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Student Development of Information Literacy Skills during Problem-Based Organic Chemistry Laboratory Experiments

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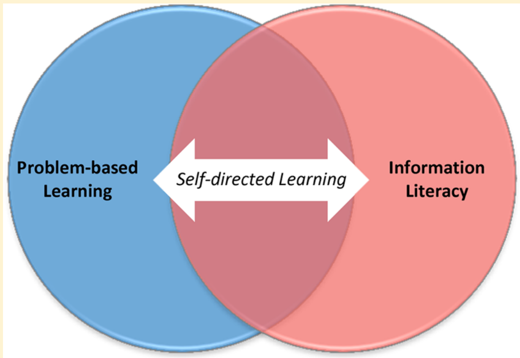
Supporting Information

ABSTRACT: Problem-based learning methods support student learning of content as well as scientific skills. In the course of problem-based learning, students seek outside information related to the problem, and therefore, information literacy skills are practiced when problem-based learning is used. This work describes a mixed-methods approach to investigate the information seeking behavior of students in a problem-based organic chemistry laboratory course, when information literacy is not explicitly taught. Discourse analysis was used to analyze student audio recordings taped during problem solving sessions in order to explore the process by which students' find and use outside sources of information during a set of problem-based learning activities. Student generated artifacts produced during problem solving were quantitatively transformed and used to evaluate the product of students' searching processes. Evidence from both aspects of the study suggests that students do not demonstrate development of information literacy skills in the absence of explicit instruction.



KEYWORDS: *First-Year Undergraduate/General, Second-Year Undergraduate, Organic Chemistry, Laboratory Instruction, Problem Solving/Decision Making, Synthesis, Cheminformatics*

FEATURE: Chemical Education Research

A primary goal of national science education is to move toward educational methods that integrate the learning of scientific content with the learning of scientific practices.[1] Traditional recipe-based laboratory courses are not considered to be effective in supporting this dual emphasis.[2,3] By contrast, contemporary laboratory course models, such as Problem-Based Learning (PBL),[4−7] which provide students with the opportunity to do inquiry, have the capacity to emphasize both learning goals.[1] For example, during the problem-solving process, students need skills, such as seeking and evaluating information and integrating it into their own knowledge systems. Thus, PBL naturally interweaves with information literacy (IL) skills to fill students' knowledge gaps and to activate their creativity.[8]

Despite the potential of PBL in addressing contemporary objectives for science education, few studies have examined the development of science practices through PBL curriculum in the context of the chemistry lab. Zoller and Pushkin found a positive impact for a PBL chemistry laboratory curriculum on the development of higher-order cognitive skills in a freshman organic chemistry course.[9] Sandi-Urena et al. investigated the effect of PBL Lab instruction on metacognition and problem-solving skills in general chemistry and found that students developed these skills even without explicit instruction.[10] To our knowledge, no prior studies have focused specifically on the development of information literacy skills in PBL chemistry labs.

PROBLEM-BASED LEARNING AND INFORMATION LITERACY

Problem-based learning (PBL) is a collaborative student-centered approach that engages learners in applying their knowledge and skills to solve complex, open-ended, and authentic problems.[4−6] PBL is explained by constructivist theory, which describes learning as an active and iterative process where learners construct their knowledge through experiences.[2,11] There is also a significant social learning component in PBL as students solve problems collaboratively.[12] Schmidt describes PBL as a form of constructivist learning that is connected to information literacy (ref 13, p 20):

> *Students are engaged in constructing theories about the world, represented by the problems presented. They do so collaboratively and in a meaningful context provided by those same problems. While doing so they construct new knowledge about the world using a variety of informational resources.*

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Indeed, the collaborative and active learning environment provided by PBL is intended to support students' growth from novice learners to information literate experts.[12] The recently filed Framework for Information Literacy for Higher Education by Association of College and Research Library (ACRL)[14] renewed "the vision of information literacy as an overarching set of abilities in which students are consumers and creators of information who can participate successfully in collaborative spaces" (ref 14, p 2). To this end, the PBL process directly relates the threshold concepts of the ACRL IL framework because it creates collaborative environment for students to both consume information and create hypothesis and solutions to a given problem with context. PBL has been used to design IL instruction[15−19] across disciplines including Sciences, Social Sciences, Business and Law.

Self-directed learning is the key feature of PBL that connects it to student development of information literacy skills (Figure 1). In the process of problem-solving, students exercise self-directed learning as they collaboratively seek what information they need to understand the nature of the problem.[13] Through this process, they make use of their prior knowledge and work together to identify gaps in their collective knowledge. As outlined in the Information Literacy Standards for Higher Education by ACRL,[20] an information literate student would first determine the nature and extent of the information that is needed, then acquire the information, evaluate it, process it, and finally utilize it in their problem solving.[12] However, novice learners may skip one or more of these steps. Some may ignore the needs of information as a whole and let the frustration of lacking sufficient knowledge keep them from solving the problem. They may recognize the needs of information but be unable to articulate the type and extent of information needed, thus retreating to any random Google search results they can grab quickly. Others may completely disregard the problem-solving process and start to look for final solutions other people have presented. These habits start to take their form when students first interact with search engines and stay with many students throughout their high school years.[21] In reality, accessibility becomes a crucial criterion when it comes to selecting information sources for self-directed learning among undergraduates[22] and even developed scientists.[23]

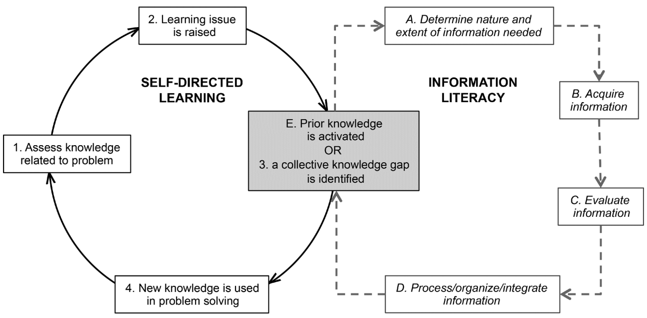

Figure 1. Processes employed by students as they engage in problem-based learning curriculum. Self-directed learning is related to information literacy as students recognize a knowledge gap and seek outside information. Copyright 2000 from Hmelo and Lin, ref 24. Adapted by permission of Taylor and Francis Group, LLC, a division of Informa plc.

The undeniable power of Google search and the breadth of freely available online portals like Wikipedia have, no doubt, facilitated the adoption of an approach that involves searching directly for a solution to the posed problem. The gap between computer literacy and information literacy was recognized in the 1980s,[25] and seems to have grown broader over time. In our study, we closely examined students' intuitive problem-solving and information-seeking behavior in order to identify the gaps of information literacy skills which may weaken their ability to solve the proposed problems in the PBL Chemistry lab. Our findings will inform the design of interventions to fill these gaps while also promoting creativity and innovation. The study is guided by the following research questions:

1. How do students find, evaluate and use outside information for problem based experiments in organic chemistry laboratory?
2. Do students develop information literacy skills in problem-based organic chemistry laboratory when it is not explicitly taught?

METHODS

The work reported here is framed in a qualitatively driven parallel mixed-methods design.[26] With this approach, qualitative evidence was collected to explore the process by which students find and use outside sources of information during a set of problem-based activities. Student generated artifacts produced during problem solving were quantitatively transformed[26] and used to evaluate the product of students' searching processes.

Setting and Participants

The study was conducted at a public university in the Midwest United States over a single 14-week semester. Study participants were nonmajors enrolled in a second semester chemistry laboratory course. The class met weekly for a pre-lab lecture (50 min) and in individual lab sections (n = 17 per section) taught by graduate teaching assistants (GTAs) for a single 4-h lab session each week. Neither the course instructor nor the GTAs were part of the research team. No textbook was used, and instructor-generated course materials, including open access sources for laboratory topics, were organized on the learning management system. As freshman and sophomore students, most students in the course had not had a formal course on chemical information. GTA staff meeting and training did not specifically address information literacy excepting as it related to grading. A total of 155 students participated in the pilot implementation of the PBL curriculum in the course that was the focus of the study. Only the coursework of those students who consented was analyzed (>98%), and IRB approval was obtained for all aspects of the study. Six participants (two groups of three) were recruited and consented to audio record meetings during which they planned their experiments.

Laboratory Activities

Students performed seven 2-week experiments during the semester, three of which were PBL experiments (Table 1). Students worked collaboratively in groups of 2−4 to identify a solution to a synthetic organic problem, design an experiment to test their solution, implement their planned experiment in lab, and evaluate the efficacy of their solution. Each experiment centered on an organic chemistry reaction that was refocused around an authentic synthetic problem. Students were directed to organize meetings with their group (in or out of class as time allowed) to plan for their experiment and were guided by a procedure and worksheet with design prompts. Students

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Table 1. Problem-Based Organic Chemistry Laboratory Experiments

Experiment	Objective
Wittig Reaction	Find an alternative solvent that is greener than dichloromethane.
Fischer Esterification	Modify an existing protocol in order to investigate the relative reactivity of a series of alcohols.
Aldol Condensation	Modify an existing protocol in order to investigate the relative reactivity of a series ketones or aldehydes.

submitted the worksheets detailing their experimental design 72 h in advance of their lab session, and graduate student instructors then reviewed the worksheets and provided feedback at the start of the next lab session. In this manuscript, we focus on the planning phase of the experiment, which we evaluated through audio recordings, semistructured interviews, and student artifacts.

Data Collection

The two participating student groups who were audio recorded during their planning sessions met on three occasions outside of class during the interim days after the corresponding pre-lab lecture and prior to their lab session. Planning sessions ranged in duration from 1 to 2 h and audio recordings were transcribed verbatim. Critical incidents were used as the primary unit of analysis of student dialogue[27] and were identified as instances in which students recognized a gap in their collective knowledge and sought outside information (Figure 1).[24]

All students who participated in problem-based experiments (N = 155) submitted a collaborative worksheet assignment (N = 137 worksheets in total for 3 experiments), which were completed collaboratively and described their proposed solution, formulated hypotheses, and the design of their experiments. Students were advised, but not required, to cite any outside resources that were used to support their proposed solution and hypothesis. No explicit instructions were provided as to how and when to cite.

Each of the six students who were recorded during their planning sessions participated in interviews that were conducted at the end of the term. Interviews lasted 15−20 min. Each interview followed a semistructured protocol and allowed researchers to contextualize the information seeking behaviors of the students during their planning sessions. Sample interview questions included "Which experiment was the most challenging and what made it more challenging?" and "What resources did you use when planning the experiments?"

Data Analysis

Thematic analysis of the transcripts, interviews, and student design worksheets was conducted using the constant comparison method[28,29] and guided by the study research questions as well as theory on self-directed learning in PBL,[4,6,24] information literacy and information seeking

Table 2. Summary of Codes for Learning Issue Discussions

Code	Definition	Example
I. Purpose of Search		
a. Solution	Searching for solution to proposed problem	"Why don't we just Google Chalcone reactions?"
b. Defining the Problem	Searching for information about a chemistry concept in order to define or better understand the nature of the posed problem.	Pam: "So I just read the reason it's [DCM] used is because, like, everything can dissolve in it." Kelly: "So we need something that everything can dissolve into I guess?"
c. Confirmation of Solution	Search for information to confirm a solution idea has precedence	"Okay. So part of this water was...Part of this paper was, um, talking about how you can at least like add stuff to water."
d. Analysis of Solution	Search to analyze a possible solution or compare 2 or more possible solutions	Pam: "Would that allow product to form that way?" Kelly: "That's a good question. Let's figure that out. Ummm..." Pam: "Um, right here it says ether."
e. Planning Experiment	Search for information related to designing or planning the experiment	"So it says here that hexanes is usually used."
II. Topic of Search		
a. Structure−Property	Students relate and aspect of structure (atom, bond, charge, symmetry) to a property of the compound (intermolecular forces, polarity, solubility)	"So it's a carbon attached to 2 hydrogens and um 2, um chlorine atoms."
b. Mechanism	Students discuss aspects of the reaction mechanism.	"So it looks like something just like attacks that carbon, it pops up, and then eventually this comes down to attach, one breaks off."
c. Reagent	Students discuss any reagent involved in the reaction (solvent, starting material, catalyst, product) and its physical properties or behavior.	"I read the reason this is used is because, like, everything can dissolve in it kinda thing."
d. Reactivity	Students discuss reactivity (i.e., rate, slow, fast, yield, stability) in terms of a change in reagent of variable of the reaction.	"So, I think it's gonna run slower. So we probably wanna just come up with various ratios and see which one would run fastest."
e. Lab technique	Students discuss a lab technique related to the reaction of interest.	"Will diethyl ether evaporate with the stream [N_2]?"
f. Other	Other items	"Wikipedia told me how to pronounce ylide"
III. Learning Approach		
a. Deep	Examines new facts critically, forms links between ideas, and relates new knowledge to prior knowledge	Dwight: "So it says like the carbonyl oxygen of aldehydes and ketones undergo hydrogen bonding with water. And kinda stuff like that." Jim: "Umm...So, if this can do like hydrogen bonding with water wouldn't it..." Dwight: "We'd need something that also has a hydrogen to hydrogen bond with this aldehyde."
b. Surface	Accepts new facts uncritically, uses them as unconnected items and does not relate new knowledge to prior knowledge	Jim: "Okay, let's just figure out then the boiling point of all three of those compounds are and then choose the one with the highest." Dwight: "Okay, um, okay, well methanol's 64.7. T-butanol 83, and cyclohexanol is 161.61." Jim: "Okay. Let's do 161.61."

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Table 3. Rubrics for Evaluating If and/or How Students Cited Information Resources

(0) No citation	(1) Poor	(2) Developing	(3) Average	(4) Good
Did not cite or mention any resources	Mentioned outside information, but did not provide traceable[a] information resources	Integrated untraceable outside information sources in writing OR Provided traceable information but not integrated in writing	Integrated traceable information sources in writing	Integrated information sources in writing with correct citation style

[a]"Traceable" indicates that the citation can be located by the audience of the worksheet, the students and instructors in the same class.

Table 4. Categories of Information Resources Cited in Student Groups' Worksheets and Examples

Category	Characteristics
Scholarly Resources	
Research article	Research articles published in scholarly journals
Instructional materials	Materials developed by instructors/educators, available online but not formally published
Database	Scholarly database indexing research articles and other scholarly resources
Books	Scholarly books published formally
Thesis and dissertation	Thesis and dissertations published by creditable institutions
Nonscholarly Resources	
Wikipedia	Entries on http://en.wikipedia.org/
Web sites with warning signs	Web sites not designed with communicating scholarly information and data as primary goals, but for commercial interests or technical testing etc.; or without clearly stating creator's credentials; usually without specifying primary data sources
Personal communications or learning experiences	Conversations or exchanging of ideas between individuals and previous learning experiences
Unclear	
Unspecified materials provided by instructor	Generally referring to resources provided on the course Web site without specifying which ones used
Unclear	Resources mentioned but not traceable
No Resources Cited	
	No resources cited

behavior,[14,20,30,31] and student learning approaches.[32−34] The research team open coded each object and developed codes identifying patterns within each data theme. Finally, representative examples for each emergent theme were identified and the team discussed them to arrive at operational definitions for each code. One author applied the codes to the entirety of the transcripts and interviews and the other author applied the codes to student design worksheets.

To estimate inter-rater reliability, selected portions of the transcripts were given to two independent coders accompanied by a dictionary with operational definitions and directions for coding. Both coders had previous experience with discourse analysis and were instructed to both code the transcripts using the framework provided and to identify themes for which an appropriate code had not been identified. After completing the task, the coders and manuscript's authors discussed their experiences with the coding scheme and modified the operational definitions as discussed. The transcripts were recoded and final inter-rater agreement was >92%. Each critical incident, which represented a discussion around a learning issue (Figure 1), was evaluated on three primary themes including purpose of the search, content focus of the search, and the learning approach that was used by students when they discussed the new information (Table 2).

The student-designed worksheets were analyzed as a product of their information searching process. Paragraphs related to citing resources were excerpted from the students' worksheets and scored using a rubric to identify if students cited and how they cited information resources (Table 3). The rubric was designed to evaluate how effectively the citations met the two primary purposes of citing resources, which include (1) giving credit to original authors/creators of the resources and (2) allowing readers to identify and locate the resource. In addition, the rubric also measured if the students articulated the specific information or data they cited through integrating the cited sources into their writing.

The rubric used to evaluate students' citing behavior does not include the measurement of how students evaluated the information resources before citing them. Thus, an inventory of resources cited by students was created and analyzed to identify the information literacy skills that students demonstrated in the identification and evaluation of the resources. The resources cited in the worksheets were organized into 11 categories (Tables 4 and S2). An additional approach used to capture the problematic issues that were observed in students' worksheets (Tables 5 and S3) and the students' citations were also organized accordingly by common failure types.

Table 5. Criteria To Identify Failures in Evaluating and Citing Information Resources

Failures	Characteristics
Failed to cite scholarly resources	Cited resources appeared to be nonscholarly
Failed to cite true sources	Cited the webpages disseminated the information but not the original/true source of the information or data
Failed to recognize warning signs	Cited Web sites with warning signs as described in Table 4
Failed to comment on limitations	Cited resources with significant limitations without commenting on those limitations

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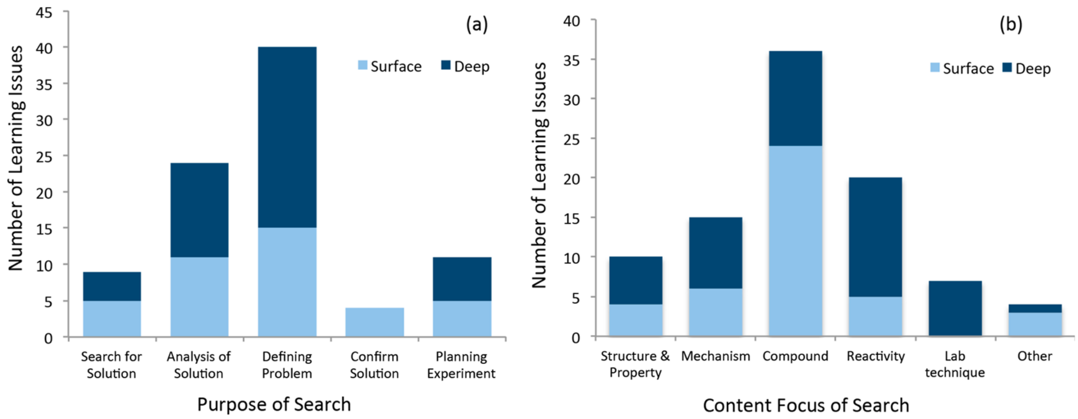

Figure 2. Proportion of learning issues that students engaged with a surface vs deep learning approach by (a) search purpose and (b) content focus of search.

■ RESULTS

How Do Students Find, Evaluate, and Use Outside Information for PBL Experiments?

Multiple data sources were analyzed to investigate the process by which students (1) determine the nature and extent of information needed, (2) acquire outside information, (3) evaluate the information, and (4) process information for use in problem-based experiments (Figure 1). Student discourse, recorded during planning sessions, was analyzed to generate an overall picture of the process by which students used outside information. Students' proposed experimental designs were analyzed to investigate the degree to which they evaluated and integrated outside information in their proposed experiment. Finally, semistructured interviews were used to contextualize results from analysis of student discourse and students' experimental designs.

Student discourse was analyzed to investigate the full process by which students sought, evaluated, and used outside information to fill a knowledge gap. Two student groups were audio recorded while planning for each of the three experiments, and the purpose of their search, the content focus of their search, and the depth at which they engaged with outside information were the primary themes that emerged from analysis (Table 2). Students searched for information for multiple purposes indicating that they were actively engaged in determining the nature and extent of information that was needed to understand and solve the problem. For both groups, the most common purpose of the searching was to define the problem and to validate or narrow in on a potential solution (Figure 2a). Relatively fewer searches were related to a direct search for a solution. Both groups conducted searches focused on the reaction and associated mechanism and to obtain standard information about reagents and their reactivity (Figure 2b).

Student discourse was also analyzed to determine when and how students acquired information. Often students did not directly articulate how they conducted searches, and thus, their search approach was inferred through verbal context. For example, "Yeah, I'm gonna look up the pKa stuff. Those three. So isopropyl is 16.5". The groups also directly articulated their intention to do a search. For example, when communicating an intention to do a Google search, they used Google as a verb "I'm going to Google that". For both groups, it was evident that each student conducted multiple independent searches throughout the course of their discussions.

The depth at which students engaged with each outside information source was analyzed to better understand how students evaluated and integrated information in their problem solving. The depth varied by group, experiment, search purpose and content focus of the search (Figure 2). Students more critically evaluated outside information when defining the problem and when evaluating a proposed solution. Students more frequently engaged superficially when searching for a solution and when seeking for information to confirm a group-proposed solution. For example, during experiment 1, student groups were tasked with improving the environmental impact of the Wittig reaction. Students in group 1 searched for outside information related to the greenness of organic solvents and found a site that provided a summary table with numerical ratings for "air, water, and waste issues" by solvent:

> Frank: *Okay, so we would need probably something, let's see...mmm...another green organic with another greener, ok, solvent. So, let's see...so this one scores a 9, 6, and 7 for air, water and waste. So we want stuff with 4 or more numbers?*
> Claire: *I guess*
> Frank: *Wanna look this up, um diethyl ether?*
> Claire: *Diethyl ether?*
> Frank: *That one that looks like a bat you know? I wanna look up the environment things on that one. Yeah! Okay, let's look at that. Okay, so that one is a 4 for water and a 4 for waste, but air is a 7. But I think its still better than the...*
> Claire: *Original one [dichloromethane].*

In this incident, the numerical values were used as-is to select candidate replacement solvents. Students did not discuss or seek to find additional information about what each green criterion meant and this incident did not appear to enhance their understanding of green chemistry.

The discourse analysis results also suggests that students did not evaluate the credibility of the outside sources because neither group discussed credibility at any point during their planning sessions. Both groups tended to use information "as-is" and did not discuss whether the source was credible or how to justify the use of their sources to support their experimental design. Only group 2 discussed whether and how to cite sources. However, it also is possible that individual students in these groups evaluated the credibility on their own and simply did not articulate that process to their group.

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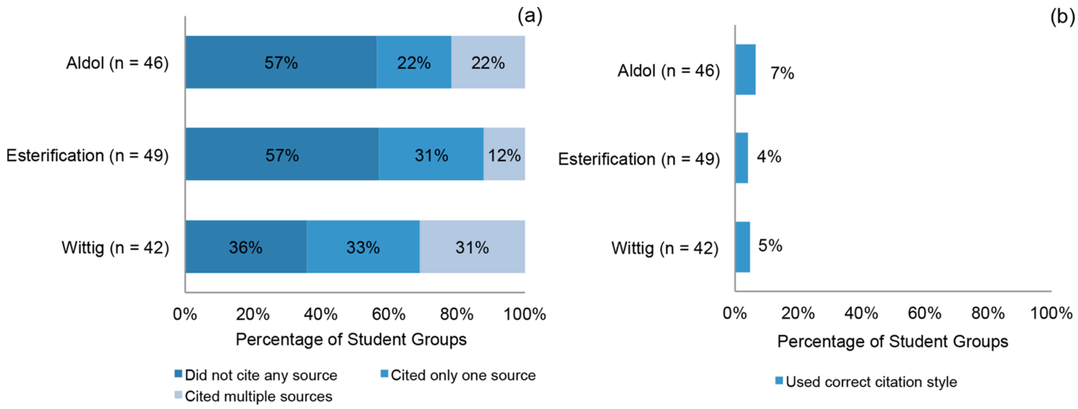

Figure 3. (a) Students citing behavior in each experiment and (b) percentage of students who correctly used a citation style in each experiment.

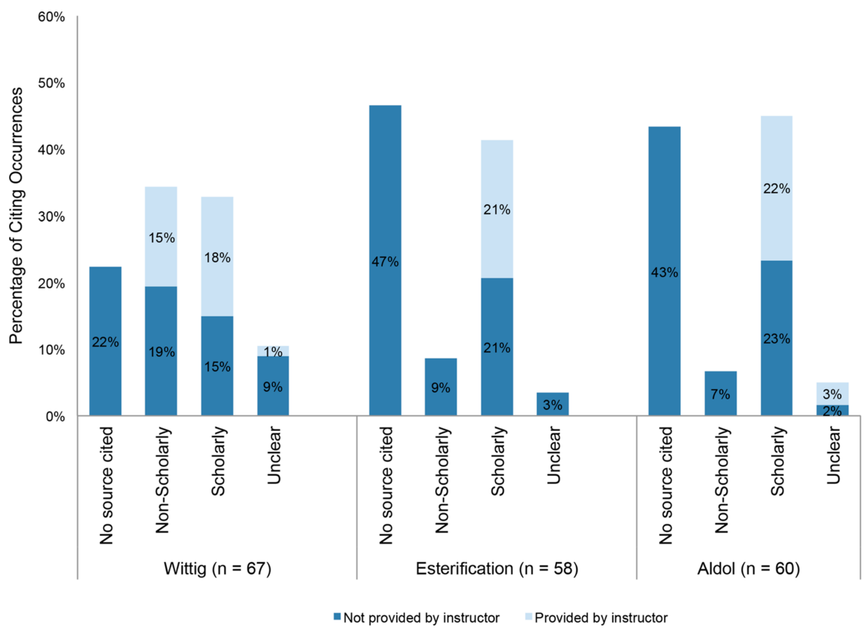

Figure 4. Percentage of citation occurrences by experiment in four categories: (1) no source cited, (2) nonscholarly source, (3) scholarly source, and (4) source unclear on analysis.

Students' proposed design worksheets were also analyzed to determine how they acquired information as well as the extent to which they evaluated and integrated the information found. Their worksheets (N = 137) were coded using a citation scoring rubric (Table 3), organized into categories by resource type, and analyzed with respect to the quality of their evaluation and citation. The overall analysis indicated that a large percentage (ranging from 36% to 57% by experiment) of student groups did not mention or cite outside information resources as shown in Figure 3a. This suggests that, when they searched and used outside information, they did not recognize the need to cite sources. Or, they may not have used any external information sources during their experimental design.

We observed that many of the sources cited by students, particularly the ones from the Wittig Reaction worksheets, were among top 10 Google search results for simple keywords like "green solvents", "dichloromethane replacement", "4-chloro-benzaldehyde solubility", or "steric hindrance" etc. This observation suggests that most students relied on Google to acquire information. This is corroborated by the discourse analysis of Group 2 who frequently articulated their use of Google when searching during their planning sessions. The Google-dominated search strategy is consistent with previously reported trends of students[22] and scientists[23] adopting Google search for problem-solving information seeking.

The resources cited in students' worksheets were organized into the categories listed in Table 4 (more examples of cited resources can be found in the Table S1). The percentage of citations in each category for each experiment are plotted in Figure 4. Among the scholarly resources cited in the worksheets, about half were provided by the instructor and half were discovered by students. One of the Web sites provided by the instructor (http://molsync.com/demo/greensolvents.php) for the Wittig Reaction was considered with warning signs and thus categorized as a nonscholarly resource. As a demonstration of web-facing technology, this site only gave a link to the ACS Green Chemistry Institute Pharmaceutical Roundtable as its data source, but no original data or its provenance were found in the linked site. Citing the data source used to populate the demonstration site directly would be a more informed approach, but the true data source was not identifiable with the clues from the Web site. It is also worth noting that students frequently cited instructional materials from other universities for similar experiments and

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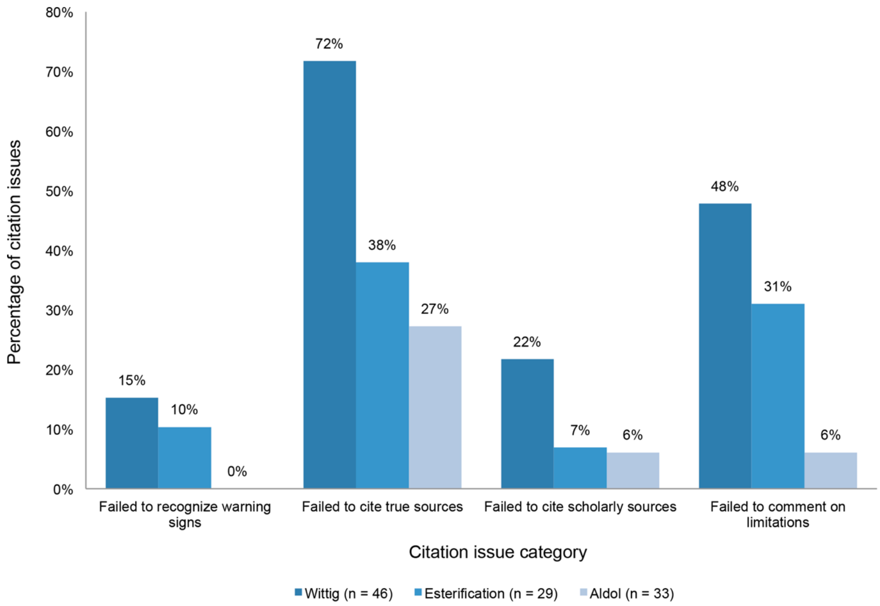

Figure 5. Citation issues that occurred across experiments. The percentage of citation issues are calculated with respect to the total occurrences of items cited (no sources cited and unclear citations are excluded).

textbooks, mostly outdated but easily accessible online. Only a small number of student groups used major databases in Chemistry, such as Reaxys and SciFinder, and they did not cite these secondary resources and primary sources (discovered through the databases) correctly. The citations of databases only appeared in the second and third experiment and there was insufficient data to determine how or why they used them.

The tendency of student groups to accept resources at face value was also reflected in worksheet analysis. The issues around students citing behavior were evaluated with respect to the four criteria listed in Table 4 and the percentage of failures with respect to the total citation occurrences (excluding no resources cited and unclear citations) were plotted in Figure 5. The large number of citation failures under categories like “Failed to cite true sources” and “Failed to recognize warning signs” support the claim that students did not evaluate sources. For example, many students cited commercial catalog pages for chemicals and Web sites compiled that were populated with chemical information to attract advertisement. Some of these commercial sites cited scholarly articles, but students failed to recognize and cite those true sources. Some students located relevant scholarly articles through Google search, but did not recognize and cite them as journal articles. Instead, they cited the authors’ ResearchGate.com profile with only the abstract and supplemental information from the article.

The propensity to use information without evaluation of credibility is corroborated by the discourse analysis, which also demonstrated that students did not evaluate information that they used. For example, group 1 used a Web site with warning signs to identify an alternative green solvent for the Wittig reaction. In their proposed solution they stated:

> *We looked at the chart of green chemicals and chose diethyl ether because it has relatively positive hydrogen atoms, due to the oxygen atom that could be used to dissolve our reagent.*

The students used the chart they obtained as a guide for selecting an alternative solvent, but did not justify otherwise how diethyl ether was determined to be greener than dichloromethane. Nor did they cite the original source.

Semistructured interviews were conducted in order to contextualize results from discourse and worksheet analysis. Each interview was analyzed for the presence of themes associated with student discourse (search purpose, content focus, and learning approach) and design worksheet analysis (search method and source). Students from both groups indicated that they primarily searched for two reasons: (1) to find a solution and (2) to validate a proposed solution. No student directly indicated that they were seeking out information to better understand (define) the problem, which suggests that their intention was to find solutions expediently through their search. This finding is not consistent with discourse analysis from the planning sessions, which demonstrated that students spent the least amount of time searching for direct solutions to the posed problem. All students who were interviewed noted that the reaction mechanism was the main content focus of their searching, which is consistent with the discourse analysis because mechanism was the most prevalent content focus of their discussion. Finally, students’ conveyed a tendency to use outside information superficially, but each student indicated that they “had their lecture notes open” for every experiment in order to “go back and look” at the reaction mechanisms. This suggests that deep learning approaches were employed by students, but were perhaps not a conscious strategy. Students appeared to recognize that “Googling” might not be better than using a scientific database or instructor provided materials, but indicated that they preferred the expedience of using Google.

Interview analysis also revealed that the two groups approached the information seeking process very differently, which is presumably due to differing levels of information literacy expertise between the groups. One member of group 2 was more information literate than the other members of the group. This group member’s skill appeared to influence the efficiency with which the group acquired and used outside information:

> Jim: *We searched on the, um, the Science Database to find journals that had the same type of information like we were trying to prove in our hypothesis. And usually we confined it*

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in their results section or their data section. We usually did that, because one of our group members like came from some science school, and he was like a perfectionist. Like he knew how to do all the citing and all that, so he was very good at finding us information to support our hypothesis.

This result was consistent with this group's performance on the worksheet, on which they scored above average based on the effective citation rubric (Table 3) for this (4 out of 4) and the other two experiments. Although the group performed well on their citation, the data does not provide information about whether the other students developed IL skills through their collaborative work with a more skilled group member. Also, this group does not appear to be representative of other student groups particularly as their performance on citation is above average.

By contrast, group 1 demonstrated lower IL skills. Two members of the group indicated that Google was preferred over instructor provided resources:

Dwight: *I mean we looked at them, but they were usually like really long and were like "Ehhh".*

This result was consistent with design worksheet analysis, which indicated that the group performed below average when citing references.

Do Students Develop Information Literacy Skills During PBL Experiments?

Students' demonstration of IL skills over the course of the term was investigated based on their design worksheets (N = 137), which were quantitatively analyzed. Students' overall citation behaviors are illustrated in Figure 3, which shows the percentages of student groups who (a) cited sources and (b) cited them correctly. Fewer student groups cited sources in their worksheets in the latter two experiments (Aldol and Esterification) than in the first experiment (Wittig). Only a very small portion of the student groups who cited used correct citation formats (Figure 3b). Only one student group cited sources in correct formats consistently across the three experiments. This group happened to be Group 2, who participated in discourse analysis and semistructured interviews and included a student who was more information literate compared to other members of the group.

A scoring rubric (Table 3) was applied to the citations in the worksheets and used to summarize students IL skills across the three experiments (Figure 6). The percentage of worksheets with no citation (score = 0) was the lowest (21%) in the first experiment and more than doubled in the later two experiments (47% and 43%, respectively). This is in part because the instructors provided five external resources for the first experiment (Wittig Reaction) on the course Web site, but only one and two external resources, respectively, in the later two experiments. Citing behaviors scoring 1 and 2 on the Worksheet of the first experiment (Wittig Reaction) were twice those for behaviors in the latter two experiments, whereas the percentages of integrated and traceable citations (scoring 3 and 4) were comparatively stable across the three experiments, which were 22%, 29%, and 28%, respectively.

Evidence of students' demonstration of information literacy skills is also seen in Figure 5, which illustrates percentage of citation failures by experiment. The percentage of failures decreased from the first experiment to the third one, giving the impression that students IL skills improved. Meanwhile, when we only consider the sources not provided by instructors (Figure 4), the ratio between the percentage of scholarly sources cited and the percentage of nonscholarly sources cited increased from 0.8 of the first experiment to 2.4 and 3.5 of the latter two experiments, respectively. However, the decrease in citation failure may not truly reflect improved IL skills because student groups, particularly those who scored poorly in the first experiment, cited less in the worksheets for later experiments. Thus, more proficient groups, who cited more consistently across, had an outsized effect on the occurrence of failures in later experiments. This is supported by Figure 6, which illustrates an increase in citations that scored 0 (did not cite) but was stable in citations that scored 3 and 4. Another possible explanation for the drop in citation overall is that the nature of the experiments varied as well as the number and type of instructor provided resources.

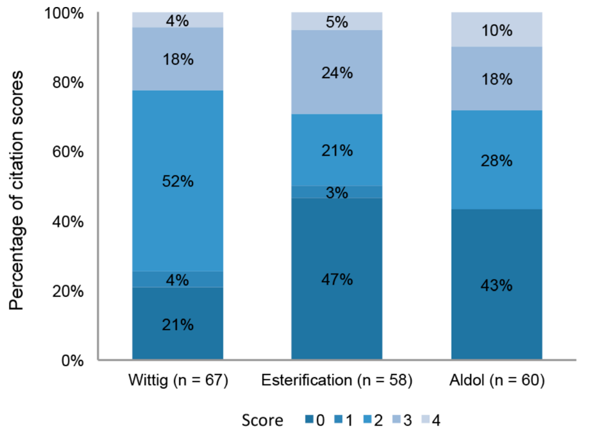

Figure 6. Citation effectiveness scores from design worksheets shown as percentage of student groups by score (0−4). Note the counts of citation occurrences at each score level are normalized with respect to the total number of citing occurrences in the worksheets of each experiment.

■ LIMITATIONS

The benefit of a mixed-methods approach is that the combined analysis of multiple data sources provides a richer portrait of a phenomenon than either qualitative or quantitative methods alone. However, the study was limited in that it relied on observational data and did not use an external measure to directly assess students' gains in literacy skills. Student discourse analysis was conducted based on short time periods in which students recorded their planning and did not capture discussion that may have happened outside of these sessions nor could it capture searching that was not articulated by the students. The student design worksheets, which were central to assessing the product of students information searching, were completed collaboratively by students and could not be used to assess individual students learning gains. Furthermore, analysis of the worksheets did not directly reveal the searching path students took. Semistructured interviews were conducted with only a small fraction of students, who were participating in other aspects of the study, and may not represent the full range of views held by students in the course. Finally, students' information seeking behavior was influenced by a complex set of factors including experiment and problem type, group expertise, and instructor-provided resources. Unobserved factors may also contribute to how they sought outside information. For example, students may be influenced by their graduate student instructor in class and through their feedback on the worksheets.

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■ DISCUSSION

This study presented a mixed-methods approach to investigate how students sought and used outside information during problem-based organic chemistry labs and to investigate whether they developed information literacy skills in this context. The process by which students sought and used outside information was investigated using multiple data sources including (1) student discourse during problem-solving sessions, (2) students' proposed experimental designs, and (3) end-of-term student interviews. Analysis of these data revealed that students searched for direct solutions to the posed problems rather than intentionally searching for information to help them understand the problem, that they acquired and used information that was most accessible, that they frequently failed to evaluate the credibility of the information, and that they used information as-is in their problem solving process.

Students engaged in self-directed learning (SDL) while seeking to solve the posed problem for each experiment (Figure 1) and sought outside information to aid in their problem solving process. Although interviews revealed that their intended goal in searching for information was to find a direct solution to the posed problem, the discourse analysis revealed that they also sought information to understand the nature and extent of the posed problem. This suggests that finding and using information to understand the problem occurred inadvertently, even though it was not necessarily a conscious strategy.

Analysis of all data sources indicated that students frequently relied on Google for expedient searching and obtained information from sites, such as Wikipedia or commercial sites, as sources to support their proposed solutions. The analysis of citations included in students' worksheets revealed that many of the sources were found as the top 10 items in a Google search. This suggests a propensity by students to use the information that is most readily available. This result is consistent with a prior study by Kim, who found that students prioritized accessibility when selecting information sources over other ideal criteria.[22]

Very little evidence suggested that students evaluated the credibility of the information they acquired. Analysis of student discourse during problem solving sessions revealed that students never discussed together whether a source of information was credible. This suggests that their evaluation of a source was done individually or not at all. The students also did not demonstrate through their experimental designs an ability to critically evaluate the credibility of outside information. They frequently cited Web sites that contained major warning signs, and when these sites were used, they failed to follow the flow of information to track the original source. In these cases, if students had the capacity to evaluate the information, they did not exercise it during the problem-based activities.

The analysis of students' design worksheets also provided quantitative information about students' citing behaviors. Students' development of IL skills was inferred from the change in citing behavior across the three experiments. Despite worksheet instructions specifying that students use external resources as well as resource examples provided by the instructor, the percentage of student groups who did not cite any sources increased from the first experiment to the latter two. The percentage of citations with traceable information that were integrated in the worksheet writing was stable around 20–30% across the three experiments. This implies that without enforcement of the requirement to cite sources, students did not recognize the need for evaluating and citing resources, unless there were grouped with a more proficient student. This was corroborated by analysis of the discourse and worksheet analysis of Group 2.

Over the course of the term, the ratio of nonscholarly sources to scholarly sources cited decreased. Issues that were observed in students' evaluation and citation of sources also decreased. However, the data was not sufficient to attribute these trends to improvement of students' IL skills because student groups who did not demonstrate a proficiency on IL in early worksheets stopped citing later on. Thus, the more proficient groups may have contributed to an appearance of improvement that was not representative of the overall class. Other factors may also influence students' citation behaviors including the nature of the experiments themselves, the resources provided by the instructor, and the failure of student groups to cite sources in later experiments which could not be accounted for. Finally, one issue may be that there simply was not a sufficient number of students in the course who had strong IL skills and could act as peer mentors to those with weaker IL skills.

These findings suggest that the IL skills for a majority of the students are not improved through PBL in this context. Thus, explicit information literacy instruction should be used to scaffold student development of these skills in the context of PBL activities particularly because weak IL skills may adversely impact their problem solving process. On the basis of our findings, we recommend that the focus of instructional scaffolding should be to help students recognize information needs and to evaluate information resources. Students should be encouraged to think about what information is needed to solve the problem and to explore external resources on their own. This should be followed by a guided discussion about how to evaluate resources so that students can more readily identify criteria and signs of credibility when selecting and using data and information. Once students recognize that results generated by simple Google search are not always reliable or sufficient to solve their problem, they can be provided with an introduction on how chemical information is organized, a list of resources including databases available, and basic search strategies as a new start point for students to begin exploring on their own. More advanced search techniques can be learned after novice learners are exposed to information in a problem-solving context or in more advanced courses.

It is important to keep in mind that instructors serve as facilitators in a problem-based learning environment. For this reason, a long lecture on information searching may not be appropriate. Preferred approaches will use a series of carefully designed group activities with guided questions or a series of brief tutorials with sufficient examples to demonstrate possibilities in exploring the chemical information world.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00523.

Additional tables and figures containing more detailed information about the results of the discourse analysis and student artifact analysis (PDF, DOCX)

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