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Developing critical thinking skills using the Science Writing Heuristic in the chemistry laboratory

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The Science Writing Heuristic (SWH) laboratory approach is a teaching and learning tool which combines writing, inquiry, collaboration and reflection, and provides scaffolding for the development of critical thinking skills. In this study, the California Critical Thinking Skills Test (CCTST) was used to measure the critical thinking skills of first year general chemistry students who were instructed using the SWH approach and first year general chemistry students who received traditional (TRAD) laboratory instruction A quasi experimental pretest-posttest design involving the use of matched groups was used to assess differences in critical thinking between the two groups. Students in the SWH group had significantly higher total critical thinking scores over their traditional counterparts. The results indicate that the SWH approach shows efficacy in improving students' critical thinking skills over the traditional approach.

INTRODUCTION

The focus of higher education institutions has traditionally been on the development of theoretical knowledge, but recently there has been a shift towards placing greater priority on the development of transferable skills. This shift in focus may be the effect of educational policy direction, the impact of technological advances, or a direct response to the call for more highly skilled graduates who not only possess job-specific skills, but are also able to respond appropriately to the dynamic and complex nature of today's workplace through the use of a wide range of skills (Andrew & Higson, 2008; Association of American Colleges and Universities [AACU], 2013; Chadha, 2006).

Transferable skills are often also referred to as core skills, soft skills, employability skills, key skills, generic skills and 21st century skills. These skills are crucial to job mastery, regardless of job sector or skill level, (UK Department of Education and Employment, 1997), and include written and oral communication, teamwork, problem-solving, time management, and critical thinking skills, among others. Unlike job-specific skills which are no longer relevant if the individual moves to a completely different job position, transferable skills remain relevant regardless of the field or career. Focusing on transferable skills has important economic consequences, as they affect productivity and employment creation.

Critical thinking is considered among the transferable skills most necessary for successful navigation of our increasingly dynamic and complex world (Halpern, 1998). As societies become more technologically complex and information rich (Halpern, 1998), there is an increasing need for members of the workforce who can analyse information critically and use it creatively and effectively to provide solutions to real world problems, more so than persons able to carry out robotic, mechanical manipulations requiring recall and regurgitation.

Many universities and colleges, including The University of the West Indies (UWI), identify critical thinking as a necessary skill for their graduates (Bok, 2006; Diamond, cited in Sternberg, Roediger & Halpern, 2007; Overton, 2001; Paul, Elder & Bartell, 1997; UWI, 2012); and most higher education faculty cite its development as one of the primary learning objectives of their instruction (AACU, 2005). Employers also identify critical thinking skills as a set of skills that graduates need to be effective in the workplace, but it has been found that a significant percentage of graduates are unprepared for the workforce because they lack these skills (AACU, 2013; Hirose, 1992; Levine, 2005; Quitadamo & Kurtz, 2007; Vance, 2007).

Critical Thinking

Critical thinking is a very popular term with a multiplicity of definitions. In this study, we adopt the definition put forward by the Delphi Report, which is based on consensus of 46 critical thinking experts across disciplines. This panel of experts provided a working definition of critical thinking, describing it as "purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or contextual considerations upon which that judgment is based" (Facione, 1990, p. 2). A more succinct rendering presents it as a process of "purposeful, self-regulatory judgment that drives problem-solving and decision-making" (Quitadamo, Faiola, Johnson & Kurtz, 2008).

Critical thinking comprises both cognitive skills and dispositions. Facione (1990) highlights analysis, inference, evaluation, interpretation, explanation and self-regulation as core cognitive skills. Critical thinking dispositions include truth-seeking, openmindedness, being analytical, orderly, systematic and inquisitive; having good interpersonal skills, and the ability to judge soundness of information. Research has shown that while cognitive skills can be developed in the short and medium terms, changes in dispositions require more long term efforts (Giancarlo & Facione, 2001; Quitadamo, Brahler & Crouch, 2009; Quitadamo & Kurtz, 2007).

Researchers agree that formal instruction in critical thinking is necessary for appreciable development of the skills (Snyder & Snyder, 2008; van Gelder, 2005). There are, however, a range of views about which instructional approaches and strategies

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should be used. Norris and Ennis (1989) put forward four instructional approaches that could be taken to the teaching of critical thinking, namely, the general instruction approach, the infusion approach, the immersion approach and the mixed approach. In the general instructional approach, critical thinking is taught explicitly as a separate course, outside of any particular discipline, while in the infusion approach in-depth instruction within the subject matter is combined with explicit teaching of general critical thinking principles. The immersion approach mirrors the infusion approach except that in the immersion approach the general critical thinking principles are not *explicitly* taught. The mixed approach involves explicit instruction in critical thinking combined with application of the skills in a specific subject matter. This approach has been found to be effective in helping students develop and hone their critical thinking skills (Abrami et al., 2008). Research also indicates that critical thinking ability is enhanced when instructional strategies, such as problem-based activities, collaborative and cooperative learning, modeling, and constructivist techniques, which support and foster other higher order thinking skills, are used (Duplass & Zeidler, 2002; Gurses, Acikyildiz, Dogar & Sozbilir, 2007; Halpern, 1999; Hollingworth & McLoughlin, 2003; Lai, 2011; Wong, 2007; Zoller, 1993). The laboratory space is considered conducive to the use of many of these strategies, and provides fertile ground for critical thinking development (Campbell & Bohn, 2008; Daempfle, 2013; Zoller & Pushkin, 2007).

The Science Writing Heuristic (SWH) is an inquiry-based, writing-to-learn approach which was developed for use in the laboratory by Hand and Keys in 1999. It provides students with an alternative format for carrying out their laboratory activities and for thinking about and writing up their laboratory report. This alternative laboratory report format replaces the five traditional sections of purpose, method, observations, results, and conclusion with prompts eliciting questioning, knowledge claims, evidence, methods, description of data, and reflection on changes to students' thinking (see Table 1). The SWH can also be used as a teaching technique to help the instructor in formatting the flow of activities associated with the experiment. As a teaching technique, it places strong emphasis on guided inquiry, collaborative work, reflection and writing.

Table 1 Comparison of the traditional and SWH Laboratory Report Formats

Traditional (TRAD) Report Format	SWH Student Template
1. Aim	Beginning Questions- What are my beginning questions?
2. Outline of Procedure	Tests and Safety-What will I do? How will I stay safe?
3. Observations	Observations
4. Data, Balanced equations, calculations	Data (including class data)- What trends do I observe
5. No equivalent	Claims- what can I claim?
6. No equivalent	Evidence –How do I know? Why am I making these claims?
7. Discussion and conclusion	Analysis- What does it mean?
8. No equivalent	Reflection- How do my ideas compare with other ideas? How have my ideas changed?

With its emphasis on inquiry, the SWH prompts students to develop their own questions based on a given scenario, devise means of collecting data to answer those questions, interpret the data, make claims, and provide evidence in support of those claims (Rudd, Greenbowe & Hand, 2007). As students develop their questions and claims, they examine underlying assumptions in their ideas, make judgments of the quality of those ideas, and articulate reasons for their judgments, thereby drawing on analysis, evaluation and explanation skills. During the designing of experiments, students use induction, analysis, evaluation and explanation skills in construction, as they draw on their own experiences, the experiences of other, the literature and other sources. In making decisions about what data to collect, students make judgments based on the meaning or significance that they attach to the data, making use of evaluation and analysis skills. Carrying out these activities in a collaborative environment forces students to confront and reflect on their own thinking, and experience cognitive dissonance in a supportive setting. Reflection increases opportunities to form associations among concepts, and to integrate information (Sobral, cited in Mann, Gordon & MacLeod, 2009). As a writing-to-learn approach, the SWH emphasizes the importance of students articulating their understandings in a variety of ways, leading to the construction of richer conceptual understandings, rather than writing to emphasize memory or mastery (Keys, 1999). During writing, students must grapple with concepts and ideas in order to construct a coherent whole, leading to the production of higher quality arguments. During SWH laboratory sessions, students are engaged in dialogic interactions with their peers, as well as with experts (demonstrators and supervisors). These negotiations help to develop and strengthen critical thinking skills as they require higher order mental processing. The generation of beginning questions, which takes place in small groups of students, involves exchange of information and interrogation of ideas to arrive at consensus. Analysis, interpretation, evaluation and explanation skills are needed at this stage. The further narrowing down of the questions to arrive at questions to be addressed by the whole class, under the prompting and guidance of the experts, also require further use of the aforementioned skills. Having generated the data, students seek to identify trends and anomalies, a process requiring strong analysis and interpretation skills. The generation of claims calls upon inferential, analytic and interpretive skills. As students describe the evidence that supports their claims, they must examine their assumptions and reasons, and present a logical explanation of their reasoning. At this juncture, analysis and interpretation, evaluation, and explanation skills are honed. As students write their reflections, they must articulate understandings, draw conclusions, make predictions and suggestions, in a logical and well-reasoned fashion. They therefore draw on inference, explanation, evaluation, deductive and analysis and interpretation skills.

Critical Thinking and the SWH

Research has linked each of the four elements of the SWH (that is, writing, inquiry, collaboration and reflection) to critical thinking. Quitadamo and Kurtz (2007) found that students in a writing group significantly outperformed their non-writing peers in critical thinking. Inquiry approaches to laboratory work, and inquiry approaches in general, have been linked to improvements in students' critical thinking (Hein, 2012; Hofstein & Lunetta, 2004;

Quitadamo, Brahler & Crouch, 2009); while similar results for reflection and collaboration have also been found (Facione, Winterhalter, Kelly, & Morante, 2013; Long, 2010; Osborne, Kriese, Tobey & Johnson, 2009). The SWH approach itself has been linked to critical thinking, although that research is much more limited. Gunel (2008) and Hand (2008) have described the SWH as an approach that scaffolds and builds students' critical thinking and reasoning skills. Fostveldt, McGill, Shelley, Hand and Thierren (2012), in comparing the critical thinking skills of fifth grade students exposed to the SWH with those who were not, found that generally SWH students showed greater improvement in critical thinking ability as measured using the Cornell Critical Thinking Test. They however noted that the effect sizes were small. Gupta (2012) also found that SWH freshmen had higher levels of critical thinking than their traditional counterparts, and that this skill improved as the semester progressed.

Published research using standardized tests to measure the impact of the SWH on critical thinking in chemistry is sparse. In addition, research suggests that students who enter university with poor critical thinking skills may be particularly at risk of not achieving success in their studies (Chaplin, 2007) and may therefore be in need of immediate intervention. It was therefore against this background that this research was undertaken.

This study attempts to reduce the dearth in the literature for empirical research into critical thinking by measuring the impact of the SWH on the critical thinking skills of first year chemistry laboratory students. Specifically, the critical thinking skills of SWH students were compared with those of their counterparts in traditional laboratory sections.

RESEARCH METHODOLOGY

Research Design

A quasi-experimental pretest-posttest design involving the use of matched groups was used to assess differences in critical thinking between SWH and TRAD students. This design was appropriate as intact laboratory groups were used. This quasi-experimental design is however vulnerable to a number of threats to external and internal validity (Shadish, Cook & Campbell, 2002). Efforts to minimize these threats included the use of pre and post tests for SWH and TRAD groups, the use of a highly valid and reliable instrument (the CCTST), and the use of a matched groups design. In addition, repeat performance on the posttest was minimized by the time difference between the pre and posttests, and because neither the students nor the test administrators have access to the correct answers on the CCTST Form 2000. Generalization of the findings of this study is however limited by the fact that the data were collected within a single university.

Participants

The participants were introductory chemistry students (i.e. students in their first year of a 3-year undergraduate degree programme), registered for the laboratory components of two general chemistry courses over the two semesters. Of the students registered for the courses, only those who had received two semesters of instruction using either the SWH or the traditional approach were considered for inclusion in the study. The SWH group comprised 42 students (26 females and 16 males. Forty two (42) students in the traditional group were chosen from an eligible cohort that had received laboratory instructions using the traditional approach, and had taken the CCTST as pre and post tests (N=209), by matching them with counterparts in the SWH group on the basis of their critical thinking pretest scores and gender, so that the two groups were equivalent on their pre-test measure.

Procedure

This study was conducted over 2 semesters (24 weeks) in two introductory level general chemistry courses in a large regional university in the Caribbean. Each course included three 1-hour lectures, two 1-hour tutorial (recitation) sessions, and one 4-hour laboratory session each week. There were 10 laboratory streams which met for 12 weeks each semester. Each student was registered in one laboratory stream in each semester. The SWH approach was implemented in 2 of the 10 streams while the other 8 streams used the traditional approach. The experiments conducted in the SWH and the traditional streams did not differ in course content, objectives or techniques, solely in the approach taken, and all groups carried out their laboratory activities in the same physical space.

Each stream accommodated a maximum of 54 students, supervised by faculty or a senior research student, who was assisted by 3 demonstrators (teaching assistants). Each supervisor/demonstrators team remained with the same laboratory stream for the entire semester. Demonstrators were responsible for assisting students during the course of the laboratory session, as well as for the marking and grading of laboratory reports. Supervisors and demonstrators who worked in SWH streams also worked in the TRAD streams. The authors were also laboratory supervisors.

Informed consent was obtained from all students who participated in the research.

Implementation of the SWH Approach

Students were introduced to the SWH laboratory report template in their first laboratory session. In that session, students were introduced to beginning questions, claims, and evidence through the use of a case-based activity, on which they worked collaboratively. There was also a general discussion to facilitate greater understanding of these concepts. SWH and TRAD students used different laboratory manuals. While both manuals covered the same content, they differed significantly in format. Each experiment in the SWH manual was guided by a scenario or case, and no aim was provided, unlike in the TRAD manual. In many instances the procedure for the experiment was modified to allow for greater inquiry, and the entire experiment was written in a more inquiry-type style.

In the weekly sessions, there was a pre-lab period during which students worked together in small groups of between 4 to 6 to generate their beginning questions based on the scenario provided for each experiment in their laboratory manual. During this stage, demonstrators and supervisors moved among groups, ensuring that activities were proceeding satisfactorily, and asked probing questions where necessary. As a class, students, with guidance from their supervisor, discussed the questions and arrived at consensus on which should be retained,removed, or modified, narrowing down the number of questions to two or three. Students then worked collaboratively in small groups of no more than 6 persons to conduct the experiment and collect the relevant data. Students remained in the same laboratory groups for the duration of the semester; and the experiments were designed so that different groups worked on different aspects of the experiment, and so the data collected differed from group to group. The procedure was provided for most experiments; however students were sometimes required to generate procedures, or to modify procedures provided. On completion of the bench work, students gathered in their groups to work on getting the 'data" to be contributed by their group. This usually involved carrying out some calculations and negotiating meaning. The data from all groups were displayed in a single spreadsheet for students to individually identify trends and anomalies, make claims, provide evidence in support of these claims, and write individual reports using the SWH student template. Significant emphasis was placed on student-directed, inquiry-based activities, collaborative work, writing and reflection.

Format of the traditional laboratory

The TRAD manual set out each experiment in a conventional format providing the title, aims, objectives, some background information, the apparatus and materials to be used, and the procedures to be followed, as well as some questions to be answered at the end of each session.

Each session began with a pre-lab quiz and a laboratory talk given by the supervisor. The lab talk addressed the theory, procedure, and safety issues related to the experiment. After the lab talk, students carried out the outlined procedure at their workstations, individually or sometimes in pairs. As all students carried out the experiment in the same way, the data gathered was expected to be the same for all students. The demonstrators assisted students with setting up their apparatus, and attending primarily to procedural matters. On completion of bench work and data collection, students are usually free to exit the laboratory. If the time allotted for the session had not elapsed when bench work and data collection were complete, students were encouraged to remain at their workstations and complete their individual "fill-in-the-blanks" type worksheet reports which guided them through the data and calculations. Correspondence with peers during this period was usually discouraged. In the TRAD groups little emphasis was placed on student-led, inquiry-based, collaborative activities.

Data Collection

Students' critical thinking skills were assessed using the pencil and paper version of the California Critical Thinking Skills Test, (CCTST). The CCTST Form 2000, which is the most recent version of the test, was administered to the students as pre-post tests. The pretest was administered in the laboratory within the first two weeks of the first semester and the posttest was administered under similar conditions within the last two weeks of the second semester. Students were allowed the standard recommended time within which to do the test which is 45 minutes. This test was chosen because it has the distinction of being the only instrument available that i. measures cognitive and metacognitive skills associated with critical thinking ii. is based on a consensus definition of critical thinking, and iii. has been evaluated for validity and reliability for measuring critical thinking at the college level (Facione, 1990; Facione & Facione, 1992; Facione et al., 2013). These features confirmed the CCTST Form 2000 as the most appropriate choice for measuring critical thinking in this study.

The test consists of 34 non-discipline-specific multiple choice items and provides scores on five subscales, namely analysis and interpretation, evaluation and explanation, inference, deduction, and induction**.** A total critical thinking skills score is also reported. According to Facione et al. (2013), the total critical thinking score describes overall strength in using reasoning to form reflective judgments about what to believe or what to do. To score well overall, the test taker must excel in the core reasoning skills including analysis, interpretation, inference, evaluation, explanation, induction and deduction. The total critical thinking score predicts the capacity for success in educational or workplace settings.

Validity and reliability testing has returned alpha values ranging from 0.70 to 0.84 (Facione, Facione, Blohm & Giancarlo, 2002), which indicates very good reliability (Miller & Salkind, 2002). The test has been used extensively across various disciplines including nursing, engineering and science.

Data Analysis

The data were analyzed using SPSS Statistics 17.0. A paired samples t-test was carried out using the students' overall critical thinking posttest scores to determine whether there was any significant difference between the SWH and TRAD groups on critical thinking. The effect size was calculated using Cohen's d.

Recommended cut scores and percentile rankings were also used in the analysis to more clearly illustrate changes in students' overall critical thinking. Both the recommended cut scores and the percentile rankings were determined based on the CCTST norming sample for 4-year colleges and universities in the United States. Although our university is a 3-year institution outside of the United States, this was the closest data available for comparison, and it is our view that the performance of our students was sufficiently similar to the norming sample to make this comparison valid.

RESULTS

This section reports on the main findings from the statistical analyses. A confidence interval of 95%, which indicates a significance level of 0.05, was used for all analyses. Normality of the pretest scores for each group was evaluated using the Kolmogorov Smirnov Test. Significance values greater than 0.05 led to a rejection of the hypothesis that the scores for both the SWH and TRAD groups did not come from a normal population.

Critical Thinking Pre and Posttest scores

No difference was found between the means of the total critical thinking pretest scores for the TRAD and SWH groups ($M= 12.61$, $SD =3.15$).

Students in the TRAD group had lower mean total critical thinking posttest scores ($M=13.60$, $SD =3.81$) than those in the SWH group ($M=15.90$, $SD =3.93$). The results of the paired samples t-test revealed that the difference was significant ($t= 2.982$, $p=0.005$). The Cohen's d value ($d= 0.59$) signaled that the SWH had a strong effect on students' overall critical thinking.

Critical Thinking Mean Gain scores

Examination of the gain difference between the TRAD and SWH groups revealed that the SWH group had a mean gain of more than 2.5 times that of the TRAD group (Table 2). Facione et al. (2013) note that an "overall gain for the group of two or more points is a strong effect" (p.76). This therefore indicates that the gain obtained by the SWH group would be considered a "strong effect". This analysis is consistent with the calculated effect size, which also indicated that the SWH had a strong effect.

The gains for the groups correspond to a 20 percentile move for the SWH group (from the 22^{nd} to the 42^{nd}), and a 7 percentile move for the TRAD group, from the 22nd to 29th (Figure 1).

Table 2 Means and standard deviations on pretest and posttest for first year TRAD and SWH groups

	CCTST Pretest Mean	Standard Deviation	CCTST Posttest Mean	Standard Deviation	Mean gain
SWH	12.61	3.15	15.90	3.93	3.81
TRAD	12.61	3.15	13.60	3.81	1.50

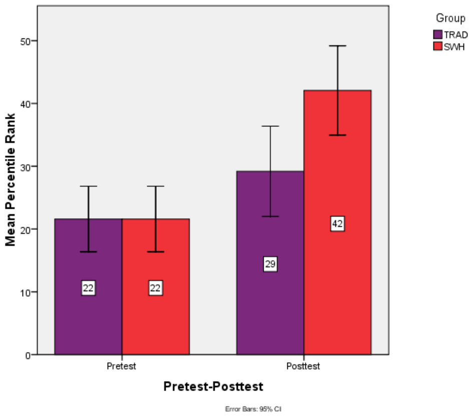

Figure 1. Percentage ranking of SWH and TRAD students using overall CCTST scores

Recommended Critical Thinking cut scores

Table 3 provides recommended cut scores for the interpretation of total critical thinking scores on the CCTST Form 2000 version of the test (Facione et al., 2013).

Table 3 CCTST Overall Score- Recommended Performance Assessment on the Form 2000 version

	Not Manifested	Weak	Moderate	Strong	Superior
34-point Form 2000 version	0-7	8-12	13-18	19-23	>24

Mean pretest and standard deviation scores for students in the SWH and TRAD groups locate their critical thinking abilities between weak and moderate. The posttest mean score and standard deviation, treated similarly, locate SWH students almost "dead centre" of the moderate scale with a range between the higher bound of weak and the lower bound of strong. The posttest results for the TRAD group indicates that the critical thinking ability of the group remains within the moderate category, with a range from the higher bound of weak to the higher bound of moderate.

DISCUSSION AND CONCLUSION

The preceding results indicate that SWH students had improved critical thinking scores over their TRAD counterparts. This finding is consistent with those of Fostveldt et al. (2012) and Gupta (2012) who, in separate studies, found that students using the SWH approach had significantly better critical thinking scores than their counterparts in TRAD streams. The results further indicate that the SWH is efficacious in enhancing critical thinking development, and support the SWH approach as one instructional method for promoting critical thinking development. The efficacy of the SWH approach lies in the combination of the elements of writing, inquiry, collaboration and reflection. Individually, each element has been shown to be linked to critical thinking development (Facione et al., 2013; Hein, 2012; Long, 2010; Osborne et al., 2009; Quitadamo & Kurtz, 2009), and the amalgamation produces a powerful synergy. Given, however, that the individual elements of the SWH were not parsed out in this study, it is not possible to say to what degree *each element* of the SWH may have impacted on critical thinking development. Further studies would be needed to elucidate this.

The results also indicated small increases in critical thinking for TRAD students as well. This finding is consistent with results obtained by Gupta (2012) and Solon (2007), who both reported modest gains in critical thinking for students in traditional classes, and suggest that gains in critical thinking can occur even in the absence of deliberate interventions. One possible explanation for the observed increase in critical thinking scores for students not involved in deliberate interventions could lie in the fact that while critical thinking and academic achievement are not synonymous, the two constructs are closely related and develop synchronously (King, Wood & Mines, 1990). Extending this thinking, it is expected that over two semesters students would have made some gain in academics, and so some corresponding development in their critical thinking would also be expected. While pursuing their academics, students would have engaged in some activities such as writing, collaboration, inquiry and reflection, which have been shown to be positively related to critical thinking (Gaddis & Schoffstall, 2007; Grimberg, 2008; Kieft, Rijlaarsdem & van den Bergh, 2008; Long, 2010; Osborne, Kriese, Tobey & Johnson, 2009; Quitadamo & Kurtz, 2007). Students in the TRAD group engaged, to some extent, in writing and collaboration, but deliberate opportunities to reflect and engage in inquiry were, to the best of our knowledge, limited. During their chemistry laboratory sessions TRAD students did not have as many opportunities to grapple with chemical concepts and ideas, construct coherent arguments, and articulate their understandings, as SWH students did. In TRAD streams, students worked in groups primarily to relieve resource constraints, but this was not a consistent feature of the lab. Therefore, although students "worked together", they did not often work as a team, and so true collaboration which might have promoted argumentation and cognitive dissonance, thereby facilitating an environment for critical thinking development, was limited. These factors could explain the smaller gain in critical thinking obtained by TRAD students compared to their SWH counterparts, who were engaged in deliberate writing, collaboration, inquiry and reflection, as these are core elements of the SWH.

The generally weak pretest scores suggest that some students may be entering university without the requisite level of critical thinking skills that their learning programmes assume. Instructors need to strike a balance between challenging students to think critically with the provision of appropriate scaffolding to help them to do so. Greater focus on critical thinking development during the pre-university years is also needed. This position is consistent with Wagner's (2010) view that schools need to teach critical thinking in order to help students ensure success in college and the workplace.

The results of this study support the position that deliberate efforts aimed at the development of critical thinking, especially efforts incorporating writing, collaboration, inquiry and reflection, are needed, and the skills need to be explicitly taught. Poor decision-making and problem-solving, misuse of resources, and an absence of a sustainable policy direction, are consequences of poor critical thinking too expensive to entertain. If universities are going to produce graduates for the workforce who are critical thinkers, then initiatives that support the development of critical thinking skills at all levels of higher education are necessary now. The SWH is one such initiative.

The results also strongly suggest that carefully designed interventions, such as the SWH, can make the laboratory fertile ground for critical thinking development.

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