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A qualitative study examining the exclusive use of primary literature in a special topics biology course: improving conceptions about the nature of science and boosting confidence in approaching original scientific research

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ABSTRACT

This qualitative study explores the experiences of six students enrolled in a special topics biology class that exclusively used primary literature as course material. Nature of science (NOS) conceptions have been linked to students' attitudes toward scientific subjects, but there has been little research specifically exploring the effects of primary literature use on NOS conceptions. To explore these effects, we used both written responses to an established and validated NOS survey taken at the beginning and end of the course and reflective essays in which students described in detail their experiences with using primary literature. The results indicate positive gains in various aspects of NOS conceptions as well as increased confidence with approaching original research. We conclude by suggesting that future research should focus on how primary literature use affects nature of science conceptions. We also suggest the expanded use of primary literature in biology education

KEYWORDS
Nature of science, confidence, primary literature

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Introduction

Although scientists do communicate in other ways—personal correspondences, presenting papers and posters at conferences, etc.—the most important, thoroughly vetted, durable, and far-reaching way that scientists communicate is by publishing primary literature. Primary literature is the vehicle by which new research is reported to the scientific community worldwide, where methods, data, analyses, interpretations, and conclusions, are

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subjected to further scrutiny, perhaps further validated, built upon, critiqued, or replicated by other researchers. Primary research may also inform policy, or inspire new research questions or technologies. Research shared in vetted publications may be viewed as the building blocks for our overall understanding of phenomena.

Primary literature has been used by science instructors in a variety of ways, often to achieve specific educational goals (Muench, 2000). Some instructors have used primary literature "journal clubs" as a sort of gateway to writing reviews and writing up laboratory exercises in the style of scientific articles (DebBurman, 2002) or to build skills in understanding, interpreting, and presenting data (Glazer, 2000). Others use primary literature to demonstrate paradigm shifts in science as a nature of science component to their course (Hoskins, 2008), to demonstrate how research progresses in the real world by focusing on works from a particular laboratory (Hoskins, Stevens, & Nehm, 2007), or to promote active and cooperative learning (Kitazono, 2010). Brill and colleagues suggest journal clubs be used by teachers to stay abreast of advances in science (Brill, Falk, & Yarden, 2003). Whole curricula may even be designed around primary literature (Yarden, Brill, & Falk, 2001). It is clear that educators have many different goals in mind when electing to use primary literature in the classroom, but what has the research shown about outcomes for students?

One of the major desired outcomes of using primary literature is boosting science literacy in students (DebBurman, 2002; Glazer, 2000; Hoskins, Lopatto, & Stevens, 2011; Hoskins et al., 2007; Kozeracki, Carey, Colicelli, & Levis-Fitzgerald, 2006; Muench, 2000; Yarden et al., 2001). In some cases, this outcome was even achieved (Glazer, 2000; Kozeracki et al., 2006). Increased critical thinking skills are also a frequently-cited outcome (Hoskins et al., 2011, 2007; Kozeracki et al., 2006; Muench, 2000; Sato et al., 2014). Improved research and data analysis skills have also been reported (DebBurman, 2002; Glazer, 2000; Hoskins et al., 2011; Round & Campbell, 2013). Confidence in approaching and understanding scientific literature is also a reported outcome of primary literature use (Glazer, 2000; Hoskins et al., 2011; Murray, 2014; Round & Campbell, 2013; Sato et al., 2014). Research has also shown that students' epistemological understandings and their conceptions of science as a human endeavor can be improved through exposure to primary science literature (Hoskins et al., 2011). One study even found evidence that teaching using primary literature helped facilitate students' transition to doctoral programs (Kozeracki et al., 2006). Certainly, there are excellent potential benefits to students from using primary literature.

Hence, we used primary literature as our sole source of content material in a special topics biology course, and during this process, we sought to better understand what effects the use of primary literature might have on the students. Because some of the readings focused on shifting understandings of phenomena (Heil et al., 2009; Janzen, 1973), research programs by a particular lab or researcher (http://evolution.berkeley.edu/evolibrary/article/0_0_0/bostwick_01), and also looked broadly at science and society by covering the targeting of some evolutionary biology research that had been branded as "frivolous government spending" by certain political pundits (Brennan, 2013), we hypothesised that students' nature of science views will improve as has been observed by Hoskins (2008). Postsecondary NOS instruction is discussed in great depth by Dushl and Grandy (2012). Notably, explicit reflective NOS instruction has been deemed necessary but not sufficient alone for improving NOS views (Khishfe and Abd-El-Khalick, 2002). Additionally, as previous research around instruction using primary literature has shown increases in content knowledge in specific areas of biology (DebBurman, 2002; Glazer, 2000; Hoskins, Lopatto, & Stevens, 2011; Hoskins et al., 2007; Kozeracki, Carey, Colicelli, & Levis-Fitzgerald, 2006; Kozeracki et al., 2006; Muench, 2000; Yarden et al., 2001), we wondered if perhaps students' overall biological content knowledge might improve based on the variety of topics covered during the course and the breadth of individual research done by the students in selecting and exploring presentation topics for the course.

Methods

Since little previous research has focused on how the use of primary literature in courses on ecology and evolution might affect students' views on the nature of science, we endeavored to explore this potential connection in the context of a course entitled "Topics in Ecology and Evolution". In this course, students were guided toward understanding how the science reported in individual research articles contributed to a broader understanding of different natural phenomena. Students read several primary research literature articles per week and participated in online discussions wherein they posted summaries of and responses to the assigned research papers, explored their thoughts on the papers, and described what types of projects they expected the researchers might pursue next. They were taught to read through these research articles following the CREATE (Consider, Read, Elucidate hypotheses, Assess the methods and data, Think of the next Experiment) approach developed by Hoskins et al. (2011). Additionally, the online discussion board was set up such that each student would have to submit a response to the assigned article before being able to see any postings from their peers. This arrangement was to ensure that the students would have to construct their own responses to the readings rather than draw from the responses of their peers.

After making their own response entries to the online discussion board, students were required to comment on one another's responses online. All readings and online responses were required prior to the in-person class meetings, and the readings were thoroughly dissected during class in group discussion. After a few class sessions of reading and discussing instructor-selected research articles, the students were asked to choose topics and find appropriate readings (both approved by the instructor), and took over the role of leading the in-class discussions for the readings they selected for the rest of the semester.

To ascertain the effects this class may have had on the students' nature of science views and biological content knowledge, we administered previously validated survey tools at the beginning and end of the course including the Biological Concept Inventory (BCI, see appendix 3) developed by Klymkowsky, Underwood, & Garvin-Doxas (2010) and the Views on the Nature of Science survey instrument – Form C (VNOS-C, see appendix 4) as developed and implemented by Abd-El-Khalick (2001) and Lederman, Abd-El-Khalick, Bell, &

Schwartz (2002). We also made use of written responses near the end of the course in which students were asked to describe in detail what they found useful about using primary literature, what was challenging, how they felt they progressed in terms of their ability to understand what they were reading, and how they felt about choosing their own topics and leading those discussions. (See Appendix 5 for the writing prompt.)

Participants in the study were six students, three male and three female, including two biology majors, a forensic science major, one pre-medicine student, one undeclared art major, and one undeclared student in the college of arts and sciences. An additional student was present for much of the class, but was excluded from this study since he did not complete the course. Participants ranged in age from 18 to 21 years old, and four were first-year university students. Where students are referred to by name in this work, pseudonyms have been assigned. Use of data for research purposes was voluntary. Also, due to technological issues with the online version of the VNOS instrument, responses were not recorded for one student (Lauren) pre-course, or for a different student (Stuart) post-course. All data were collected under IRB authorised protocols.

We employed the coding recommendations for the VNOS-C as in Lederman et al. (2002) to classify students' views of various aspects of NOS as being more naïve or more informed or as "mixed" when elements of informed views were expressed but the responses were incomplete or when elements of informed views were express along with naïve elements. Unfortunately, follow-up interviews relating to VNOS responses were not conducted due to constraints related to our IRB authorization for data collection. Responses to the VNOS-C questionnaire were independently rated by the two co-authors and thereafter discussed in conference. The raters' independent scorings were in agreement for 96.4% of the participant responses, and where there were differences, these were reconciled via inter-rater discussion. Examples of responses for each category are presented in Table 1.

Table 1. VNOS-C Exemplar statements. This table provides example statements from VNOS-C responses that were rated as more naïve, mixed, or more informed for each of the NOS aspects

NOS aspect	More Naïve Views	Mixed Views	More Informed Views
Empirical	All science should be written and recorded whether it is "correct" or not. Science cannot be correct all the time, because not many of theories are proven.	Not all parts of science are actually facts. Some are supported hypothesis and theories. Science is different from other disciplines of inquiry by carrying out experiments to support or improve the hypothesis that was already created.	None encountered.
Inferential	I am not completely certain because I have yet to see an atom	Scientists seem very certain that this is a true statement, they used many experiments to test it	The model [of atomic structure] used is more of an

	through a microscope, maybe scientist use the evidence of electricity?	like the alpha particles and gold foil.	abstract one, used to make predictions on the odds of where a certain particle of the atom is at any given point in time.
Theory/Law	Scientific theory and law may seem the same but they are not. Theories are more of proven hypothesis through multiple experiments. Scientific law is more close to a fact that were proven through multiple experiments. Both require experiments but does not have the same meaning behind it.	There is a difference between a scientific theory and a scientific law. A theory provides how the hypothesis can be tested. A law is series of tested and proven facts. One example of a law is the Law of Thermodynamics when an example of a theory is endosymbiosis theory. Theory is more like what could have happened and building a hypothesis. Theory is not exactly proven. However, a law is more like a proven fact.	None encountered.
Creative	I do not think that scientists use their imagination because they are trying to get truth out of their experiment. If a scientists was to try to be creative they may do experiments that are not very useful.	I think that scientists do use a little creativity when trying to come up with ways to test their idea. Sometimes there are multiple ways to test an idea. I would say that the creativity only applies to the planning and design of the experiment.	Yes, I believe you must use imagination and creativity during scientific investigations. If scientists did not come up with new, different, ideas and methods when constructing and carrying out experiments, no new information would be found. Creativity and ingenuity is needed all throughout the scientific process. Unique ideas and observations lead to creative questions to test. New questions call for imaginative solutions when finding a way to test a hypothesis, and when drawing a conclusion based on data collected it is important to be open minded to the results.

Sociocultural	I believe that science is universal because it does not go along with culture or social values. No matter what you think science will be truth and people think that their idea is right but almost always science will be right. I do not think that the two connect at all, they are complete opposites and really don't connect.	Science could be both universal and cultural specific. Although science should be [objective], it could not be objective the whole time… Some scientific knowledge such as theories and facts are universal because they are proven. But species specific could be different and the values on science could be different among the cultures.	Science reflects social and cultural values, in the effect that projects that are funded or not funded are usually based upon what society needs. An example is the large push in understanding of nuclear technologies in WWII and after when the Manhattan project was funded. On the other side of the spectrum, research in the USA around stem cells has to progress carefully, because of the stigma with cloning and the ethical issues surround it.
Myth of SM	I believe it does because without experimenting a hypothesis you cannot determine if it's true. If it's good on paper it does not necessarily have to be good/actual in real life.	No single statement from any participants stood as a stand-alone expression of mixed views, but one student indicated that science requires experiments but also made several comments indicating that scientific knowledge can also be generated through "observation" and "discovery".	Development of scientific knowledge can be done through many ways… Through experiments, scientists can actually see how the hypothesis will be supported or not. [However], for example, [through dissection] scientists can learn about the body parts and features more realistically and closely.
Tentative	Science is the true understanding on how things work on Earth and in the whole universe.	Theory doesn't necessarily change, it is simply modified in a way that best fits it. For example the brain, the brain was thought to have different regions of emotions back in the day, and every region accounted for something. Now, the brain still	Theories do change because as knowledge grows we are able to create more specific experiments, allowing us to

	…scientific theory does not change because one that have developed the theory it has been tested and almost proven. An example is evolutionary theory, it took time to develop this theory and it has been proven how evolution has happened over the years.	has different regions, though we see which regions are active in use when the brain is processing information.	clarify and build upon knowledge that we already have.

Results and Discussions

Effects of the course on students' views about the nature of science

VNOS-C results, shown in Table 2, were quite positive. There were decreases in “naive” responses and increases in “mixed” and “informed” responses in all but one NOS category. The only NOS aspect without a decrease in naive responses was the theory/law aspect, which was never explicitly addressed in class. Naive responses also persisted fairly strongly with regards to the myth of the singular scientific method, the idea that there is only one way to do science, typically in the familiar, step-wise fashion presented in many primary- and secondary-level textbooks. Sadly, although many of the readings discussed in class were observational rather than experimental studies, the view that all science requires experiments still persisted.

Table 2: VNOS-C results. Numbers represent total number of each type of response across all students as represented by the relevant questions on the VNOS-C instrument (Lederman et al., 2002), excluding interviews.

NOS aspect	Naive		Mixed		Informed	
	Pre	Post	Pre	Post	Pre	Post
Empirical	5	1	1	5	0	0
Inferential	2	0	3	3	0	1
Theory/Law	2	4	3	1	0	0
Creative	0	1	4	2	2	3
Sociocultural	2	1	2	2	1	1
Myth of SM	7	5	0	1	1	2
Tentative	2	0	2	3	1	2

Along with higher VNOS-C scores, some statements made by the students in their reflective written work reflect improving conceptions of NOS as well. Many of the students thought using primary literature provided insight into how science is done "in the real world," or "in real life." We take this to mean that the students were able to view science as less of an abstraction, or perhaps that they were better able to focus on the process of science. Ronaldo said, "these articles showed how science is applied in real life," and Kristin echoed that same sentiment, saying "I also feel that I have a better understanding [of] how research is done in the real world." Several students made statements that strongly indicate a more informed NOS view. Hilda stated that "scientists work continuously to bring out their discoveries to [the] world and let other people to have more scientific knowledge and attention to science," indicating that she had thought a lot about how science is communicated. Sam made the statement which perhaps indicated the greatest gains in NOS conceptions when he stated,

I think that science is done in many ways in the real world, and there are many different types of science. One example of science is going out to a certain area and observe a specific species or working in a laboratory seeing how an animal reacts to something. There are so many different ways science is done today.

It would seem that the myth of a single scientific method has been dispelled for Sam.

Effects of the course on students' biological content knowledge

Students' scores on the biological concept inventory (Klymkowsky et al., 2010) did not differ substantially from the beginning to the end of the course, as the BCI is intended to diagnose common misconceptions across the very broad and interdisciplinary field of biology. Total individual scores have a possible range of zero to thirty points. Scores ranged from 8 to 18 at the beginning of the course and from 12 to 17 at the end. The sum of all students' scores was 77 at the outset of the course, and 76 at the end. While it would have been encouraging if students had been able to overcome some of the general misconceptions they still held, we were not entirely surprised that the students retained some of these often tenaciously persistent naïve conceptions. With regard to more specific content knowledge encountered in this course, there are no extant, previously validated tools with which to objectively measure learning gains, nor could we have anticipated which topics in particular the students would select at the beginning of the course. Hence, we may only provide students' self-reports as evidence of their content-specific learning, and do not consider the results of the BCI to be appropriate for this study.

The students' perceptions of how much and what they learned is, however, enlightening and encouraging. 83% of the participants (all but one) indicated content knowledge gains in their reflective responses. Hilda, for example, said,

My knowledge of science has increased incredibly, not only about specific species that we read about but also about general ecology [and] evolution... Although I am not an environment[al] science major nor was [I] interested in ecology, I feel I have gained a lot of scientific knowledge on other aspects of science.

Sam said, "I do know that my knowledge of science has increased after taking this class." Ronaldo reported that

This class not only improved my knowledge on science, but improved my literature skills as well. I am very grateful I took this class because I now know my scientific knowledge and writing skills improved tremendously.

Lauren also noted an increased understanding of science, saying, this also increased my knowledge and understanding of the world around us and how it is constantly changing to adapt to ever-changing variables. It is easy to understand the processes that go along with evolution, but seeing examples that come from our everyday life was a completely different way of learning and beneficial in the long run.

The students clearly felt confident that they had an improved understanding of biology as a result of their work with primary literature in the course.

Students' self-described experiences with primary literature

The students had much to say about their experiences with primary literature. Most had rarely used primary literature in the past. Stuart stated in a written response, "I read a total of ten or twenty scholarly articles in my entire life before enrolling in this course." The other students had similar made similar statements about their prior use of primary literature. Sam had apparently had the most experience with primary literature, but stated that before taking [the course] I had used primary literature for a class first semester. It was different because the other class wasn't a science class so the primary literature was not similar.

Students' statements about how they perceived primary literature at the outset of the course were also very similar amongst the all students. Ronaldo said, "at first these articles were very hard to interpret." Sam echoed the same sentiment when he said, "reading primary literature in the class was difficult because I did not have a lot of experience with science articles so I got confused." Hilda expressed an interesting view, unique among the students in this study, but not likely unique among student readers of primary literature, when she explained of research articles, "although I am a science major, I thought they were for real scientists who are not I." The perception that research articles are only meant for researchers is, of course, completely understandable given the fact that many articles are inaccessible due to factors such as subscription barriers, or, as cited by nearly every student, that scientific articles are perceived as prohibitively challenging due to the complex and specialised language in which they are written. Sam noted that "when reading these articles [the] authors always used words I didn't know, so I had to use a dictionary a lot." Lauren said of reading research articles, "at first, this felt a little overwhelming and it was hard to grasp some of the scientific [jargon]," and Ronaldo also noted that "these journals have an array of vast scientific vocabulary, which was the hardest thing to get used when dissecting these journals." Kristin pointed not to terminology, but to the structure of journal articles as something she struggled with early on. She said,

when I read journals like the ones we went over in this class, it often took me a much greater amount of time, mainly due to an inability to sit down and read the longer readings word for word all of the way through at once, the way I assumed I should read them. I had no strategy for dissecting the information given to me.

This is an important point, since many readers struggle with the typical structure of research articles. In fact, grasping article structure would prove to be a turning point for several students.

“As I read more and more I really got [used] to them and I started to understand why they were broken up into sections,” Sam remarked about reading journal articles. Stuart fleshed this idea out more fully:

All of the articles we read had general trends in them that made the reading easier to understand. Almost all of the articles had an abstract section in the beginning, which summarized the entire experiment that the article discussed in 1-2 short paragraphs. After [that] an introduction would explain what the point of the experiment was. Following the introduction were normally the methods and results sections which would explain how the experiments were done, and how it ended up working out in the end.

Ronaldo noted,

at first these articles were very hard to interpret. The scholarly articles had multiple parts to them, which in beginning seemed to be confusing, but proved to make the article more organized and easy to understand.

These statements indicate that our decision to include a guide to examining research articles early in the course was a good one. In one of the first reading sets in the course, we made use of materials from Berkeley's Understanding Evolution website which provided a guide to dissecting a scientific paper about evolutionary biology (http://evolution.berkeley.edu/evolibrary/teach/journal/dissectingapaper.php). These materials provide a reading guide to accompany a study of figs and fig wasps (Dunn et al., 2008), which provides insight into each of the sections of the article. Though the students did not cite these materials explicitly in their written work, these readings and the accompanying class discussion were the foundation of the students' initial guided experience with analyzing scientific articles.

Many students also espoused the benefits of online and class discussions for their understandings of the papers. Ronaldo said,

I found the most useful part of the class came in the discussions. In this part of the class not only can you demonstrate your perspective of the articles, but other student can chime in and provide information you would not even think about. Thus, giving you a vast knowledge on the topic being discussed in class that day.

Lauren noted that

eventually it became easier to pick out the key points and summarize after seeing how other students viewed the article and how they interpreted the information. Discussions in class also made it easier to understand the over all goal of the project and sharing thoughts with my peers also opens up the opportunity to discuss possible alternatives to the projects.

Online and class discussions were perhaps most helpful to Hilda, who said,

There were some articles that I interpreted wrong and realized what the study was actually about during class discussion. If I am in hurry or the article gets confusing, I tend to get lost easily and end up with wrong interpretation of the article.

She also noted that seeing other students' online summaries and discussion of the readings about which she was to lead discussion was helpful in "interpreting the thoughts that [she] had and also [she] understood how others thought about this issue." Stuart also found discussions helpful in correcting his misinterpretations. He said,

I feel as though the discussions during class really helped to get the point of the articles across. When reading them sometimes I wouldn't understand some of what went on, but class discussions really helped to clear up any confusion that I had.

Students universally described changes in how they experienced primary literature. As noted above, Sam became more familiar with the structure of research articles as he read more of them. He also said, "I really don't know if my abilities have changed from primary literature because I really haven't used primary literature outside of this class," but he added, "I have practiced reading these different articles so if I am required to read primary literature for another class I will be able to do it." Stuart said,

I feel like my abilities to read primary literature [have] definitely increased since I began taking this class. I feel more confident when reading it because the types of articles we read are all written the same way.

Kristin said, "I feel that my skills in understanding how to interpret primary literature have increased in this course." Hilda noted, "I can now read faster but still [make] notes and highlights to understand better about the studies." Ronaldo was very specific in how he described his semester-long experience:

Coming into this class I had no clue how to even dissect these types of scholarly articles... It may have seemed repetitive doing the same thing every week, but with every new week each reply and summary took less time.

Lauren also found repetition helpful, saying "Over the course of this semester, my ability to understand and decipher articles has greatly improved due to the amount of practice we have been doing."

It is clear that more practice with reading original research was helpful for the students, but did the skills they gained in this course carry over to other courses or more broadly to other parts of their lives? Many students thought so. Kristin stated,

I definitely feel more [confident] in my skills of reading and understanding journal articles, and it is something that has already begun helping me in my current classes that require journal readings. Currently I am in a lab course in which a significant part of my grade was based on reading and understanding a long research paper. At the beginning of the semester I dreaded putting it off, but because of how this course broke down how to summarize and understand a paper I was able to complete the assignment with ease.

Hilda noted, more briefly, “As this course is ending, I feel more prepared to [enter a] science career.” Lauren found the methodical way of reading articles that she developed very helpful, as she explained, “I eventually figured out a method that best worked for me when reading through articles to make sure that I do not miss the key points and have gone on to use this in several of my other classes.” Ronaldo said,

With all the lessons and skills I learned from this class I feel more prepared for future science classes, an also my future in my scientific career. I realize that I do not want to pursue a career and research, because of all the writing that comes with it.

Perhaps the last part is disheartening, but the realization that science involves writing is not without merit. Sam said, “I did become more confident in my abilities in science after this class, it’s almost like practicing. I think this class has opened my mind up more than prepared me for other classes.” Stuart spoke broadly about his gains in confidence, but also predicted that the skills he has gained will lead to success in his chosen field, saying,

This class has definitely made me more confident in the field of science. I understand how to read journal articles a lot more than I did before, and I feel as though this class has made me able to locate information within journal articles much more quickly than I could before. Since I hope to work with animals one day, I feel as though this class has taught me how to better interpret information when reading scholarly articles.

It is clear that some students felt their experience with original research either was already helping them in other pursuits or would in the future.

One student, Lauren, also confirmed what many science teachers suspect about self-selected topics, that they lead to increased investment and a generally more positive experience for the student. In her words:

This was one of the more fulfilling projects I have been a part of because not only were you able to research a project that pertained to your interests, you were able to hear what your peers thought of the topic as well as educate them on what can be/has been done which was a major plus for me.

It would seem that self-directed projects using primary literature can be quite positive for students, and may be especially effective when done with a large amount of class discussion.

Connecting the constructs

Analyzing the VNOS results along with the students’ personal reflections demonstrates that similar results were observed using different measures and indicates that students’ self-professed gains are truly indicative of advances in their thinking. However, a full comparison is difficult given two of the students did not complete the VNOS both pre- and post-course. Of the four students who did complete all constructs, all showed gains in at least some aspects of their NOS conceptions, and all claimed to have gained insight into the scientific process in their reflective writings. Additionally, three of the four claimed gains in content knowledge, and three of the four claimed increased skills at interpreting scientific literature.

Conclusion

Though the students did not show gains in a test of biological content aimed at common, broad misconceptions (the BCI), their nearly universal statements (83% of participants) claiming increased understanding of specific biology content support our expectation that students' biology knowledge might increase. Further, the students reported increased confidence and facility with reading and understanding research articles (83% of participants), and more confidence in their abilities to understand or engage in science generally (67% of participants). These findings are similar to those of various other studies in which content knowledge (Glazer, 2000; Kozeracki et al., 2006) and confidence (Glazer, 2000; Hoskins et al., 2011; Murray, 2014; Round & Campbell, 2013; Sato et al., 2014) have been shown to increase.

Although previous research has discussed improvements in student outlook on science (Hoskins et al., 2011), this work represents the first research on the effects of using primary literature on NOS conceptions per se. We can conclude, based upon both the students' accounts of how they think about science, and also upon the results of the VNOS-C instrument (Abd-El-Khalick, 2001; Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002), that the use of primary literature did lead our participants to more informed views on various NOS aspects, especially the empirical, inferential, and myth of the scientific method aspects. The students' responses also indicate that they now view science as a more human endeavor, a finding shared with Hoskins et al. (2011). It is important to note that there was no explicit discussion of NOS during the course. Rather, insight into NOS was implicit in the many exemplars of scientific inquiry including studies using various methods, experimental and observational, and collections of readings in which the understanding of phenomena is shown to change over time.

Based on our findings, we concur with our colleagues who recommend expanding the use of primary literature in biology education (Hoskins et al., 2011; Yarden et al., 2001). Many students cited a better understanding of the structure of scientific papers as helpful in improving their overall confidence, so including an explicit primer on how to dissect a scientific research article as we did in this course is a practice we also recommend. Beyond the journal club resources from Berkeley's Understanding Evolution website mentioned above, we recommend explicit discussion of the purpose of typical journal article sections. For example, in order to aid students in reading introductions, one might note that introductions will often establish what is known about a particular idea or phenomenon, what is unknown, and how the article will attempt to fill that knowledge gap. The students indicated that repetition was helpful in becoming more confident with reading and understanding research articles, echoing the findings of previous research (Sato et al., 2014). Thus, we recommend spreading the use of primary literature across entire course curricula, with one to several articles being read each week. Group discussions, both online and in person, were also helpful to the students in clearing up confusion, expanding their thinking about research, and generally in building confidence about their experiences. Weekly journal clubs, then, may be a very helpful activity in or alongside formal biology instruction. Developing modules using primary literature as a vehicle for students to learn specific content may also better support content knowledge gains for students. An online platform, www.teachcreate.org, provides an archive of "roadmaps" with articles grouped together into learning modules with explicit content areas and concepts.

There are a number of avenues that future research on this topic could follow. Expanding into a larger sample size has many benefits, especially enhancing the generalizability of findings, although the intensive scoring required in using the VNOS instrument makes it more difficult to use at larger scales. We have used the Thinking about Science Survey Instrument (Cobern, 2000) as a quantitative measure of NOS conceptions in large scale studies (Carter and Wiles, 2014) and found it compares favourably to the VNOS. Another approach to future research could involve a more controlled experiment in which the VNOS is used along with follow up interviews for both pre-course and post-course surveys. In a larger scale study, ideas like the efficacy of online discussions could be more finely explored with differential treatment of different sections of a course, or a "journal club" style component of the course could be compared with a different activity that doesn't involve primary literature. Perhaps most importantly for future research, there is an apparent disconnect between studies of NOS conceptions and studies of primary literature use, with different terms used to discuss similar ideas in the two bodies of work, and without much overlap in citations. For example, NOS literature such as Lederman et al. 2002 often refers to science as a human endeavor (subjective, sociocultural, creative), while Hoskins et al. (2012) refer broadly to the humanizing of science through experiences with primary literature. Because of this disparity, we recommend further studies in which these two bodies of education research are investigated together.

Overall, these results are quite encouraging, and they suggest that engaging in primary literature is informative to students both in terms of biological content knowledge and nature of science conceptions.

Disclosure statement

No potential conflict of interest was reported by the authors.

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