or two transcripts and identified as categories through open coding. These initial categories were coded as instances in which students described using skills (Table 2) that were consistent with planning, monitoring and evaluating (Schraw & Moshman, 1995). An example of this process is as follows:

> And then I had my research I did at home, I told you that I looked up stuff of how does this react with that, and why does it happen, and everything. So I kind of had an idea [about how to run the experiment].

In the first round of coding, this statement was coded as planning. As more transcripts were coded, it became apparent that students described actions consistent with several types of metacognitive skills in each category of planning, monitoring

Table 2. Coding scheme for metacognitive regulation strategy use individually and with peers in student interviews

Code (listed under phase in lab problem)	General metacognitive strategy code	Operational definition of metacognitive regulation strategies (Schraw & Dennison, 1994)
Plan experiment (before lab)		
Draws on previous knowledge and experience	Plan	Allocate resources prior to learning/ procedural knowledge
Researches information while planning experiment	Plan	Allocate resources prior to learning
Plans lab problems procedure	Plan	Mentally prepares for conducting lab procedure, reads, organizes plan for lab and notebook set up, information management strategies
Conduct experiment (during lab)		
Monitors for knowledge to check understanding	Monitor	Comprehension monitoring
Monitors for execution of procedure	Monitor	Comprehension monitoring
Makes error correction during experiment	Monitor	Debugging (error detection) strategies
Compare data results	Monitor	Comprehension monitoring/debugging strategies
Data analysis (during and after lab)		
Data analysis—planning	Plan	
Data analysis—monitoring	Monitor	
Data analysis—evaluation	Evaluate	
Evaluate experiment (after lab)		
Evaluate strategies used in experiment	Evaluate	Considers all options to solve problem, reflects on whether goals were accomplished and reflects on better/easier way to solve problem
Evaluates own thinking process through writing	Evaluate	Through writing, reflects on whether goals were accomplished, reflects on better/easier way to solve problem

and evaluation. The phrase was later recoded as 'researches information while planning experiment' as a more defined code within planning. Because of these data and following prior studies in this area (Brown, 1987; Meijer, Veenman, & van Hout-Wolters, 2006; Schraw & Dennison, 1994), further codes within each regulation category were identified. Additional examples include monitors for knowledge to check understanding and monitors for execution of procedure under the general category of monitoring (Table 2). All transcripts including initial transcripts were coded with the detailed categories. The codes were then grouped into four phases that occurred while students solved the open-ended lab experiment: plan the experiment, conduct the experiment, perform the data analysis and evaluate the experiment. The phases helped not only to define the process that students used to solve the open-ended problems, but also helped to separate the metacognitive skills students might be using in the laboratory during the experiment from those used during report writing about the experiment. As coding into the second round continued, it became apparent that there was a difference in how students described their metacognitive strategy use by themselves or with their peers. Students' use of peer interactions to support their metacognitive skills use was coded separately to compare to their individual use of these skills.

Students' perception of how the weekly labs (SWH or traditional) scaffolded their solving of the open-ended laboratory problems was another theme that emerged from the coding process. Statements in which students discussed the characteristics of their weekly instructional environment (SWH or traditional) and related them to solving their open-ended problems were coded as can be seen from Table 3. Students generally described the ways that their weekly lab environment helped or hindered their ability to solve their open-ended lab problems. Many of these statements described students' metacognitive regulation strategies. For example, SWH students often stated that the SWH labs helped them to ask questions while they performed the open-ended problems. An example statement is as follows: 'SWH gets you thinking more about the actual lab, of what happened, so it asks you more engaging questions in the rubric'. This instance was coded as 'makes me ask guiding questions and describes a characteristic of the weekly lab environment that is metacognitive.

In order to describe students' experience in the lab, phrases that compared their current lab experience to previous lab experiences as well as how weekly labs compared to solving open-ended problems were coded. These codes provided a richer description of metacognitive use in the instructional setting.

Each transcript went through an iterative consensus coding process and was coded by at least two coders. When the two researchers were not in agreement about a code or category, the data from that category were reviewed together until both researchers reached agreement on the labeling of the data (Creswell, 2009). In the 38 interviews, coding was performed until no more instances of metacognitive skills and themes were found in the data. Theses iterations of coding led to the saturation of the codes

Table 3. Coding scheme for characteristics of instructional environment (SWH or traditional) and their relationship to students' metacognitive strategy use

Code	General metacognitive strategy code	Operational definition of metacognitive regulation strategy (Schraw & Dennison, 1994)
Makes me ask guiding questions	Plan/monitor/evaluate	Information management strategies
Structures my thinking process	Plan/monitor/evaluate	Information management strategies
Provides structure for conducting and writing my lab problem	Plan/monitor/evaluate	Information management strategies

(Creswell, 2009). The constant comparison method was used to ensure that the categories matched the data in all documents. If codes did not match data in all documents, then re-coding of previous data occurred (Merriam, 2009). The frequency of codes by group (SWH vs. non-SWH) was calculated to compare individual use of strategies and peer use of strategies. This provided a way to compare metacognitive strategy use in the two instructional environments (Miles & Huberman, 1994).

Results

Baseline Results

Pre-study assessments, the GALT and MCAI, were analyzed using two one-sided *t*-tests (Lewis & Lewis, 2005) to test for equivalency between groups. Results in Table 4 show that students in both SWH and non-SWH groups entering the study were equivalent on scores for the GALT and MCAI.

Content Knowledge Results

Students were also given the First- and Second-Term General Chemistry Paired Questions ACS exams at the beginning and end of each spring semester. Again, the groups were found to be equivalent on both measures as seen in Table 5.

However, both groups significantly increased in ACS score from the First Term to Second Term exams as determined by a mixed model Analysis of Variance (ANOVA), Wilk's $x = .723$, $F(1{,}60) = 22.98$, $p = .001$. A *post hoc* ANOVA showed that both groups significantly increased their ACS score: SWH—Wilk's $x = .727$, $F(1{,}26) = 9.77$, $p = .004$, $d = 0.6$ and non-SWH—Wilk's $x = .714$, $F(1{,}34) = 13.61$, $p = .001$, $d = .62$. The lack of difference between groups on the ACS exam scores may be because of two phenomena: (1) lab experiences, including the use of SWH, develop skills and content that are not measured by these ACS content exams or (2) content knowledge gains (or losses) that could be measured by these exams are delayed and did not take effect in the time frame of either portion of this study.

Table 4. Results of the equivalence tests for the baseline assessments

Assessment	$X_{\text{non-SWH}}$ ($N =$ 35)	X_{SWH} ($N =$ 27)	Interval	t_1[c]	t_2[c]	Results
Pre-GALT score	.813	.761	(−.163, .163)	4.34	2.91	Equivalent
Pre-MCAI score	.796	.820	(−.159, .159)	8.99	7.65	Equivalent

Notes: N (non-SWH) is 34 for pre-MCAI score; the critical value for these scores is $t_\alpha\, 0.10 = 1.29$. Mean values are shown as decimals not percentages. The interval was calculated by multiplying the average by 0.2.

Table 5. Comparison of SWH and non-SWH students on content knowledge ACS scores

Assessment	$X_{\text{non-SWH}}$ (N = 35)	X_{SWH} (N = 27)	Interval	t_1	t_2	Results
ACS First-Term exam	.640	.688	(−.128, .128)	2.36	1.43	Equivalent
ACS Second-Term exam	.776	.824	(−.155, .155)	2.48	1.67	Equivalent

Notes: The critical value for these scores is t_a 0.10 = 1.29. Mean scores are shown as decimals not percentages. The interval was calculated by multiplying the average by 0.2.

Similar use of Individually Applied Metacognitive Strategies Between Groups Revealed Through Their Process of Solving Open-Ended Problems

Students in each group were interviewed about their experiences of learning in the laboratory setting. The interviews not only identified when students used metacognitive strategies while solving open-ended problems, but also how they used these regulation strategies to complete their experiments and how the two groups compared in their metacognitive strategy use. When asked what steps and strategies they used to conduct the experiments, students in both groups consistently began that they always did some planning before they performed their experiment for the lab problem. This planning phase occurred prior to or during the first half hour of the lab. The amount of time for planning generally depended whether students felt they had a procedure prepared that would accomplish their goal. Olivia, a student in the non-SWH group, responded to the question, ‘How much time do you set aside to prepare for lab?’ with:

> If we get a lab problem, I’ll sit there, and I’ll do research for an hour or two. I’ll just go on the internet and see what I can find, like, flip through my book, read those sections, so I have a really thorough understanding of what is even going on. Like, what I’m even looking for before I can even set up an experiment.

Students interviewed described very specifically the steps they took to prepare for the lab. At a minimum, they read the lab problem prompt before arriving in lab. Like Olivia, this suggests that most students used planning regulation strategies which included thinking of several ways to solve the problem, choosing the best one and asking themselves questions about the lab before it began. When asked how they conducted their experiment, students, unlike in the planning stage, spent little time describing their actual process or steps for completing the lab. Students sometimes explained how they asked themselves questions in order to monitor their knowledge or their execution of the procedure. Lydia, from the SWH group, when asked, ‘How are you learning in lab?’ said:

> So even if I get stuck, I know, like, I can look through it in my head, that this is what we did like the rates [of reaction] problems. It [the lab problem] was like the rates lab, which was the same week as the lecture lab. So that helps.

Not only does Lydia stop to check her comprehension, but she also relates it back to previous knowledge in order to find relationships in the data and the lab procedure. Another area in which students regulated themselves was through monitoring strategies in which they recognized errors that occurred and corrected them while performing the experiment. Some students returned to planning if they recognized that they were not performing the experiment well enough to obtain useful data. Henry, an SWH student, said when asked, 'How did you approach this specific lab problem?':

> I thought I was gonna be using the well plates, but that was a little, a lot, way too small of a thing to actually see anything. And so I went with test tubes and then test tube holders, so I would have, um, half of it in one test tube, half of it in other, and right by each other.

This indicates that he likely used a monitoring strategy; one that resulted in a change to his current procedure because he realized that would not produce useful data with it. Monitoring while performing the lab was not as commonly described as planning procedures were, yet students in both groups provided evidence that they using monitoring strategies while running the experiment by themselves.

In terms of data analysis, when asked, 'What were the steps you took to write up your report?' Lydia (SWH group), explained how she had identified each of the five unknown powders in solving the lab problem:

> I'm the type of person that matches things up, like, if they are spread out. So I, like, spread my data tables out ... And I read through the book and then, like, I started with baking soda. And then I'll, like, write down the qualities and the characteristics of baking soda. And then I'll go through my data and see which ones match up. And then I'll be, like, okay, so this could be a possible baking soda. And then I'll do it for each of the Alka Seltzer, chalk, vitamin c ...

Lydia used planning and monitoring strategies during data analysis. For example, she used planning when she mentions that she looked up information in her book to figure how to analyze the different powders. She used monitoring skills to match up her experimental data with the information she found in the book. Overall, during interviews, SWH students brought up data analysis more often and more clearly described how they analyzed their data than non-SWH students.

Evaluation was not always present in students' description of problem solving but emerged frequently enough to be included as a distinct phase. Students evaluated their experience in two ways. The most common way was a reflection on their experience across the semester. Students were also reflective in the open-ended lab problem process when they evaluated the strategies they had used to complete their experiment for the lab problem. When asked, 'Have your problem solving strategies changed over the semester?' Liam, from the non-SWH group, shared that:

> For the last lab, I walked out of there, and I figured out the fastest way to do it in my head at least. And I was just like, oh, I could have done it like this. And I could have finished the whole entire thing in an hour.

Being reflective on the strategies that they used to complete the experiment suggests that they were aware of how they performed the procedure and what they could have

Table 6. Comparison of individual and peer use of metacognitive strategies while solving open-ended lab problems

Phase of lab problem	Specific metacognitive regulation strategy	Students reporting use of strategy individually: Non-SWH group ($N = 9$) (%)	Students reporting use of strategy individually: SWH group ($N = 10$) (%)	Students reporting use of strategy with peers: Non-SWH group ($N = 9$) (%)	Students reporting use of strategy with peers: SWH group ($N = 10$) (%)
Plan experiment	Plans lab procedure	89	90	67	80
	Draws on previous knowledge and experience	100	100	0	0
	Researches information for experiment	67	50	0	0
Conduct experiment	Makes error correction during experiment	56	50	44	10
	Monitors to perform procedure	44	40	44	30
	Monitors to check understanding	11	30	56	80
	Compares data results	0	0	22	70
Perform data analysis	Plans during data analysis	44	50	0	20
	Monitors during data analysis	67	90	0	10
	Evaluates during data analysis	22	20	0	10
Evaluate experiment	Evaluates strategies used in experiment	67	60	0	10
	Evaluates thought process through writing	56	70	0	0

done to improve their experimental procedure. This is evidence of the use of an evaluation strategy.

Students in both groups described applying metacognitive regulation strategies individually while solving the lab problems. When students were asked about their individual use of strategies, the groups used planning, monitoring and evaluation strategies to the same degree. These results are displayed in Table 6 in the middle column. Within the use of strategies, students used planning to a greater degree than either monitoring or evaluating while planning, conducting and evaluating their experiment. All the students interviewed in SWH and 80% of non-SWH students described their data analysis phase. Within data analysis, fewer than half the students in both groups mentioned using planning and evaluation strategies. Yet, under monitoring during data analysis, 90% of the SWH students mentioned monitoring themselves, while 67% of non-SWH students used monitoring skills.

Students Experience Differential Use of Peers for Support in Metacognitive Strategies Use

A theme that emerged and differentiated the SWH from the non-SWH group was the use of peers to support metacognitive strategies while solving open-ended laboratory problems. When students were asked about the steps and strategies they used to perform and to report on lab experiments, students acknowledged that feedback from peers helped them gain more confidence to conduct the experiments. At least two-thirds of students in both groups identified the usefulness of peers when planning their experiments (Table 6, right column). The SWH group reported using more peer collaboration when monitoring to check understanding of their lab experiment, comparing their data results and conducting data analysis when compared with the non-SWH group. The phase in which students from either group did not describe using peers was evaluating their experiment. Only one SWH student described using peers to evaluate the strategies they used to solve their open-ended lab problem.

Table 6 shows that over half of the interviewed students in both groups used peers to plan lab procedures and check how to perform procedures. Sam, from the non-SWH group, used peer collaboration for planning a lab problem when asked, 'What in the lab helps you learn?' said:

> Someone to bounce ideas and things off of . . . and really, we all sort of looked at [the lab problem] and were, like, we don't know what we're going to do and then we talked and sort of came up with some ideas just through talking. And I feel like that was probably the most valuable way of doing [planning].

Sam used the planning strategy to think of several ways to solve a problem and chose the best one with his peers. Other students worked with peers to ask questions about the lab before it began. While students conducted their open-ended experiments, they used monitoring strategies with their peers that included checking their understanding of the procedure and the chemistry content of the lab. Abby, an SWH student, used her peers to ensure that she performed her experiment correctly:

> Well, I feel it helps me a little because I'm obviously talking to another person and then there is, like, they have ideas that I don't have or I have ideas maybe that they didn't think of. So we can, like, work things out like that. Also, it helps, maybe by myself, I can't get something done, so I can ask them, hey, I need your help to do this.

Students in the SWH lab collaborated with their peers to a greater degree to monitor themselves and to check their understanding of the chemistry concepts while performing the lab. SWH students continued to use peers to support metacognitive strategies by reviewing with their peers whether or not their data made sense. William, an SWH student, used his peers to compare his data before coming to his final argument: 'It's assuring to be able to, you know, look to colleagues, and be like, hey, did you get this as well?' The data comparison not only helped them check their understanding of the data, but it also helped them check for any errors that may have affected their data. Only about 22% of non-SWH students described any sort of peer comparison of data results during lab, whereas at least 70% of SWH students described comparing data results with peers. This provided students with opportunities to re-run their experiment if their data did not match their peers' data.

As the students moved into the data analysis stage, the frequency of peer use decreased for both groups, but 30% of SWH students still reported using peers during data analysis, whereas non-SWH students did not report using peers. For example, Henry from the SWH group, when asked to describe the steps or strategies, he took to complete his lab report, responded with: 'Then I'll go through my procedure, write that out, and then analyze the data with people. Just to get that extra, like, point of view and seeing how their[data] is affected'. Within this coding scheme, most students used peers as a way to check that they had performed the data analysis correctly and had similar results. It was not apparent whether or not students used peers to evaluate their procedures and strategies used to perform the lab experiment, such as asking questions about whether they had considered all the ways to solve the lab problem. These types of strategies were used, but more individually than with the support of peers.

Students Experience Differential Support from Structure of Weekly Instructional Labs for Metacognitive Skill Use

Additionally, students' responses about metacognitive skill use during open-ended lab problems were affected by their weekly experiences with the instructional format (SWH or non-SWH). This theme provided an additional difference between SWH and non-SWH students' experience of metacognitive skill use. Students were asked in the interview 'How do you think the weekly [SWH or regular] lab experiments prepare you to solve and report on the open-ended lab problems?' The non-SWH and SWH groups did not describe similar experiences when asked whether their weekly instructional labs (non-SWH or SWH) supported them solving the open-ended problems. It became clear from the interviews that the weekly SWH lab experiments provided students with more effective opportunities to transfer metacognitive regulation skills from the weekly labs to the open-ended lab problems than the non-SWH weekly experiments. SWH students described that the lab problems were comparable to their SWH experiments, whereas the non-SWH group found little or no connection between their weekly traditional labs and the open-ended problems. Charles (non-SWH) replied to the above question with:

> I would say it [the weekly experiment] gives me, like, a general direction of where to go with the lab problems. How to start, I guess, and how to approach coming up with a procedure. But other than that I think they're kind of different, so I don't know. I kind of have trouble seeing any direct correlation between them.

Charles found that his weekly lab experience did not support or prompt him to think about how to solve the open-ended problems. Sam, a non-SWH student who had performed open-ended lab problems in high school, found the lab problems easy and thought that the scientific method in general provided structure. He responded to the same interview question with:

> I guess just through all of my, like, chemistry experiences, even high school, there is a set structure that everything is supposed to [go through], you make the procedure and then you make a hypothesis, then you make a procedure, and then you perform it. So, like, that structure is still the expectation in the lab problems. And I mean that's the proven scientific method.

Students in the non-SWH group who may have not have had as much experience with lab problems from prior courses as Sam felt lost while performing the open-ended lab problems. Some cited that they always needed examples to start something. With respect to the open-ended problems compared to the traditional weekly labs, Holly said, 'Yeah, my senses are overloaded, and I don't know where to begin'.

On the other hand, SWH students felt that the weekly SWH labs and the open-ended lab problems were about the same. Sometimes they even cited that the lab problems were easier than the SWH labs. They thought SWH labs provided both writing and thinking frameworks for solving the open-ended lab problems. Answering the question, 'How do the SWH labs help you to prepare for the lab problems?' Sophie, an SWH student, shared that:

> [An SWH lab experiment] helps me to process things and think through things. Like, if I can't deal with certain things. Like, with the phenolphthalein, I just couldn't just put it with the solids. You have to dissolve it with water. It helps me think more, if we do the group discussions or just thinking.

The SWH instructional format provided Sophie with instances in which she described using metacognitive skills, including monitoring her knowledge and correcting for errors that occurred in lab. Forty percent of the SWH students found that the prompting from the SWH made them keep in mind to ask questions while they performed their open-ended lab problems. Lydia, an SWH student, stated, 'In the SWH lab, we were told to ask these questions, to think about these concepts. So, it's like, maybe I should keep that in mind, what concepts are related to this, and what questions I should ask'. This structure of prompting encouraged them not only to ask questions about the lab before they began the experiment as a planning regulation skill, but also to check that they understood what was going on while running the experiment as a monitoring skill.

SWH students also found the actual format for the SWH labs to be useful while performing the lab. The structure of the beginning question, claims with evidence, and reflection provided a base on which they could build their open-ended lab experiments. It appears likely that SWH students were applying the organizational structure, the actual heuristic, from the SWH to their open-ended lab problems. The fact that the SWH prompts for data analysis may provide support for why SWH students described using more regulation skills in solving their lab problems especially the data analysis section (see Table 6). SWH students perceived that the SWH had them think in a more organized way that assisted them when solving the lab problems.

Students in both non-SWH and SWH labs had traditional labs in first semester. This often brought up comparisons between what students experienced in the second semester lab as compared to first semester. Henry, an SWH student, responded to, 'How do you compare what you did this semester with your first semester lab?':

> Not really because a lot of it [first semester lab] was just worksheet-based, and so, they just told us to do this and then you're just supposed to write your observations. Like, I mean you didn't really have to think about anything that much, and this [SWH lab] is more, this is making thinking more like a second nature.

The SWH students made many connections between the structure of the SWH, metacognitive strategy use and how it prepared and guided them to solve open-ended lab problems. Students in the traditional lab did not describe having an instructional environment that supports their metacognitive skill use. They provided little, if any description of transfer of their work in weekly labs to the open-ended lab problems.

Discussion

The intent of the study was to examine students' described use of metacognitive regulation skills while solving open-ended laboratory problems as well as how the environment in which they regularly worked (traditional laboratory instruction vs. SWH laboratory instruction) affected these skills. Interview data revealed key differences between the two groups on their use of metacognitive strategies. These findings confirm and expand earlier research that shows inquiry-based labs provide opportunities for students to use metacognitive skills during laboratory (Kipnis & Hofstein, 2008). This research provides a detailed description of students' use of metacognitive skills while in the lab. The type of weekly instructional environment elicits qualitative differences in the types and degrees of use of these strategies when transferred to solving open-ended problems.

The first distinguishing feature between the two instructional environments is that students in the SWH group described using their peers for regulation activities to a greater degree than the non-SWH group. The finding that students employ peers for metacognitive skill use is supported in other research as well (Sandi-Urena et al., 2011, 2012). This research expands those results and describes the ways in which students used their peers and found variation in peer use with the phases of solving the open-ended lab problems (Table 6). Even though both groups used peers to about the same degree in planning and checking that they were performing the procedure correctly, SWH students used peers to support metacognitive regulation to a greater degree when conducting the experiment by comparing their data during data analysis. This result suggests that students sought out different points of view from peers to support their conducting of the experiment and is supported by Grimberg (2007) in her analysis of students' reflective actions in an SWH environment. By checking with their peers about procedural steps, both non-SWH and SWH students were monitoring their procedures in order to get reliable data for analysis. For the non-SWH students, the use of peer support seems to stop there. They did not use their peers much to foster understanding for why they were doing the experiment. SWH students, on the other hand, used their peers to monitor and to help them understand what was happening in the experiment and how this knowledge might be used for data analysis. The instances in which students compared data with peers while conducting the experiment informed decisions about running more trials and helped them check if they had consistent results. Only SWH students reported using their peers outside instructional time in order to gather another viewpoint on their data as a way to support their data evaluation. Again, the instructional setting may have influenced this decision. SWH students work together to form beginning questions, decide on procedures and compare data results during lab instruction. The non-SWH labs in this study did not explicitly prompt students to work together to plan, monitor or evaluate their experiments. This may explain why students in non-SWH, traditional lab courses use peers less during metacognitive regulation. It is not part of their regular practice to use peers.

The second distinguishing feature between instructional settings was students' described use of how their weekly (SWH or traditional) labs helped them to structure their open-ended lab problems. Overall, SWH students described behaviors that demonstrated that the structure of the SWH scaffolded their use of metacognitive regulation skills when solving open-ended lab problems. It also improved their perception of their ability to actually solve open-ended lab problems. These results are consistent with two other studies on SWH instruction in secondary school age students (Grimberg, 2007; Hohenshell & Hand, 2006). Both studies support that when students, who are prompted by the reflective statements in their SWH labs, demonstrate behaviors consistent with metacognitive awareness and skill use. SWH students tended to describe that their weekly lab instruction was teaching them ways to think: teaching them how to ask themselves questions, how to plan an experiment and how to frame their thinking, which are all metacognitive processes. As a result, students transferred these ways of thinking to their open-ended problems.

Although SWH students did not have higher content knowledge as measured by the post-exam (ACS Second Term), it is clear from the interview results that they had opportunities to practice their regulation strategies which suggests that they may be more aware of their learning processes. Both groups also exhibited the same pattern of statistically significant growth in scores from the First-Term ACS exam to the Second-Term ACS exam. Both groups were instructed with the Process Oriented Guided Inquiry Learning (POGIL) method in the classroom, which has been shown to significantly increase content knowledge scores when compared to lecture (Daubenmire & Bunce, 2008; Straumanis & Simons, 2008). Although SWH had an effect on content knowledge in the Greenbowe and Hand (2005) study, the POGIL method in the lecture course may have overshadowed any detectable differences in this study. Although the ACS exams did not detect a difference in content knowledge between groups, SWH students described opportunities where they learned how to support their learning in lab.

Overall, students in both groups described practicing regulation strategies, specifically planning more than monitoring or evaluation strategies with and without peers. However, SWH students practiced more metacognitive regulation strategies while conducting the experiment and the data analysis in the open-ended problems. Strategies that were predominately used by SWH students included checking understanding of concepts and data comparison during the experiment. This indicated that they likely spent more time making sense of their data. SWH group also performed data analysis with their peers. On the other hand, non-SWH students used many metacognitive strategies individually; however, they found less support through their peers and almost no support for their practice through weekly lab instruction. The SWH students' use of metacognitive regulation strategies during lab time and outside of lab may suggest that they are learning how to better integrate and organize knowledge into their long-term learning structures. It also allowed them to feel more prepared to solve their open-ended lab problems. Non-SWH students described that they enjoyed solving the problems but did not always feel prepared or that they 'felt more lost'. These results are consistent with research that suggests that students in inquiry-based labs perceive that they learn more and enjoy the open-ended problems more than traditional forms of instructional labs (Berg, Bergendahl, Lundberg, & Tibell, 2003). Our research not only provides a lens into students' perceptions of their regulation strategy practices in the laboratory, but it also supports that the way the laboratory environment is arranged affects these regulation strategy practices and their transfer to new situations. By providing an environment with inquiry strategies, effective prompting and productive peer interactions, instruction can strengthen and deepen students' use of metacognitive regulation strategies and their transfer to new situations.

Limitations and Implications

The SWH was implemented for one semester, and research supports that one semester of a new environment may not provide enough support for students to change their learning or skill use in subsequent learning situations (Engelbrecht, Harding, & Du Preez, 2007). Even though students described using metacognitive strategies during this laboratory experience, the data here did not provide a longitudinal view on students' metacognitive skill use as they take other chemistry laboratory courses. The students selected for the study were declared chemistry majors who generally came into the university courses with considerable high school background in chemistry, that is, Advanced Placement or honors high school chemistry. Most participants, though, had no experience in solving open-ended problems and many came with poor high school laboratory experience. The type of students chosen reduces the ability for generalization to other types of students taking chemistry such as non-majors. Yet our study suggests that students of all levels of academic achievement use some degree of metacognitive skills, and students in the SWH group generally used more of those skills. Further research is required to understand if students' enhanced use of metacognitive strategies in SWH-type environments may or may not continue in subsequent laboratory classes, regardless or even in spite of instructional approaches. Since the population only consisted of chemistry majors, it is important to understand how different sets of students, for example, non-majors or students who took less chemistry in high school, would respond in an SWH environment as well.

As the DBER report suggests, there is a need for a better understanding of how to integrate metacognitive strategies into the laboratory setting (National Research Council (US), 2012). Results from this study support that setting up an environment such as the SWH provides opportunities for students to use regulation strategies and to have them supported with peer interactions, prompting and the inquiry-based instructional format. It also shows that these strategies can be transferred to more open-ended laboratory experiments. These results may be useful for instructional purposes to those instructors who are interested in adding metacognitive regulation to their instruction to improve their students' use of regulation strategies and move them to have more expert-like thinking. The SWH is a well-established instructional strategy and can be implemented directly or can provide a template for an instructor to build an instructional environment where metacognitive strategy use is encouraged.

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No potential conflict of interest was reported by the authors.

Note

1. All experimental procedures in this research were approved and complied with protocols for conducting research with human subjects (IRB Approval #2052).

Supplemental data

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