

Primary Literature in Undergraduate Science Courses: What are the Outcomes?

By *Jeremy David Sloane*

Primary literature—consisting of novel peer-reviewed articles and conference proceedings—has been associated with several positive outcomes for students within undergraduate science courses. Primary literature is the principal method of written scientific communication and emphasizes the development of scientific knowledge. It also provides a window into researchers’ methods and logic used to explain natural phenomena. However, despite evidence demonstrating the benefits of using primary literature in undergraduate science courses, no review of this literature exists. This article reviews several approaches to teaching with primary literature in undergraduate science courses and student outcomes associated with these approaches.

Databases that feature research in science education, including Web of Science and ERIC, were searched for the keywords “primary literature” and “scholarly literature.” Only those articles that featured descriptions of the use of primary literature in undergraduate science courses and outcomes were selected. After selecting all of the papers found through these searches that fit this description, the bibliographies of each of these papers were explored for further selection. In all, 19 articles were selected for review.

Articles reviewed were published between 1997 and 2017, described instruction in general science, biology, neuroscience, chemistry, and biochemistry courses, and relied heavily on self-reported data. Use of primary literature ranged from a single assignment to a full semester of primary literature as the sole source of curriculum materials to a yearlong undergraduate research program. In this literature review the major outcomes that have been documented will be described, as will the methods used to help students learn through primary literature. Recommendations for future research and practice are also provided. The outcomes emerged through review of the introduction sections of several articles (Carter & Wiles, 2017; Gottesman &

Hoskins, 2013; Hoskins et al., 2007; Hoskins et al., 2011; Kozeracki et al., 2006; Porter et al., 2010; Round & Campbell, 2013; Segura-Totten & Dalman, 2013; Stevens & Hoskins, 2014; Stover, 2016) and sorting based on the descriptions of the outcomes provided. Example phrases and descriptions that were categorized under each outcome include:

- Content knowledge: “content knowledge,” “conceptual understanding,” and “achieve content-specific course goals.”
- Research and data analysis skills: phrases that included references to skills related to research or data (e.g., “data interpretation skills,” “skills in designing experiments,” “abilities to interpret data,” “explain research,” and “scientific process skills”).
- Critical-thinking skills: references to Bloom’s Taxonomy, “critical thinking,” “critical analysis,” “logical,” and “illogical.”
- Scientific literacy and information literacy: “scientific literacy,” “information literacy,” “literature searching skills,” “biological literacy,” and descriptions of the ability to distinguish between primary and secondary literature.
- Understanding of the nature of science: “nature of science” as well as characteristics of science

(e.g., how it is done, the creativity of scientists, and the certainty of knowledge).

- Attitudes toward science and scientists: “attitudes,” “appreciation,” and “interest.”

Table 1 identifies which approaches have been associated with each outcome. The blank cells in this table help to identify potential avenues for future research.

The approaches used to help students learn through primary literature will be described in detail in the following sections; however, working definitions of each approach are as follows:

- **Journal Club:** a group discussion on journal articles that generally involves a rotation of the individuals leading the discussion.
- **C.R.E.A.T.E.:** a novel, well-defined approach that involves students reading four articles from one laboratory in sequence and analyzing the figures of each article before gaining access to the full text.
- **POGIL:** another well-defined approach wherein students are given a model and tasked with exploration, development, and application.
- **Figure Facts:** a template that students fill in as they read an article; similar to C.R.E.A.T.E., Figure Facts requires that students take a data-centric approach to reading the paper by analyzing the figures and figure panels.
- **Read Articles and Answer Questions:** instructor selects an article for students to read (in class or outside of class) and tasks students with answering a set of instructor-selected questions

based on the article.

- **Literature Search Instruction:** instruction on how to locate and access scholarly literature.

The research question for this study is: What outcomes have been associated with the use of primary literature in undergraduate science courses, and which methods of teaching with primary literature are associated with which outcomes?

Content knowledge

Improved content knowledge is one of the most widely cited outcomes of using primary literature in undergraduate science courses. For example, DebBurman (2002) reported that students perceived improvements in their understanding of cell biology after exposure to primary literature as part of a sophomore-level course that integrated five mock experiential research projects with a lecture and laboratory. According to post-course surveys, students believed that the research projects helped them achieve content-specific course goals and strengthened cell biology learning (DebBurman, 2002).

Yeong (2015) also used primary literature in a cell biology course. The author chose a specific paper (Yalcin et al., 2009) because it explored the functional interactions of seemingly unrelated processes, including glycolysis, protein transport, and cell cycle regulation. Students were asked to read this article and answer several questions in essay format. Students indicated in a postintervention survey that the assignment helped them understand the three previously mentioned cellular processes individually and collectively (Yeong, 2015).

The C.R.E.A.T.E. (Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experi-

ment) method is a novel approach and has shown promising results regarding content knowledge (Hoskins et al., 2007). It requires students to read four articles from the same authors in sequence to study the evolution of scientific knowledge over time. The method takes a data-centric approach, requiring instructors to withhold large portions of the text from students as they first answer questions related to the article’s figures. In their article that first introduced the C.R.E.A.T.E. method, Hoskins and colleagues concluded that using the C.R.E.A.T.E. method in an upper-level biology elective resulted in increases in students’ conceptual understanding of course content based on increased complexity of concept maps from pre- to postinstruction (Hoskins et al., 2007).

Content knowledge was also reported to improve when the C.R.E.A.T.E. model was used in a special topics ecology and evolution course for which primary literature was the only source of content material (Carter & Wiles, 2017). Students in this course participated in online discussions where they posted summaries of the papers, responses to summaries, and potential experiments. Eighty-three percent of the students in the course indicated that they believed their biology content knowledge improved after taking the course.

Kozeracki and colleagues also found evidence of improved content knowledge resulting from an intensive, literature-based teaching program known as the Howard Hughes Undergraduate Research Program (HHURP) (Kozeracki et al., 2006). It consisted of a weekly journal club, research presentations, seminar speakers, career guidance, and a scholarship. The weekly jour-

nal club was considered the central component of the program. Alumni of the program indicated in a survey that they believed participation in the journal club had a positive impact on their knowledge of scientific content outside their majors or main areas of research.

Additionally, content knowledge was reported to improve when Process Oriented Guided Inquiry Learning (POGIL) was used in a biochemistry sequence (Murray, 2014). POGIL engages students in small groups on materials provided by the instructor intended to develop process skills in addition to content knowledge. Students are typically given a model (figures, tables, etc.) and tasked with exploring the model, developing related concepts, and applying them to new situations. Murray used figures and tables from primary research articles for four POGIL activities throughout the academic year. Students self-reported gains in their understanding of course topics throughout the academic year and that each article and activity helped their learning, suggesting that using POGIL to read and understand primary literature increases students' knowledge of relevant content (Murray, 2014).

Content knowledge was also reported to improve when a journal club was integrated into a senior seminar on evolutionary biology that featured a gradual transition of leadership of the discussions from faculty to students (Muench, 2000). Students self-reported that the course helped them understand primary literature better than they were able to before and they learned more from writing the paper based on primary articles than they learned from writing in other courses (Muench, 2000).

With the exception of the study by

Hoskins and colleagues (2007), all of the studies that report improved content knowledge rely on self-reported data and none include a comparison group (Table 1). This is problematic as students may overestimate or underestimate their content knowledge. Future research should use performance data and include a comparison group to determine whether primary literature really is more effective at improving content knowledge than other curriculum materials, such as textbooks.

Research and data-analysis skills

Other commonly reported benefits of using primary literature in undergraduate science classrooms are enhanced research and data analysis skills, the latter of which broadly includes data in the form of raw data, figures, and statistical analysis output. Evidence of this comes from a study by Round and Campbell in which the authors introduced a new data-centric approach to reading primary literature called "Figure Facts" (2013). The Figure Facts template is mostly related to the figures, and for each figure panel, students write out which technique the authors used and what the conclusion was for that panel. Round and Campbell used Figure Facts in an advanced cellular neuroscience course and administered data interpretation skills tests at three times during the semester. The students experienced statistically significant improvement in their data interpretation skills as measured by their test scores between weeks 1 and 9 of the semester, with further improvement between weeks 9 and 15 that did not reach statistical significance (Round & Campbell, 2013).

The C.R.E.A.T.E. method has

also shown promising results regarding research and data analysis skills (Gottesman & Hoskins, 2013; Hoskins et al., 2011; Hoskins et al., 2007). Students involved in the first study on C.R.E.A.T.E. self-reported improved skills in designing experiments and relating methods to data in survey responses (Hoskins et al., 2007). Students involved in a later study exhibited statistically significant improvement from the beginning to the end of the semester in their self-assessed abilities to interpret data (Hoskins et al., 2011). Additionally, when Gottesman and Hoskins adapted the method for an introduction to scientific thinking course for first-year students, survey scores indicated significant improvement in self-assessed abilities to interpret data for students in both courses over the course of the semester (2013). Scores on an Experimental Design Ability Test (EDAT) also improved significantly for the first-year students from pre- to postsemester (Gottesman & Hoskins, 2013).

Stover also reported improved data analysis skills when primary literature and Penn & Teller's Showtime TV series *Bullshit!* were used in a current topics in biology course to distinguish between science and pseudoscience (2016). Most of the papers studied described experimental studies, and students were asked to answer basic questions about each paper. Before class discussions, the topic was introduced in an episode of *Bullshit!* in which Penn & Teller reinforce their opinions on the topics with scientific evidence. Students were encouraged to critique the reasoning Penn & Teller used. Stover reported that students learned to recognize the type of study presented in a journal article and how to analyze the data accordingly, although no analysis of

TABLE 1

Outcomes associated with each approach for utilizing primary literature.

		Outcome					
		Content knowledge	Research and data-analysis skills	Critical-thinking skills	Scientific/information literacy	Understanding of the nature of science	Attitudes toward science and scientists
Approach	Journal Club	DeBurman (2002) (SR) Kozeracki et al. (2006) (SR) Muench (2000) (SR)	DeBurman (2002) (SR) Glazer (2000) (ND) Kozeracki et al. (2006) (SR)	Kozeracki et al. (2006) (SR)	Glazer (2000) (ND) Kozeracki et al. (2006) (SR)		
	C.R.E.A.T.E.	Carter & Wiles (2017) (SR) Hoskins et al. (2007)	Gottesman & Hoskins (2013) Hoskins et al. (2007) (SR) Hoskins et al. (2011) (SR)	Gottesman & Hoskins (2013) (CG) Hoskins et al. (2007) Segurra-Totten & Dalman (2013) (CG) Stevens & Hoskins (2014) (CG)		Carter & Wiles (2017) Gottesman & Hoskins (2013) (CG) Hoskins et al. (2007) (SR) Hoskins et al. (2011) Stevens & Hoskins (2014) (CG)	Hoskins et al. (2007) (SR) Stevens & Hoskins (2014) (SR, CG)
	POGIL	Murray (2014) (SR)					
	Figure Facts		Round & Campbell (2013)				
	Read Article & Answer Questions	Yeong (2015) (SR)	Janick-Buckner (1997) (SR) Yeong (2015) (SR)	Sato et al. (2014) (CG) Smith (2001) (SR)	Smith (2001) (SR)		
	Literature Search Instruction			Smith (2001) (SR)	Ferrer-Vinent et al. (2015) (SR) Porter et al. (2010) Smith (2001) (SR)		
	Other	DeBurman (2002) (SR) Kozeracki et al. (2006) (SR)	DeBurman (2002) (SR) Kozeracki et al. (2006) (SR) Stover (2016) (ND)	Kozeracki et al. (2006) (SR) Segurra-Totten & Dalman (2013)	Ferrer-Vinent et al. (2015) (SR) Kozeracki et al. (2006) (SR) Porter et al. (2010)		

Notes: (1) "SR" denotes an outcome that is based only on self-reported data; (2) "ND" denotes an outcome for which there is no discussion of how it was assessed; (3) "CG" denotes a study that used a comparison group.

data analysis skills was presented or discussed. Stover also reported that students became more cognizant of reasoning errors used by the general public to reject scientific evidence. Stover did not delineate whether the cause for these improvements was the primary literature, the Penn & Teller series, or both.

Janick-Buckner has also conveyed that her students' research and analysis skills improved after taking a cell biology course based on the critical reading of primary literature (1997). For this course, students were required to read journal articles and respond to questions posed by the instructor. Student responses to survey questions at the end of the semester indicated that the course helped them with their own undergraduate research in that they felt their ability to design their own experiments and interpret their own data improved. Students also indicated that they felt their analytical skills improved as a result of their experience in the course.

Similarly, Glazer reported that students who took a developmental biology course with a journal club component experienced improvement in their data interpretation skills (2000). Students in this course read primary literature before class and then worked in small groups to prepare specific topics for presentation during class. Glazer stated that "the journal club proved to be a successful vehicle for introducing a variety of new skills" (p. 324), including data interpretation skills, although it is unclear whether she based her conclusion off of student surveys, her observations of the students, or something else (2000).

Three of the studies described in the previous section also reported improved research and/or data analysis skills. Students who took the sophomore cell biology course exper-

rienced significant improvement in self-reported scientific process skills, including their ability to communicate contemporary research and primary literature (DeBurman, 2002). Additionally, when an instructor asked students to read primary literature to help them make connections among different cellular processes, student comments revealed that they believed the course helped them learn how to analyze research data (Yeong, 2015). Furthermore, alumni of the HHURP program self-reported that participation in the weekly journal club improved their abilities to critique scientific research, formulate probing questions about scientific journal articles, explain their own research to others, and design and implement their own undergraduate research (Kozeracki et al., 2006).

It should be noted that only two of the studies (Gottesman & Hoskins, 2013; Round & Campbell, 2013) in this section actually use performance data by students; the others rely on self-reported data or do not discuss how the outcome was assessed (Table 1). Furthermore, only Gottesman & Hoskins (2013) used a comparison group in their study, although how the comparison group scored on the EDAT was not discussed. Future research should use performance data and, ideally, compare scores or gains to a similar group to determine how effective the primary literature was at improving these skills.

Critical-thinking skills

There is also evidence that the use of primary literature in undergraduate science courses can boost students' critical-thinking skills. For example, when a critical-thinking test containing six questions based on the Field-tested Learning Assessment Guide (FLAG; National Institute for Science Education, n.d.) was adminis-

tered before and after a C.R.E.A.T.E.-based neuroscience course, students gave a significantly greater number of logical statements for four of the six questions on the posttest as compared to the pretest and a significantly lower number of illogical statements for three of the six questions on the posttest as compared to the pretest, with the other questions showing no significant differences (Hoskins et al., 2007). These results suggest that exposure to primary literature improves students' abilities to think critically about data and whether conclusions drawn from data are logical. Similarly, when C.R.E.A.T.E. was adapted for a first-year science course, scores on the Critical Thinking Ability Test (Stein et al., 2012) showed that students experienced significant improvement in their critical-thinking abilities precourse to postcourse, with a large effect size (Gottesman & Hoskins, 2013).

Stevens and Hoskins also found that students from many different types of institutions experienced critical-thinking skills gains after exposure to the C.R.E.A.T.E. method (2014). The critical-thinking test administered before and after the course contained four questions from the critical-thinking test used in the original C.R.E.A.T.E. study (Hoskins et al., 2007). Pooled data from all of the C.R.E.A.T.E. implementations across institutions showed that students overall exhibited significant increases in their logical statements for all four test questions, suggesting improvement in their abilities to critically analyze data. The authors also found that gains were seen on more of the test questions and with larger effect sizes for the full-semester implementations as compared to the partial-semester implementations, suggesting that the greater the exposure to primary literature, the greater the

improvement in critical-thinking skills (Stevens & Hoskins, 2014).

Segura-Totten and Dalman were interested in whether the critical-thinking gains experienced by students involved in C.R.E.A.T.E. were specific to the C.R.E.A.T.E. method (2013). They compared scores of students in a modified C.R.E.A.T.E. section of cell biology to those in a section that used a more traditional method of exploring primary literature that featured discussions of instructor-generated questions. The authors designed their own critical-thinking test consisting of six questions based on Bloom's Taxonomy. Students in both groups showed equal gains in analysis and synthesis questions but not evaluation questions. They also found that while there was significant improvement in students' article critiques throughout the semester across the board, there was no significant difference in scores between the groups (Segura-Totten & Dalman, 2013).

Smith also found evidence of critical-thinking gains when he used primary literature in an ecology and evolution course (2001). Students were gradually introduced to primary literature throughout the course through various literature explorations. The students also completed a library project during the semester for which they had to find their own primary sources to investigate a scientific question. At the end of the semester, students self-rated their ability to think critically as a scientist as significantly different (greater) than a null hypothesis of three out of five (Smith, 2001). Of course, whether the students' own perceptions of their critical-thinking skills matched their actual critical-thinking gains is unknown. Additionally, it is unknown whether perceptions of critical-thinking skills were the result of the literature search explorations,

library project, or another factor.

Two additional studies also reported improved critical-thinking abilities resulting from working with primary literature. When a primary literature module that required students to answer questions about journal articles was used in biochemistry, molecular biology, and microbiology lab courses, and students completed a quiz based on levels one through six of Bloom's Taxonomy, returners scored higher on the quiz than first-time students (Sato et al., 2014). Because the returners had previously taken another one of the lab courses with the primary literature module, these results suggest that using primary literature may result in longitudinal gains in the ability to think critically. Additionally, when students participated in the HHURP, some self-reported that the program pushed them to think critically and gave them confidence in criticizing research papers, a task that certainly requires critical thinking (Kozeracki et al., 2006). However, the specific components of the program that influenced their critical-thinking skills are unknown, and may or may not have included the weekly journal club.

The evidence reviewed for improvement in critical-thinking skills is stronger for this outcome as compared to previously reviewed outcomes. Several studies used a comparison group, and all but two analyzed performance data as compared to self-reported data (Table 1). Evidence that is based on performance data and uses comparison groups is more substantial than that which does neither, as there is greater reason to believe that the primary literature is truly responsible for the observed outcome.

Scientific literacy and information literacy

Information literacy refers to a gen-

eral ability to locate, evaluate, and use information when it is necessary (Association of College and Research Libraries, 2006). A related concept is scientific literacy, or the ability to comprehend, analyze, and evaluate scientific data while integrating these data into a larger body of scientific knowledge (Gillen, 2006; NRC, 1996; Porter et al., 2010). Information literacy and scientific literacy require similar skills and cognitive abilities (Porter et al., 2010). In fact, the American Association for the Advancement of Science (AAAS) has called for undergraduate science courses to work toward improving students' scientific (biological) literacy (2011). Porter and colleagues found evidence that an integrated information literacy program (known as the Scientific Method and Information Literacy Exercise, or SMILE) within a general biology course holds the potential to improve both information literacy and scientific literacy for college students (2010). SMILE students attended two workshops, which introduced information literacy concepts and modeled how to effectively read and analyze a research paper. Students later selected, retrieved, analyzed, and evaluated an article of their choosing. The students completed a pretest before the workshops and a posttest at the completion of SMILE. The authors found that significantly more students changed their answers from incorrect to correct than vice-versa on the questions about the definition of a secondary article and the definition of a figure. Furthermore, 90% of students were able to correctly identify the definition of a primary article at the completion of SMILE. The authors interpreted these results to mean that SMILE helped students distinguish between primary and secondary scientific literature, a skill necessary for both informa-

tion literacy and scientific literacy. Whether the workshops, article activity, or both are responsible for the reported results remains unknown.

Evidence of improved information literacy resulting from exposure to primary literature was also reported by Ferrer-Vinent and colleagues after they implemented primary literature modules in two general chemistry courses (Ferrer-Vinent et al., 2015). The general chemistry I module consisted of formal library instruction from a science librarian and exercises in retrieving articles and writing proposals for follow-up experiments. Analysis of scores on a literature-searching skills test before and after the library instruction session revealed significant improvement in these skills. For the general chemistry II module, students again were asked to design their own experiments using primary literature, but also had to work in the laboratory to design the actual procedures for the experiment. Throughout the academic year, students kept track of the number of resources they located and viewed. The authors proposed that because information literacy refers to the ability to locate and use information, the number of resources viewed is an indication of competency in these skills (Ferrer-Vinent et al., 2015). However, this can be viewed as problematic because it is plausible that students viewed resources that were not useful. Additionally, while 50% of the students self-reported never having used a scientific literature database before the course, only 4% self-reported not having used these tools since the completion of the course. The authors interpreted these results to mean that the students received a strong foundation in the information literacy skills necessary to locate and assess scientific literature, although

they acknowledged that the general chemistry course likely did not cause students to use literature in later courses. Student survey responses revealed that they believed that the instruction was useful in helping them find relevant information for their projects (Ferrer-Vinent et al., 2015).

Improved scientific literacy resulting from working with primary literature has also been reported in other sources. After primary literature explorations were used in an ecology and evolution course, students self-reported that the literature explorations were effective in advancing the departmental goal of biological literacy (Smith, 2001). Kozeracki and colleagues concluded that HHURP improved students' scientific literacy based on student answers to program assessment questions (2006), although how exactly this conclusion was drawn from the responses and which components of the program were responsible for the improvement were not discussed. Glazer determined that a journal club integrated into a developmental biology course was a "successful vehicle to science literacy" (p. 324) because of the skills that the club was designed to help students develop (2000). For all three of these studies, however, any strong empirical evidence for improvement in scientific-literacy skills is lacking. Of the articles in this section, only Porter et al. (2010) analyzed performance data and none contained a comparison group (Table 1).

Understanding of the nature of science

The nature of science generally refers to the values and beliefs inherent to the development of scientific knowledge, although the term often encompasses a great deal more than one concise definition (Crowther

et al., 2005). It is often regarded as an essential component of scientific literacy (AAAS, 1990; Lederman et al., 2013). The study by Carter and Wiles provided empirical evidence that using primary literature may influence students' conceptions of the nature of science (2017). Students' conceptions were assessed using the VNOS-C as described by Lederman and colleagues at the beginning and end of the semester (Lederman et al., 2002). The authors observed increases in informed responses and decreases in naïve responses in all nature of science categories except for the theory/law category. Student comments also revealed that the course helped them understand how science worked "in the real world" or "in real life" (p. 530), which the authors interpreted to mean that the students potentially viewed science as less abstract and better understood the processes of science (Carter & Wiles, 2017).

There have also been other reports of improved understanding of the nature of science after exposure to the C.R.E.A.T.E. method in undergraduate science courses, although how this benefit was worded varied. Students from the first C.R.E.A.T.E. study self-reported that C.R.E.A.T.E. helped them make gains in understanding "how science is done" (Hoskins et al., 2007). In a later study, researchers concluded that after working with the C.R.E.A.T.E. method, students experienced significant positive shifts in their conceptions of the certainty of knowledge, the creativity of scientists, whether scientists know what the outcomes of their experiments will be, whether scientists collaborate, and the motives that drive scientists (Hoskins et al., 2011). Gottesman and Hoskins reported that first-year students exhibited shifts in their conceptions

of the certainty of knowledge, the creativity of science, and scientists as people (2013). Students enrolled in an upper-level course exhibited significant shifts in their conceptions of the certainty of knowledge, sense of scientists as people, and sense of scientists' motivations (Gottesman & Hoskins, 2013). Furthermore, pooled data from full-semester C.R.E.A.T.E. implementations across several different institutions showed significant shifts in students' views of the creativity of science and their sense of scientists and scientists' motivations (Stevens & Hoskins, 2014).

In this section, all but one article used performance data and several used comparison groups—providing strong evidence that the C.R.E.A.T.E. method improves students' conceptions of the nature of science (Table 1). However, C.R.E.A.T.E. is the only approach that has been investigated for this outcome. Future research should attempt to quantify whether other approaches, such as the journal club and reading article/answering questions, can also improve students' conceptions of the nature of science.

Attitudes toward science and scientists

The C.R.E.A.T.E. method has been shown to improve students' attitudes toward science and scientists. For example, students self-reported gains in their appreciation of biology, their enthusiasm for scientific research, and the extent to which they believed their interest in scientists would be remembered and carried with them into other classes or aspects of their lives (Hoskins et al., 2007). Similarly, when data from C.R.E.A.T.E. implementations at several different institutions were pooled, results indicated that students experienced significant positive shifts in their ap-

preciation of the scientific field that they learned about in their respective courses (Stevens & Hoskins, 2014). For the former study, students self-reported shifts in their attitudes at the end of the semester (Hoskins et al., 2007); for the latter study, students self-reported their attitudes at the beginning and end of the semester and the researchers quantified the changes (Stevens & Hoskins, 2014). Again, however, both studies used the C.R.E.A.T.E. approach; future research should attempt to quantify changes in attitudes towards science and scientists for other approaches.

Conclusion

Primary literature is the principal method of written communication between scientists and is unique in its emphasis on how knowledge is developed. Clearly, the use of primary literature is beneficial for undergraduate students in a variety of ways, and can simultaneously expose students to scientific methods while promoting active learning in and out of the classroom. It is evident from this review, and particularly Table 1, that certain approaches are associated with specific outcomes more than others. For example, literature search instruction is associated with improved scientific and/or information literacy, and the C.R.E.A.T.E. method is associated with improved understanding of the nature of science. It is impossible to know, though, whether these associations exist because these specific approaches lead to these outcomes, or because researchers who studied specific approaches only tested for certain outcomes. Future research should delineate which approaches lead to which outcomes by testing for several or all of these outcomes for each approach.

Furthermore, most of the studies reviewed here rely on self-reported data from students. While such evidence is informative, it is not as reliable as evidence derived from performance data or validated instruments since students may overestimate or underestimate their own knowledge or abilities. Ideally, future studies should rely less on self-reported data and more on performance data and previously validated instruments (e.g., the Biology Concept Inventory [Klymkowsky et al., 2003] for content knowledge, the California Critical Thinking Skills Test [Facione, 1990] for critical-thinking skills, and the VNOS-C [Lederman et al., 2002] for nature of science).

Additionally, while these studies report benefits of using primary literature in undergraduate science courses, few of them actually compare the benefits of one source of content material versus another. Future studies should compare the benefits obtained by using primary literature to those obtained by using other materials, such as textbooks. Future research can also compare different methods of using primary literature to others and also explore the outcomes of using primary literature in additional disciplines, including physics and geology.

The major limitation of this study is that it is not a systematic review, and thus may not contain all published articles that describe the use of primary literature. Another limitation is that there is likely to be overlap among some of the outcomes (e.g., data-analysis skills and critical-thinking skills). These outcomes were treated separately in this review as they were reported independently by researchers. Regardless, given the vast number of documented benefits of using primary literature in undergraduate science courses and wealth

of evidence supporting them, I highly recommend that undergraduate science instructors give their students the opportunity to read, analyze, and discuss primary literature in their courses so that students behave more like scientists. Providing literature search instruction and helping students learn how to read and understand primary literature, specifically, may go a long way toward helping students grow as scientists and prepare for their careers in science.

While scientific literacy is the only outcome here that is aligned with a main goal in AAAS's *Vision and Change*, the AAAS goal of cultivating biological literacy also contains elements of some of the outcomes described here (2011). For example, the "core concepts for biological literacy" (p. 12) contain concepts that can be considered essential components of content knowledge in biology, including evolution; structure and function; and information flow, exchange, and storage (AAAS, 2011). Furthermore, the biological literacy core competencies of "ability to apply the process of science" and "ability to use quantitative reasoning" (p. 14) are partially aligned with the outcome of "research and data analysis skills," as these skills involve applying science and quantitative reasoning. Finally, outside of the specific discipline of biology, the National Academy of Sciences has called for improving underrepresented minority participation in STEM in part through offering research experiences (2011). While using primary literature in undergraduate science courses does not provide a fully authentic research experience, it helps expose students to research through study of the principal form of written communication between scientific researchers. It is possible that by using primary literature in undergraduate science courses,

we may help get underrepresented students excited about research and interested in participating. ■

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Jeremy David Sloane (jsloane@skidmore.edu) is an instructor in the Department of Biology at Skidmore College in Saratoga Springs, New York.
