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Impact of Peer-Led Team Learning and the Science Writing and Workshop Template on the Critical Thinking Skills of First-Year Chemistry Students

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ABSTRACT: The Peer-Led Team Learning (PLTL) and the Science Writing and Workshop Template (SWWT) are two active learning instructional approaches which combine writing, inquiry, collaboration, and reflection, elements which have been associated with critical thinking development. In this study, we used a quasi-experimental pretest−post-test design to investigate the impact of the implementation of these two approaches on the critical thinking skills of first-year chemistry students, measured using the California Critical Thinking Skills Test (CCTST). The results indicate that implementation of the PLTL and the SWWT instructional strategies led to significantly higher gains in critical thinking.

KEYWORDS: *First-Year Undergraduate/General, Chemical Education Research, Laboratory Instruction, Collaborative/Cooperative Learning, Communication/Writing, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, Constructivism, Student-Centered Learning*

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INTRODUCTION

Globally there is concern that the level of critical thinking (CT) among university graduates is below that required for them to be effective contributors to the workforce. This has led to increased calls from various stakeholders for major reform in higher education.[1−6] An important part of this proposed transformation is a shift toward the incorporation of more student-centered, active learning instructional strategies such as case-based learning, peer instruction and discussion, inquiry-based learning, problem-based learning, and flipped classrooms, among others. Many of these strategies have been associated with positive outcomes such as increased academic achievement, improved enrollment and retention rates, improved attitudes toward the subject matter, increased literacy, and development of better communication and problem-solving skills.[7−15]

Peer-Led Team Learning (PLTL) and the Science Writing and Workshop Template (SWWT) are two student-centered, active learning initiatives which combine, to varying degrees, the elements of writing, inquiry, collaboration, and reflection, which have been associated with CT development.[16−21] While there have been studies exploring the impact of these individual elements on students' CT skills, few have examined the impact of initiatives in which these elements are combined. In an earlier paper, we reported that implementation of the Science Writing Heuristic (SWH), a laboratory approach which combines guided inquiry, collaboration, writing, and reflection, led to significantly higher CT scores for SWH students over their counterparts in the traditional laboratory.[22] Despite our success with the SWH in developing students' CT skills, laboratory sessions provided limited opportunities for students to exercise the CT skills introduced in the lab and to reflect on how they could apply these skills to their learning generally, and to their learning of chemistry outside the laboratory specifically. The SWWT is a modified SWH approach which introduces CT-development-focused workshops into the SWH to provide students with these opportunities. In this paper, we report on the impact of the SWWT and the Peer-Led Team Learning (PLTL) initiatives on students' CT skills.

Despite an abundance of research using active learning pedagogies and their impact on student performance in the chemistry education literature, there is little research that examines the relationship between the use of active learning pedagogies in chemistry and CT development using empirical and standardized measures of CT. Many studies examining the effect of various pedagogies on the development of students' CT skills provide only anecdotal evidence.[23] Few articles that cite CT as an important outcome address the construct in a fulsome way or provide any measures/empirical evidence of CT,[23] and so there is a need for more empirical research into CT.[16,24] Additionally, while critical thinking is listed as an important goal in many course descriptions, few of these courses actually address this goal.[25−27] This paper focuses on measuring students' CT skills before and after participation in the PLTL and SWWT initiatives, providing empirical evidence of the impact of these two active learning pedagogies on their CT skills, using a standardized instrument. We believe that our work provides well-needed empirical evidence about the impact of two active learning pedagogies (PLTL and

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SWWT) on students' CT development and, therefore, narrows the gap for more empirical studies in this area.

Critical Thinking

Critical thinking is recognized as one of the key indicators of the quality of student learning by many college faculty.[16] Despite its popularity however, CT remains a difficult construct to define. In this study, we adopted the consensually agreed, expert definition of CT 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".[28] As the definition indicates, CT is not viewed as a single skill, or a single set of skills, but rather as a composite of a number of higher order cognitive skills, knowledge, and attitudes,[29] including but not limited to analysis, inference, evaluation, explanation, interpretation, inquisitiveness, skepticism, and openmindedness.[28]

Analytical skills allow for the identification of the components of the whole and the relationships among them, while interpretation involves clarifying and determining meaning and significance. Evaluation and explanation skills are used to assess evidence and decisions arrived at, and to describe the rationales for these decisions. Inference skills lead to evidence-based decision-making. In chemistry, students use CT skills in the collection and analysis of data to arrive at justifiable conclusions, making CT an imperative for students of chemistry.[25,26,30−32]

Notwithstanding the constant need for purposeful, reflective, and reasoned judgment and decision-making in everyday life, human beings are not natural critical thinkers, and generally find CT challenging.[33−35] However, cognitive CT skills can be developed over a relatively short period of time with targeted intervention.[16,22,36]

Peer-Led Team Learning (PLTL)

Peer-Led Team Learning (PLTL) is a small group learning model developed by Woodward, Gosser, and Weiner[37] at the City College of New York. It involves the placement of students into small groups (usually between 6 and 8), under the guidance of a peer leader. Peer leaders are students who successfully completed the course, usually in the previous year, and who "have been trained in small group dynamics and learning theory".[36] They are not expected to be content experts or substitute teachers, but they act as mentors, coaches, and facilitators for the workshop groups.[38] The students and their peer leaders meet in weekly, 2 h workshop sessions to solve problems and discuss difficult chemistry concepts.

In PLTL strong focus is placed on collaboration through student−student interactions within groups. The workshop environment, which adopts a seating arrangement that facilitates discussion, is designed to maximize these interactions. A strong inquiry component is also evident, most clearly seen in the problem-solving approach which is encouraged, and the emphasis on respect for "the chain of reasoning". During workshop sessions students engage in working with their peers to seek solutions to problems. They are involved in advancing possible methods of solution, constructing explanations for their solutions, connecting explanations to scientific knowledge, and communicating and justifying their explanations. Students are also encouraged to make explicit their problem-solving processes by writing down their thoughts and ideas, and revising them on the basis of discussions with their peers. Through argumentation and a process of reflection, that is, deliberately revisiting and rethinking conclusions reached based on evidence presented,[39−41] students arrive at consensus which is usually a "changed conceptual perspective" for most, if not all.[42] PLTL therefore strongly incorporates the elements of collaboration, inquiry, and reflection, with a lesser emphasis on writing.

The broad aims of PLTL workshops are to allow students to construct their own knowledge of chemistry by working through gaps in their understanding, and taking responsibility for their own learning. The model is associated with improved student performance, retention, and learning experiences, and has also earned the interest of faculty, peer leaders, and participants themselves.[43−48] Specifically, participants have found PLTL to be socially engaging and intellectually stimulating, as well as a productive use of their time.[47] The model also enhances general communication skills[43] and has been linked to the development of students' CT.[36] "The largest untapped area for future research" related to PLTL has been identified as evaluating its impact on students' development of reasoning and CT skills.[24] This study is a part of the response to this need.

Science Writing and Workshop Template (SWWT)

The Science Writing and Workshop Template (SWWT) is a modified Science Writing Heuristic (SWH) approach which introduces workshop sessions focused on CT development alongside SWH laboratories. The SWH laboratory approach is an active learning strategy developed by Hand and Keys[49] in 1998. It is a model of laboratory instruction that consists of two templates: a student template and an instructor template. The student template provides students with an alternative format for writing up their laboratory report, in which the five traditional sections of purpose, method, observations, results, and conclusion are replaced by prompts eliciting questioning, knowledge claims, evidence, methods, description of data, and observations and reflection on changes to students' thinking. The instructor template is used as a guide to help format the flow of activities associated with the experiment and strongly emphasizes actions that support guided inquiry, collaborative work, and reflection.

The SWH more closely resembles the way scientists operate in the real world than traditional approaches.[50,51] During an SWH laboratory session, students work with their peers to develop researchable questions, design experiments to address the questions, carry out experiments, collect data, make claims, and provide evidence in support of those claims. Students also write a report on their experiment and reflect on their experiences by responding to a set of prompts that lead them to identify assumptions, and suggest or consider alternatives. Students are therefore engaged in collaborative inquiry, writing, reflection, and argumentation, ultimately leading to meaning-making and knowledge construction.

In workshop sessions students work together in small groups, interacting with resources aimed at promoting CT, and solving guided-inquiry-type problems aligned to laboratory and lecture content. As they problem-solve, students are encouraged to write down their responses, and to revisit these on the basis of the ensuing discussion. Through discussion and debate with their peers and workshop facilitator, students reflect on and refine their ideas. The sessions provide a forum where students can air their misconceptions, grapple with difficult concepts, examine their

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Table 1. Study Participants and Their Weekly Activities

Activity	TRAD (N = 53)	PLTL (N = 53)	SWWT (N = 53)
Lectures	Three 1 h lectures delivered in traditional style	Three 1 h lectures delivered in traditional style	Three 1 h lectures delivered in traditional style
Laboratories	One 4 h traditional, verification-type session (semesters 1 and 2)	One 4 h traditional, verification-type session (semesters 1 and 2)	One 4 h SWH-based session (semesters 1 and 2)
Tutorials	Two 1 h, traditional	Two 1 h, traditional	Two 1 h, traditional
Workshops	None	One 2 h PLTL-based session (semester 1/2)	One 2 h critical-thinking-focused session (semester 1/2)

own thinking, and experience cognitive dissonance in a supportive environment. The SWWT therefore allows for the union of collaboration, inquiry, writing, and reflection.

The PLTL and SWWT are second-generation pedagogies rooted in social constructivism.[52−54] As such, students' prior knowledge and its role in shaping new knowledge through a process of social negotiation to arrive at generally shared meanings are central to these approaches. One of the most significant ideas in social constructivism is the zone of proximal development (ZPD), the "distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers".[55] It is within this ZPD that learning takes place. Therefore, in organized, sociocollaborative spaces such as PLTL and SWWT, where students work in groups among themselves and with their peer leaders and facilitators, students have access to appropriate scaffolding during discussion, debate, and other dialogic interactions which can help them to bridge the gap between one level of thinking and a higher level.

■ RESEARCH QUESTIONS

This study reports on the impact of two student-centered, active learning instructional strategies, PLTL and SWWT, on the CT skills of first-year chemistry students in a regional three-year university in the Caribbean. The study addresses the following questions:

(i) Do PLTL and SWWT approaches produce greater gains in overall CT than the traditional (TRAD) approach?

(ii) Do PLTL and SWWT approaches produce greater gains on the analysis and interpretation, evaluation and explanation, and inference CT subscales than the TRAD approach?

■ RESEARCH METHODOLOGY

Research Design and Participants

A quasi-experimental pretest−post-test design involving the use of matched groups was used to assess differences in CT among PLTL, SWWT, and TRAD students. The use of matched groups minimized threats to internal validity that could result from selection bias as well as the use of unequal groups. Other measures to minimize threats to internal and external validity included the use of pretests and post-tests, with sufficient time between tests to minimize repeat performance, and the utilization of a valid, reliable instrument in the California Critical Thinking Skills Test (CCTST).[56,57]

Introductory Chemistry is a 2 semester general chemistry series which includes one 4 h laboratory session, three 1 h lectures, and two 1 h tutorial or recitation sessions each week. The course covers foundational topics in chemistry including electronic configuration and the periodic table, covalent bonding, molecular structure, energy and chemical reactions, acids and bases, and transition metals and coordination compounds, and it is a prerequisite for advanced chemistry courses as well as for entry into a number of other disciplines.

Participants were first-year chemistry students (i.e., students in the first year of a 3-year undergraduate degree program), registered for Introductory Chemistry over both semesters of an academic year. All students were STEM majors pursuing diverse degree options including Life Sciences, Chemistry, Biochemistry, Mathematics, and Physics. There were 101 females, representing 63.5% of the participants, and 58 males. Participants were predominantly of African descent (>95%) and had a modal age of 19 years. The mean percentage scores on a common chemistry content knowledge test administered prior to interventions were 46.91, 47.23, and 51.58 percentage points for TRAD, PLTL, and SWWT groups, respectively. The chemistry content knowledge test was developed by the authors to obtain a measure of students' chemistry knowledge at the beginning of their first year. There was no significant difference in the participants' beginning chemistry knowledge ($F(2, 139)$; $p = 0.22$).

Participants were matched on the basis of their overall pretest scores on the CCTST 2000, so that all three groups had equivalent pretest mean scores. Each group (TRAD, PLTL, SWWT) comprised 53 students who had taken either two semesters of SWH laboratories or two semesters of traditional laboratories, and for whom both pretest and post-test scores on the CCTST 2000 were available. Workshop students (PLTL and SWWT) were a part of the respective workshop group in at least one of the two semesters. Each workshop participant attended at least 50% of the workshop sessions held. The requirements that study participants must have (i) taken two semesters of SWH or TRAD laboratories, (ii) taken the CCTST in both the pre- and post sittings, and (ii) attended at least 50% of the workshop sessions held limited the number of students eligible to participate in the study. Students' timetables changed from one semester to the next, often necessitating changes to their laboratory streams in order to accommodate these changes. This meant that some students who were in a SWH lab stream in semester 1 joined a TRAD stream in semester 2 and vice versa (which means that they would not have satisfied the requirement of having two semesters of TRAD or SWH laboratories). In addition, both pre- and post-CCTST scores were unavailable for some students for a number of reasons, primarily because they joined the course late, after the CCTST had already been administered. Such students would not have been included in the study. Informed consent was obtained from all participants. Table 1 provides a summary of participants and their activities.

Procedure

The PLTL and SWWT initiatives were implemented at the first-year chemistry level over 2 semesters (24 weeks). Each

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student was registered in 1 of 10 laboratory sections and attended lectures and tutorials (see Table 1). Each laboratory section accommodated a maximum of 54 students who were managed by an instructor, who had overall supervisory responsibility for the section, and 3 demonstrators who were recent graduates. Two of the 10 sections implemented the SWH approach while the remaining sections used a traditional laboratory approach. SWWT workshops were available to students in SWH laboratory sections, and participation in SWWT workshops was voluntary. Registration in PLTL workshops was open to all students. Students voluntarily signed up for one of several weekly PLTL workshops at the beginning of the semester.

Implementation of the Traditional Approach

The traditional lecture was typically a 50 min, instructor-centered, content-packed presentation, supported by PowerPoint slides. Students were usually passive recipients of knowledge, although questions for clarification were allowed.

The traditional laboratory session usually began with a prelab quiz and a lecture-style laboratory talk by the supervisor. The lab talk provided a theoretical background for the experiment, and addressed procedural and safety issues specific to the experiment to be conducted. Following the lab talk, students worked individually (although they sometimes worked in pairs, if there were equipment or material constraints), to carry out the procedure set out in their laboratory manuals, and so there was little to no collaboration among students. Each student (or pair) conducted the same experiment, without variation, and collected similar data, which they recorded on "fill-in-the-blanks"-type worksheets. Upon completion of the experiment, students continued to work on their worksheets individually. Alternatively, they were allowed to complete their worksheets outside of the lab for later submission. Demonstrators usually helped students in setting up their experiments, and in attending to procedural issues that arose.

The traditional tutorial or recitation was a 1 h session where students had the opportunity to meet in smaller settings than lectures to work through previously posted "tutorial questions" and clarify misunderstandings which might have arisen during lectures, with their tutorial assistants. Although these were smaller groups, the sessions were usually conducted in lecture style so there was no deliberate collaboration among students. Generally, students attended tutorials with the expectation of receiving "correct answers" to tutorial questions from their tutorial assistants.

Implementation of PLTL

PLTL students participated in traditional lectures and traditional verification-type laboratory sessions, and attended traditional tutorial sessions. Prior to the start of the weekly workshop sessions, peer leaders (students who had obtained grades of B^+ or better in first-year chemistry in the previous year), were selected and trained by the Workshop Coordinator. Training focused on pedagogical issues surrounding PLTL, group dynamics, and roles and responsibilities of peer leaders. The Workshop Coordinator also held weekly 1 h sessions with peer leaders to support and reinforce the core principles of PLTL, ponder alternative approaches to the solution of problems, and share experiences and best practices.

In workshop sessions, students worked together in groups of 8−10 to discuss and solve coursework-related chemistry problems. Workshop materials were drawn from a number of sources, including lecture notes, past examination questions, and texts[37,38] and were vetted by instructors of first-year chemistry and modified where necessary. The materials were compiled into a manual which was segmented into weekly exercises. Each exercise comprised preworkshop and workshop material. The manual also provided room for students to record their responses. The material was designed in a manner that would review and strengthen students' background knowledge, improve competence in current concepts being taught, challenge student thinking and problem-solving skills, and facilitate student preparation for their final course examinations. Further details of PLTL, including the rationale, guidelines for implementation, evaluation, and workshop resources, are available.[43,48,58,59]

Implementation of SWWT

Students involved in SWWT participated in traditional lectures and tutorials but had SWH laboratory sessions. In addition, SWWT students voluntarily participated in weekly workshops aimed at CT development.

In preparing for implementation of SWWT, traditional laboratory manuals were revised to reflect the SWH approach. During this revision process, experiments were rewritten to reflect a guided-inquiry approach, while ensuring that the content coverage remained the same. There was also extensive training for demonstrators in theoretical and practical aspects of the SWH.[60,61] Detailed descriptions of the SWH approach have been provided by a number of authors.[50,60−63]

The laboratory component of SWWT, the SWH, began in the first laboratory session where students were introduced to the SWH student template. Beginning questions, claims, and evidence, which were novel aspects of the report format, were introduced using a case-based activity on which students worked collaboratively, and further clarified through questioning and discussion. Students were introduced to the SWH laboratory manual as a resource for finding more information on the SWH approach, as well as a guide to writing their laboratory reports, among others. Each activity began with a case-based scenario and provided no aim for the experiment. There was a significant emphasis on the inclusion of safety considerations, as well as on incorporation of a greater degree of inquiry into the experiments.

A typical laboratory session began with students meeting in their groups of usually 4−6 persons to generate their beginning questions which would drive their activities for the day. As students discussed, demonstrators and supervisors moved discreetly among groups, ensuring that everyone was on task. Demonstrators and supervisors rarely interfered in discussions at this point, but where necessary, they would ask probing or clarification-type questions to help students think through their ideas. The whole class then discussed the questions put forward by the groups, with the supervisor acting as facilitator, and eventually came to consensus on two or three questions which the class would use for the day. Data gathering was also discussed, and different groups were assigned to gather data on particular aspects of the experiment. Students then worked in their groups to carry out assignments. While a full procedure was provided for most experiments, students were sometimes required to help in designing the experiment by generating or modifying procedures. After completing their bench work, each group would work together to generate the "data" needed. This usually required calculation and argumentation. All groups entered their data onto a single spreadsheet, and this became

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the class data. From this data sheet, students identified general trends, (as well as any anomalies), from which they generated claims and later provided evidence. After leaving the laboratory, students wrote their reports individually using the template provided.

The workshop sessions were 2 h meetings between students registered in an SWH laboratory section and their workshop leader, who was trained in CT instruction. The sessions could be considered to have had three segments. In the first segment which lasted about 30 min, students read a non-subject-specific case, at the end of which they were prompted to take a reasoned position. After students had read the case, taken a reasoned position, and discussed with a partner, the workshop leader facilitated a whole-group discussion where students were invited to share their views openly. This was an opportunity for debate and argumentation, and students supported their arguments, considered other viewpoints, sometimes conceded their own arguments, and identified assumptions and weaknesses in their arguments as well as those of their peers. This discussion was followed by readings from Paul and Elder[64−66] on various aspects of CT, and a discussion led by the workshop leader on how students could incorporate ideas about CT into their everyday life and learning ensued.

The second segment lasted an hour. Students worked in pairs or small groups on carefully crafted or selected guided-inquiry chemistry exercises, provided as worksheets. The activities were drawn predominantly from Straumanis' *Organic Chemistry: A Guided Inquiry*[67] and Hanson's *Foundations of Chemistry*.[68] Topics included Nomenclature of Organic Compounds, Alkanes and Alkenes, Substitution Reactions, Electronic Configuration and the Periodic Table, Acids and Bases, Transition Metals, and Coordination Compounds, among others. As they worked, students discussed meaning and approaches to solving problems,and eventually presented solutions. Much emphasis was placed on students *recording their answers on the worksheet in the same way they would have were they in an examination setting*. Students were usually provided with resources in the form of texts, which they were free to consult. They were also encouraged to use their lecture notes and Internet resources.

In the final segment of the workshop, the last 30 min, group members were encouraged to share their *written responses* with the whole group, and there was discussion about the extent to which the intellectual standards (accuracy, clarity, depth, breadth, logic, and relevance of the responses), as expounded by Paul and Elder,[64−66] were present. This discussion was facilitated by the workshop leader but was student-driven. Students explained their decisions (answers) and provided evidence to support them.

Data Collection

The paper version of the CCTST 2000 was used to gather data on students' CT skills. The instrument was administered using a pretest−post-test format. The pretest was administered in the laboratory within the first 2 weeks of the first semester, and the post-test was administered under similar conditions within the last 2 weeks of the second semester. The interval between the two administrations was 26−28 semester weeks. Students were allotted the recommended time of 45 min to complete the test. Insight Assessment, the providers of a suite of CT tests from which the CCTST 2000 was chosen, provided independent blind-scoring of the CCTST, as well as recommended performance assessment ranges for interpreting scores on the CCTST. These are shown in Table 2 below.

Table 2. CCTST 2000 Recommended Performance Assessment (RPA)

Recommended Performance Assessment Overall Score and Subscales	CCTST 2000 (34-Point Version) Recommended Performance Assessment				
	Not Manifested	Weak	Moderate	Strong	Superior
Overall score	0−7	8−12	13−18	19−23	>24
Analysis and Interpretation	0−2		3−4	≥5	
Inference	0−5		6−11	≥12	
Evaluation and Explanation	0−3		4−7	≥8	

The CCTST measures cognitive and metacognitive skills associated with CT, is based on the consensus definition of CT used in this study, and has been evaluated for validity and reliability for measuring CT at the college level.[28,69,70] The CCTST 2000 is considered a more robust instrument for evaluating CT than previous versions.[71] The test was developed primarily for assessing CT skills of undergraduate students and consists of 34 non-discipline-specific multiple-choice items. The test provides scores on the subscales of analysis and interpretation, evaluation and explanation, inference, induction, and deduction, as well as a total CT score. Sample assessment items are available to the reader.[72] Validity and reliability testing on the CCTST returned a Kuder−Richardson (KR) 20 statistic of between 0.64 and 0.67, which indicates good reliability.[73]

Data Analysis

The data were analyzed using SPSS Statistics 23.0. An analysis of variance (ANOVA) test was used to compare gains in CT between PLTL, SWWT, and TRAD groups on the analysis and interpretation, evaluation and explanation, and inference subscales, as well as on total CT. (Scores on the induction and deduction subscales were not reported as these overlap with analysis and interpretation, evaluation and explanation, and inference subscales.) Paired samples t tests, using a Bonferroni adjusted α level of 0.0167 (0.05/3) per test, were used to compare CT pretest to post-test scores for each group to determine whether changes in scores were significant. Means, standard deviations, and effect sizes were computed.

■ RESULTS

The results of a Shapiro−Wilk test for normality of samples provided insufficient evidence of a departure from a normal distribution, having returned a value of $p > 0.05$. The mean total CT pretest scores was the same for all three groups (M = 12.02, SD = 3.13) as the groups were matched on the basis of pretest scores. For the TRAD group, the post-test score (M = 12.74, SD = 3.38) was 0.72 points above the pretest score, which was not a significant improvement ($t(53) = 2.05$, p = 0.045). The PLTL group experienced a gain from pretest to post-test of 2.26, resulting in a post-test score of 14.28 (SD = 4.12). This gain was over three times that of the TRAD group and represented a significant increase ($t(53) = 5.03$, $p <$ 0.001). An effect size of 0.69, indicative of a medium or moderate effect, was calculated. The SWWT group had a

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higher post-test than pretest score (M = 15.21, SD = 4.30), with a gain of 3.19 points. This gain was over 4 times that of the TRAD group. The difference between pretest and post-test scores was significant ($t(53) = 5.98$, $p < 0.001$), with an effect size of 0.82, indicative of a large effect. ANOVA results and Tukey's HSD post hoc analysis indicated significant differences in CT gains between SWWT and TRAD groups ($p = 0.000$, $\eta^2 = 0.24$) as well as between PLTL and TRAD groups ($p = 0.043$, $\eta^2 = 0.11$). However, there was no significant difference between SWWT and PLTL groups ($p = 0.318$).

Probing the CT subscales, there were no significant differences in the students' pretest scores on all three subscales. However, students in SWWT and PLTL groups showed significant gains on the inference and evaluation and explanation scales from pretest to post-test with effect sizes ranging from small to large, while students in the TRAD group showed no significant gains on either subscale. PLTL students experienced over 6 times the gain experienced by TRAD students on the evaluation and explanation subscale, and almost twice the gain they experienced on the inference subscale. SWWT students had gains that were 8 times greater than TRAD students on the evaluation and explanation subscale, and over 3 times greater on the inference subscale. Interestingly, no group had significant gains on the analysis subscale, and the TRAD group saw no movement at all from pretest to post-test on that subscale.

Between groups analysis of the subscales revealed significant differences between TRAD and SWWT groups on the inference and evaluation and explanation subscales ($p = 0.012$, $\eta^2 = 0.11$ and $p = 0.035$, $\eta^2 = 0.07$, respectively). However, no significant differences were observed between TRAD and PLTL groups or PLTL and SWWT groups on any of the three subscales. These results are summarized in Tables 3 and 4.

Table 3. Comparative Performance by Group of Pretest and Post-Test Measures on the California Critical Thinking Skills Test

		Overall Critical Thinking Test Results				
		Pretest		Post-Test		
Group by Instructional Approach	Number	Mean Score	SD	Mean Score	SD	Mean Score Gain
TRAD	53	12.02	3.05	12.74	3.38	0.72
PLTL	53	12.02	3.20	14.28	4.12	2.26
SWWT	53	12.02	3.19	15.21	4.30	3.19

■ DISCUSSION

This study reports on the impact of the implementation of PLTL and SWWT initiatives on students' component and overall CT skills in a first-year chemistry course. The results indicate that students in PLTL and SWWT groups experienced significant gains in their overall CT from pretest to post-test. The results further show that the difference in gains made by SWWT and PLTL students were significantly greater than those made by TRAD students.

Writing, reflection, collaboration, inquiry, and deliberate CT emphasis, elements of the SWWT and PLTL, have individually been positively associated with the development of CT skills.[10,16,21,36] We believe that the combination of these research-based elements produces a synergistic effect which explains the greater increase in CT scores for PLTL and SWWT participants over TRAD students.[22]

One possible explanation for the largest gain by the SWWT group is the double reinforcement of the elements through the laboratories and workshops. In both laboratories and workshops, students are engaged in collaborating, writing, inquiry, and reflection (although to different degrees), with the added deliberate CT focus in workshops. The marginally lower gain for PLTL when compared to the SWWT can be explained by considering that there is no double reinforcement of the elements in PLTL as occurs in SWWT. Students in both SWWT and PLTL had a greater number of opportunities to engage with the elements than TRAD students, and this is consistent with the larger gains in CT for these groups, although gains would vary depending on the extent to which individual students chose to engage in the activities. We find it necessary to point out that a "greater number of opportunities to engage with the elements" should not be equated with time in class. With respect to CT in particular, research shows that students can spend a long time in class but engage in little or no CT: rather, it is the *nature* of the activity or task in which students are involved that determines whether or not there is CT development.[16,21] A significant body of research investigating the relationship between educational time and student outcomes found that time in class has no significant effect on student achievement and is inadequate to explain improved student outcomes.[74] Studies of student outcomes using PLTL and SWH approaches and their variants found that students using these pedagogies had significantly greater outcomes than their TRAD counterparts, even though they all spent similar time in class.[19,22,46,75−80] These findings give support to studies using PLTL or PLTL-like initiatives which, though lacking time controls, found that participating students

Table 4. Comparative Component Skills' Performance by Group of Pretest and Post-Test Measures on the California Critical Thinking Skills Test

			Pretest		Post-Test					
Component Skills	Group	N	Mean Score	SD	Mean Score	SD	Mean Gain	t-Value	p-Value	Effect Size, Cohen's d
Analysis and Interpretation	TRAD	53	3.34	1.02	3.34	1.29	0.00	0.00	1.000	
	PLTL	53	3.45	1.51	3.79	1.34	0.34	1.37	0.177	
	SWWT	53	3.60	1.34	3.92	1.22	0.32	1.57	0.123	
Explanation and Evaluation	TRAD	53	2.68	1.62	2.81	1.56	0.13	0.60	0.552	
	PLTL	53	2.60	1.45	3.45	1.93	0.85	3.09	0.003	0.42
	SWWT	53	2.36	1.51	3.40	2.02	1.04	3.89	0.000	0.53
Inference	TRAD	53	6.00	2.05	6.58	2.19	0.58	2.10	0.041	
	PLTL	53	5.96	2.00	7.04	2.30	1.08	3.52	0.001	0.48
	SWWT	53	6.06	1.84	7.89	2.23	1.83	5.61	0.000	0.77

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experience more significant outcomes than TRAD students.[45,48,81,82] Both sets of studies indicate that whether time in class was controlled or not, students in PLTL and SWH-type settings had more significant outcomes than TRAD students. This similar finding in two sets of studies lends credibility to the results even if each study has flaws in its approach.[47,48]

The nonsignificant increase from pretest to post-test experienced by the TRAD group is consistent with the small increases in CT that have been reported for students in traditional classes,[16,58] and may be the result of maturation. Additionally, while TRAD students were not deliberately engaged in activities aimed at developing their CT skills, as they moved through their courses they would have engaged from time to time in activities that required some collaboration, writing, inquiry, and reflection. However, the absence of long-term, consistent, and *synchronous* fostering of these elements militate the formation of synergistic effects.

The results indicate that gains for PLTL and SWWT groups were not only statistically significant but also had practical significance. The SWWT approach produced a large effect, while the PLTL approach produced a moderate effect. These suggest that SWWT and PLTL were effective in influencing and improving students' CT skills. Facione et al.[83] noted that an "overall gain for the group of two or more points is a strong effect". On this basis, PLTL and SWWT had strong effects on students' CT skills, a finding consistent with the effect sizes calculated in this study.

Considering the component skills, gains were made by SWWT and PLTL groups on all three subscales, but only gains in evaluation and explanation and inference were significant. TRAD students had no significant change on any subscale. Significant differences between SWWT and TRAD groups were also observed on the evaluation and explanation and inference subscales, but differences between TRAD and PLTL groups were not significant on any subscale. The results show that PLTL and SWWT led to greater improvements on all three component skills over TRAD, with the SWWT group having the largest increases, followed by PLTL. The significant gains for PLTL and SWWT students on the evaluation and explanation and inference subscales may be linked to the collaborative-inquiry elements of the initiatives. As students worked together in workshop sessions to articulate solutions and conclusions, justified their solutions/conclusions with evidence and reasoning, and revised their conclusions based on discussion and new evidence, among others, they developed and strengthened these skills.

There were smaller gains on the analysis and interpretation subscale than the other subscales for PLTL and SWWT students, while there was no change for the TRAD group. We believe that the gains made by students, especially PLTL and SWWT, on this subscale may be greater than reported here, as activities that targeted analysis and interpretation took place within the chemistry domain, and so the gains may have been primarily domain-specific, and therefore not all gains may have been captured by the domain-general (non-discipline-specific) CCTST. For this reason we support the recent proposal of administering parallel domain-specific and domain-general tests that target the same CT skills to obtain a complete understanding of the development of CT.[84] However, as yet there are no such tests for chemistry, presenting a fertile area for research.

■ LIMITATIONS

The main limitation of this study is that while PLTL and SWWT students spent two additional hours in workshops each week, TRAD students spent that time in unstructured activities over which there was no control. While this complicates comparison of the groups, we maintain that the differences between workshop groups and the nonworkshop TRAD group remain significant and cannot be adequately explained solely by a difference in time in class.

When compared with some similar studies in the field, the size of the sample was relatively small. This resulted from the requirements that participants must have taken either two semesters of SWH or TRAD laboratories, had available pretest and post-test CCTST scores, and attended at least 50% of the workshop sessions held. Despite the relatively small size of the sample, however, post hoc analysis using G*Power 3.1[85] showed the sample size used in the study to be adequate. Calculations (power of 0.80, $\alpha = 0.05$, two-tailed) showed that, in order to detect a large and medium effect, a sample size of 66 and 159, respectively, would be needed. The achieved power for the effect sizes obtained in this study showed the power to be greater than 0.95.

Any biases arising from maturation or selection were minimized by the use of matched groups.

■ CONCLUSION

This study provides empirical evidence that the implementation of two active learning instructional approaches, PLTL and SWWT, led to significant gains in inference, evaluation, and explanation, and overall CT for participating students, while students who were exposed to a traditional approach did not experience significant gains. The findings suggest that active learning pedagogies combining writing, inquiry, collaboration, and reflection with deliberate CT focus, have the potential to significantly improve students' CT skills and, thus, should be favored over more traditional approaches which do not. Providing more opportunities for students to engage in such activities is recommended.

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Notes

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