EXAMINING LITERACY PRACTICES AMONG NOVICE AND EXPERT BIOLOGISTS: IMPLICATIONS FOR INSTRUCTION UTILIZING PRIMARY RESEARCH LITERATURE

by

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To my parents, for instilling the value of education.

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ABSTRACT

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Title: Examining Literacy Practices Among Novice and Expert Biologists: Implications for Instruction Utilizing Primary Research Literature.
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Primary literature serves an integral role within disciplinary communities to facilitate communication and mediate knowledge construction. As such, scientists devote much of their time immersed in primary literature to negotiate and update disciplinary knowledge. Despite the importance and relevance of this task, many biology students express considerable difficulties in engaging with such literature. In a time where knowledge production exceeds students' capacity to learn content, undergraduate biology instructors must focus efforts to promote skills that will enable students to successfully navigate disciplinary literature. While various studies have emerged offering novel instructional approaches on how to teach students how to read primary literature, many rely on either anecdotal evidence or a tacit understanding of how novice and expert biologists read primary articles. Thus, the purpose of this study is to examine the literacy practices of expert and novice biologists to better inform teaching practices related to primary literature.

For this study, we identified and characterized the literacy practices of seven biology faculty members and nineteen upper-level biology undergraduates at a large midwestern research institution. Data were collected using a semi-structured interview format. Participants described their actions while reading a primary research article of their choosing. Additionally, we examined the ways in which biology faculty implement primary literature in undergraduate

coursework. Data were analyzed using primarily constant comparative approaches. Quantitative and mixed-methods approaches were also used, where appropriate.

The results show that expert and novice biologists read primary literature in distinctively different ways. While both populations tended to read the articles in a selective manner (i.e., reading particular sections while omitting others), experts often skipped the Introduction whereas students often skipped the Methods section. Students also tended to read articles in a linear manner, whereas faculty navigated the articles less linearly. Based on participants narration of reading, we generated unique reading-related actions. Experts were highly specific in their actions (e.g., predicting experimental approach, evaluate statistical methodologies), suggesting that they approached articles with an *a priori* framework. In contrast, students' described actions tended to be more general (e.g., using text to reinforce understanding). Reading actions were further analyzed by organizing actions into cognitive domains (e.g., remember, understand, evaluate, etc.). Experts' reading aligned with diversity of cognitive domains, with actions distributed around understand, apply, analyze, and evaluate. In contrast, students primarily focused on understand and remember-related actions. We also identified factors that both populations cite when determining the credibility of an article.

Furthermore, we examined faculty members' self-reported teaching practices with primary literature. Faculty agreed that students ought to develop competencies aligned with understand and evaluate cognitive processes. Despite this expectation for students to be develop evaluative reading skills, few faculty members explicitly describe instruction that target evaluative thinking. We also examined how instructors described implementation of primary literature and found that a majority of instructors describe practices that align with instructive practices. Lastly, we describe the criteria in which faculty selected primary articles for classroom usage.

The findings of this study contribute to the understanding of literacy practices of novice and expert biologists, which can help to inform curricula development. While instructors agree that students ought to be able to critically evaluate primary articles, students rarely describe engaging in evaluative reading practices, with most of their efforts spent on understanding. Learning to read primary literature in a manner that allows students to engage disciplinary ways of knowing is a difficult task, yet necessary for students to address the challenges of 21st century biology. Thus, scaffolded instruction spanning undergraduate biology curricula must be considered to help students move beyond comprehension and engage in evaluative practices.

CHAPTER 1: INTRODUCTION

Biology for the 21st Century

Calls to action within the past decade by multiple organizations have advocated for the reconceptualization of biology education at the undergraduate level (AAAS, 2011; AAMC-HHMI, 2009; NRC, 2009). These calls were spurred by recent revolutionary changes in technology, access to information, and the increasingly interdisciplinary nature of the sciences (NRC, 2009). In their document, *Vision and Change in Undergraduate Biology Education: A Call to Action* (2011), the American Association for the Advancement of Science (AAAS) advocated an agenda for change in undergraduate biology education that includes the following: integration of core concepts and competencies throughout the undergraduate biology curricula, emphasis on student-centered learning, and support of a climate for change at the campus and community levels. Core concepts and competencies highlighted by the *Vision and Change* document refer to the many skills that biologists use in their practices. Coined as “science process skills”, these include but are not limited to: data interpretation, problem solving, experimental design, scientific writing, oral communication, collaborative work, and critical analysis of primary literature (Coil, Wenderoth, Cunningham, & Dirks, 2010). Despite faculty expressing the need and value in teaching these skills, many cite barriers that prevent addressing these skills.

With ongoing biology research rapidly expanding the boundaries of knowledge, covering the growing wealth of information in undergraduate curricula is increasingly difficult. As highlighted by Geddes, Cannon, and Cannon (2018), students are unable to keep up with the rate of information production due to advances in information generation and distribution. Given the rate of knowledge production, how can educators appropriately address this glaring issue? Currently, traditional forms of biology instruction are unable to provide instruction that enables students to cope with such advancements, as they focus on the telling and remembrance of facts, rather than the developing students' ways of knowing within the discipline (Alberts, 2009). Failure to develop such scientific ways of knowing have problematic repercussions, including the acceptance of simplistic explanations to complicated issues.

It would impossible to discuss ways of knowing within a discipline without acknowledging the role of primary research literature – one of main forms of communication and dissemination of knowledge among researchers. Scientists spend a considerable amount of work time engaged in reading primary literature, with estimates ranging from 23% - 30% of total work time dedicated to reading (Tenopir & King, 2003; Tenopir, King, & Bush, 2004). As such, one would expect undergraduates to develop literacy skills associated with reading primary literature; yet, many upper-level science majors express fear and intimidation in reading primary literature (Smith, 2001). To this end, discipline-based education research (DBER) scholars have highlighted incorporating primary literature in undergraduate classes, mainly with two approaches: developing students science practice skills (e.g., interpreting data, designing an experiment), and developing students' scientific literacy. Over the past several of decades, researchers have explored many novel approaches that utilize primary literature in undergraduate classrooms.

Literature Review: Primary Literature in Undergraduate Education

In surveying the scope of research conducted by researchers over the past several decades, studies fall into one of the following categories: intervention, recommended/best practices, and descriptive studies (Table 1). Intervention studies are the most abundant (82.5%), followed by recommended/best practices (12.5%), and descriptive studies (5.0%). Intervention studies are characterized by implementation of a (novel) pedagogical approach that either provides instruction on how to read primary literature (e.g., Abdullah, Parris, Lie, Guzdar, & Tour, 2015; Clark, Rollins, & Smith, 2014; Murray, 2014; Van Lacum, Ossevoort, & Goedhart, 2014) or use primary literature as a vehicle to develop certain process skills (e.g., Abdullah et al., 2015; Hoskins, Stevens, & Nehm, 2007; Round & Campbell, 2013). Common features among these types of articles are using pre- and post-intervention assessment of process skills and/or surveys that measure students' affective gains. Constructs measured in these studies include: self-efficacy of skills related to primary literature (e.g., Elrod, 2007; Hoskins, Lopatto, & Stevens, 2011; Kozeracki, Carey, Colicelli, & Levis-Fitzgerald, 2006), data analysis skills (e.g., Abdullah et al., 2015; Round & Campbell, 2013), experimental design skills (e.g., Abdullah et al., 2015; Gottesman & Hoskins, 2013), evaluation skills (Ferenc et al., 2018), and students' conception of the nature of science (Carter & Wiles, 2017; Gottesman & Hoskins, 2013), among others.

Recommended/best practice articles detail pedagogical approaches to implement primary literature, usually providing either anecdotal student data or little empirical evidence (e.g., Herman, 1999; McNeal, 1989; Muench, 2000). These types of studies tended to be published early in comparison to other works, as biology DBER scholarship was relatively new. Lastly, descriptive studies were cross sectional and examined several of aspects of reading primary literature, including how experts and novices identify evidence and conclusions within an article (Van Lacum, Ossevoort, Buikema, & Goedhart, 2012) and perceptions of primary literature across multiple career stages (Hubbard & Dunbar, 2017).

At this point, incorporating primary literature into undergraduate courses clearly provides many benefits, even with minimal scaffolding (e.g., Liao, 2017); however, it is unclear which approach(es) is best to enable students to tackle biology of the 21st century. While many intervention-type studies highlight the positive benefits of instructional approaches that utilize primary literature, very few studies compare such approaches to alternative forms of primary literature instruction. For example, the CREATE (Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experiment) method, one of the most commonly published approaches to primary literature has documented increases in students' critical thinking and self-efficacy (e.g., Gottesman & Hoskins, 2013; Hoskins et al., 2007; Stevens & Hoskins, 2014); yet, other forms of instruction, such as a scaffolded journal club, seem to produce similar gains in critical thinking and self-efficacy of learning gains (Segura-Totten & Dalman, 2013).

Despite the wealth of studies on primary literature implementation, very few characterize *how* students engage with primary literature (Hubbard & Dunbar, 2017; Lie, Abdullah, He, & Tour, 2016; Van Lacum et al., 2012). Furthermore, only one of the aforementioned studies has examined characteristics of primary literature usage among experts (Van Lacum et al., 2012). As such, further research is required to better understand how students and faculty engage with primary literature. Examining and comparing how novice and expert biologists approach and utilize primary research literature can provide insights that better inform teaching practices in undergraduate biology education.

Table 1 Studies examining primary literature in the context of undergraduate biology.

Study Citation	**Study Purpose**	**Study Format**	**Data Sources/Outcome Measures**
McNeal, A. P. (1989). Real science in the introductory course. *New Directions for Teaching and Learning*, 1989(38), 17-24.	Describes the implementation of primary literature into an undergraduate course	Recommended/Best Practices	Descriptive and anecdotal evidence of student learning outcomes
Janick-Buckner, D. (1997). Getting undergraduates to critically read and discuss primary literature. *Journal of College Science Teaching*, 27.	Evaluates an intensive primary literature-based advanced cell biology course	Intervention	Student grades; course evaluations
Herman, C. (1999). Reading the literature in the jargon-intensive field of molecular genetics. *Journal of College Science Teaching*, 28(4), 252.	Describes the implementation of primary literature in an undergraduate microbiology course	Recommended/Best Practices	Descriptive and anecdotal evidence of student learning outcomes
Muench, S. B. (2000). Choosing primary literature in biology to achieve specific educational goals. *Journal of College Science Teaching*, 29(4), 255-60.	Provides guidelines for primary literature selection	Recommended/Best Practices	N/A
Kozeracki, C. A., Carey, M. F., Colicelli, J., & Levis-Fitzgerald, M. (2006). An intensive primary-literature–based teaching program directly benefits undergraduate science majors and facilitates their transition to doctoral programs. *CBE—Life Sciences Education*, 5(4), 340-347.	Evaluates an intensive primary literature-based seminar course for highly motivated students. Consists of journal club style seminar, research presentation opportunities, career guidance, and seminar speakers	Intervention	Post-course and alumni course evaluations (self-efficacy)
Elrod, S. L., & Somerville, M. M. (2007). Literature-based scientific learning: A collaboration model. *The Journal of Academic Librarianship*, 33(6), 684-691.	Evaluates a primary literature-based case study approach	Intervention	Student survey and self-assessments of learning experiences

Table 1 continued

Hoskins, S. G., Stevens, L. M., & Nehm, R. H. (2007). Selective use of the primary literature transforms the classroom into a virtual laboratory. *Genetics*, 176(3), 1381-1389.	Evaluates CREATE approach in undergraduate classes	Intervention	Critical Thinking Test (CTT; adapted from flaguide.org); SALG survey (Hoskins et al., 2007); student interviews
Porter, J. A., Wolbach, K. C., Purzycki, C. B., Bowman, L. A., Agbada, E., & Mostrom, A. M. (2010). Integration of information and scientific literacy: promoting literacy in undergraduates. *CBE—Life Sciences Education*, 9(4), 536-542.	Evaluates information literacy and scientific literacy exercise in a first-year biology course	Intervention	Scientific literacy: post-activity assessment based on selecting and assessing primary literature article
Hoskins, S. G., Lopatto, D., & Stevens, L. M. (2011). The CREATE approach to primary literature shifts undergraduates' self-assessed ability to read and analyze journal articles, attitudes about science, and epistemological beliefs. *CBE—Life Sciences Education*, 10(4), 368-378.	Evaluates CREATE approach on self-efficacy of reading skills, attitudes about science, and epistemological beliefs	Intervention	Pre- and post-surveys of student attitudes and self-rated abilities; CREATE survey based on Schommer (1990)
Wiegant, F., Scager, K., & Boonstra, J. (2011). An undergraduate course to bridge the gap between textbooks and scientific research. *CBE—Life Sciences Education*, 10(1), 83-94.	Evaluates an advanced cell biology course that aims at bridging textbook knowledge and research practices	Intervention	Final course grades; student course evaluations and self-efficacy; alumni course evaluations
Robertson, K. (2012). A journal club workshop that teaches undergraduates a systematic method for reading, interpreting, and presenting primary literature. *Journal of College Science Teaching*, 41(6), 25.	Evaluates a journal club workshop that provides explicit instructions on how to read a primary research article	Intervention	Post-workshop survey; comparison of paper presentations grades between intervention and control group

Table 1 continued

Van Lacum, E., Ossevoort, M., Buikema, H., & Goedhart, M. (2012). First experiences with reading primary literature by undergraduate life science students. *International Journal of Science Education,* 34(12), 1795-1821.	Examines how students and experts are able to identify conclusions and evidence within a primary literature article. Also provides descriptive information on student reading strategies.	Descriptive	Assignments identifying conclusion and evidence statements; expert and student interviews
Brownell, S. E., Price, J. V., & Steinman, L. (2013). A writing-intensive course improves biology undergraduates' perception and confidence of their abilities to read scientific literature and communicate science. *Advances in Physiology Education*, 37(1), 70-79.	Evaluates a writing-intensive course	Intervention	Pre- and post-surveys of student perception and confidence on ability to read primary scientific papers and to communicate to others
Gottesman, A. J., & Hoskins, S. G. (2013). CREATE cornerstone: introduction to scientific thinking, a new course for STEM-interested freshmen, demystifies scientific thinking through analysis of scientific literature. *CBE—Life Sciences Education,* 12(1), 59-72.	Evaluates CREATE strategy adapted for freshmen	Intervention	Critical Thinking Assessment Test (CAT; Stein et al., 2012); Experimental Design Ability Test (EDAT; Sirum & Humburg, 2011); Survey of Student Self-Rated Abilities, Attitudes, and Beliefs (SAAB; Hoskins et al., 2011)
Krontiris-Litowitz, J. (2013). Using primary literature to teach science literacy to introductory biology students. *Journal of Microbiology & Biology Education: JMBE,* 14(1), 66.	Evaluates students' scientific literacy skills throughout introductory biology course that utilized primary articles and accompanying homework assignments	Intervention	Interim and final exam scores (science literacy learning objectives embedded in exams)

Table 1 continued

Round, J. E., & Campbell, A. M. (2013). Figure facts: encouraging undergraduates to take a data-centered approach to reading primary literature. *CBE—Life Sciences Education*, 12(1), 39-46.	Evaluates "Figure Facts" template to promote data interpretation skills in an advanced cellular neuroscience course	Intervention	Data interpretation assessment (Round & Campbell, 2013); student attitude surveys
Segura-Totten, M., & Dalman, N. E. (2013). The CREATE method does not result in greater gains in critical thinking than a more traditional method of analyzing the primary literature. *Journal of Microbiology & Biology Education: JMBE*, 14(2), 166.	Side by side evaluation of traditional journal club-style and CREATE approaches	Intervention	SALG survey (salgsite.org); article critique assessment; exam scores; post-course survey
Clark, J. M., Rollins, A. W., & Smith, P. (2014). New methods for an undergraduate journal club. *Bioscene: Journal of College Biology Teaching*, 40(1), 16-20.	Evaluates novel journal club-style approach to teaching primary literature	Intervention	Exit survey
Murray, T. A. (2014). Teaching students to read the primary literature using POGIL activities. *Biochemistry and Molecular Biology Education*, 42(2), 165-173.	Evaluates POGIL approach to reading primary literature in a biochemistry course sequence	Intervention	Post-activity assessment; perception and self-efficacy survey
Sato, B. K., Kadandale, P., He, W., Murata, P. M., Latif, Y., & Warschauer, M. (2014). Practice makes pretty good: assessment of primary literature reading abilities across multiple large-enrollment biology laboratory courses. *CBE—Life Sciences Education*, 13(4), 677-686.	Evaluates long-term benefits of a scientific paper module in undergraduate biology (biochemistry, molecular biology, and microbiology) lab course	Intervention	Multiple regression analysis of student performance outcome measures (final grade, paper quiz score)
Spiegelberg, B. D. (2014). A focused assignment encouraging deep reading in undergraduate biochemistry. *Biochemistry and Molecular Biology Education*, 42(1), 1-5.	Proposal and evaluation of figure-focused assignment	Intervention	Student performance on exams; student evaluations

Table 1 continued

Stevens, L. M., & Hoskins, S. G. (2014). The CREATE strategy for intensive analysis of primary literature can be used effectively by newly trained faculty to produce multiple gains in diverse students. *CBE—Life Sciences Education*, 13(2), 224-242.	Examines downstream effects of CREATE Workshop	Intervention	Participant survey regarding pedagogical approaches (Likert); SALG survey (salgsite.org); Critical thinking test (CTT; flaguide.org); Student Attitude Survey (SAS);
Van Lacum, E. B., Ossevoort, M. A., & Goedhart, M. J. (2014). A teaching strategy with a focus on argumentation to improve undergraduate students’ ability to read research articles. *CBE—Life Sciences Education*, 13(2), 253-264.	Evaluates introductory course focused on argumentation as a strategy to enhance first year undergraduate students' reading of primary literature	Intervention	Pre- and post-test; self-efficacy survey; course evaluations
Abdullah, C., Parris, J., Lie, R., Guzdar, A., & Tour, E. (2015). Critical analysis of primary literature in a master’s-level class: Effects on self-efficacy and science-process skills. *CBE—Life Sciences Education*, 14(3), ar34.	Evaluates master's level primary literature intensive course on science process skills and self-efficacy	Intervention	Pre and post-course administration of science-process test; Pre- and post- survey assessing self-efficacy
Yeong, F. M. (2015). Using primary literature in an undergraduate assignment: demonstrating connections among cellular processes. *Journal of Biological Education*, 49(1), 73-90.	Evaluates a read- and write-to-learn assignment that utilizes a research article	Intervention	Pre- and post-surveys; analysis of students' essay assignment and exam answers;
Klucevsek, K. M., & Brungard, A. B. (2016). Information literacy in science writing: how students find, identify, and use scientific literature. *International Journal of Science Education*, 38(17), 2573-2595.	Evaluates science writing course that emphasized information literacy	Intervention	Pre- and post-course surveys (Likert scale); survey to measure library research competencies

Table 1 continued

Lie, R., Abdullah, C., He, W., & Tour, E. (2016). Perceived Challenges in Primary Literature in a Master's Class: Effects of Experience and Instruction. *CBE—Life Sciences Education*, 15(4), ar77.	Identifies students' perceived challenges related to primary literature before and after a primary literature intensive course	Intervention	Pre- and post-course surveys examining what students found "most challenging" while reading primary literature
Sandefur, C. I., & Gordy, C. (2016). Undergraduate journal club as an intervention to improve student development in applying the scientific process. *Journal of college science teaching*, 45(4), 52.	Evaluates "CASL Club", a journal club-style active learning approach to develop students' apply scientific processes	Intervention	Pre- and post-course surveys on self-efficacy on science communication skills
Zimeri, A. M. (2016). A Flipped Classroom Exercise to Teach Undergraduates to Critically Think Using Primary Scientific Literature. *International Journal of Environmental and Science Education*, 11(12), 5396-5403.	Evaluates of flipped classroom exercise utilizing primary literature to develop critical thinking	Intervention	Post-activity survey (student experience survey)
Carter, B. E., & Wiles, J. R. (2017). 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. *International Journal of Environmental and Science Education*, 12(3), 523-538.	Evaluates of students' conception of nature of science in primary literature intensive course, based on the CREATE approach (Hoskins, 2011)	Intervention	Pre- and post- surveys using the Biological Concept Inventory (Klymkowsky et al. 2010) and the Views on the Nature of Science survey (Abd-El-Khalick, 2010)

Table 1 continued

Hoskins, S. G., Gottesman, A. J., & Kenyon, K. L. (2017). CREATE two-year/four-year faculty workshops: A focus on practice, reflection, and novel curricular design leads to diverse gains for faculty at two-year and four-year institutions. *Journal of microbiology & biology education*, 18(3).	Evaluates of a faculty participants' views on teaching/learning, understanding of pedagogy, and confidence after participation in a CREATE workshop	Intervention	Pre- and post-workshop surveys - Survey of Teachers' Beliefs, Practices and Intentions (TBPI); Student Assessment of their Learning Gains (SALG; salgsite.org)
Hubbard, K. E., & Dunbar, S. D. (2017). Perceptions of scientific research literature and strategies for reading papers depend on academic career stage. *PloS one*, 12(12), e0189753.	Examines perceptions of primary literature across multiple career stages	Descriptive	Described the relationship between research literature and career stage (Likert survey), ease and importance of individual sections, and motives for reading
Liao, M. K. (2017). A Simple Activity to Enhance the Learning Experience of Reading Primary Literature. *Journal of microbiology & biology education*, 18(1).	Describes implementation of primary literature in undergraduate microbiology course	Recommended/Best Practices	Post-activity survey
Stevens, L. M., & Hoskins, S. G. (2014). The CREATE strategy for intensive analysis of primary literature can be used effectively by newly trained faculty to produce multiple gains in diverse students. *CBE—Life Sciences Education*, 13(2), 224-242.	Evaluates faculty attitudes about teaching/learning and students' affective gains	Intervention	Pre- and post-workshop attitude and belief survey (faculty); Critical thinking test (CTT; Hoskins et al., 2007); Student Attitudes Survey (SAS; Hoskins et al., 2011; Gottesman & Hoskins, 2013); SALG survey (Hoskins et al., 2007)

Table 1 continued

de Silva, C. (2018). Using Primary and Secondary Literature to Introduce Interdisciplinary Science to Undergraduate Students. *Bioscene: Journal of College Biology Teaching*, 44(2), 24-28.	Evaluates a course that utilizes scientific literature to introduce interdisciplinary concepts between biology and physics	Intervention	Pre- and post-tests based on a primary research article; self-efficacy survey using Likert scale
Eslinger, M., & Kent, E. (2018). Improving Scientific Literacy through a Structured Primary Literature Project. *Bioscene: Journal of College Biology Teaching*, 44(1), 13-27.	Evaluates an introductory biology course's structured primary literature project	Intervention	Student performance on projects; instructor assessment/feedback survey using a Likert scale; students' end of course feedback (Likert)
Ferenc, J., Červenák, F., Birčák, E., Juríková, K., Goffová, I., Gorilák, P., ... & Galisová, V. (2018). Intentionally flawed manuscripts as means for teaching students to critically evaluate scientific papers. *Biochemistry and Molecular Biology Education*, 46(1), 22-30.	Evaluates a master's level course using intentionally flawed manuscripts and explicit instruction of journal errors	Intervention	Pre- and post-course assessment (students tasked with identifying errors in an article)
Hoskins, S. G., & Gottesman, A. J. (2018). Investigating undergraduates' perceptions of science in courses taught using the CREATE strategy. *Journal of microbiology & biology education*, 19(1).	Examines students' perception of science as a result of CREATE approach in freshman and upper-level biology elective courses	Intervention	CLASS-Bio survey instrument (Semsar et al., 2011); Critical Thinking Assessment (CAT; Stein et al., 2012)
Kararo, M., & McCartney, M. (2019). Annotated primary scientific literature: A pedagogical tool for undergraduate courses. *PLoS biology*, 17(1), e3000103.	Describes the implementation of annotated primary literature in an undergraduate biology course	Recommended/Best Practices	Student feedback survey

Table 1 continued

Kenyon, K. L., Cosentino, B. J., Gottesman, A. J., Onorato, M. E., Hoque, J., & Hoskins, S. G. (2019). From CREATE Workshop to Course Implementation: Examining Downstream Impacts on Teaching Practices and Student Learning at 4-Year Institutions. *Bioscience*, 69(1), 47-58.	Evaluates the downstream impacts of a faculty workshop teaching CREATE approach to primary literature	Intervention	Experimental Design and Ability Test (EDAT; Sirum and Humburg 2011); Critical Thinking Test (CTT; flaguide.org); Survey of Student Attitudes, Abilities, and Beliefs (SAAB; Hoskins et al., 2011)

Major Research Questions and Aims

To examine the literacy practices employed by (competent) novice and expert biologists, the following research question guided our study: How do literacy practices differ between upper-level biology undergraduates (novices) and biology faculty (experts) while reading primary scientific literature? The following research aims, and corresponding research questions guided our work:

1. Aim 1 (Chapter 2): Characterize and identify primary literature reading practices of biology faculty members.
   1.1. How do expert biologists navigate through primary research literature articles?
   1.2. What actions do experts take while reading primary literature and what are their characteristics?
   1.3. What factors do biologists consider when determining the credibility of a primary literature article?
   1.4. What are the difficulties that experts face while reading, if any?
2. Aim 2 (Chapter 3): Characterize and identify primary literature reading practices of upper-level biology undergraduates.
   2.1. How do upper-level biology students navigate through primary research literature?
   2.2. What actions do students perform while reading and what role do these actions play in students' sense-making?
   2.3. What factors do students consider when determining the credibility of a primary research article?
   2.4. Lastly, how do these qualities compare to expert readers?

3. Aim 3 (Chapter 4): Examine current teaching practices involving primary literature by biology faculty at a large midwestern research institution.
   3.1. What primary literature-related competencies should undergraduate biology students possess upon completion of a 4-year program according to faculty with research and teaching appointments?
   3.2. How do such faculty implement primary literature into their curriculum and how does this implementation align with developing students' disciplinary literacy skills?
   3.3. What explicit strategies on reading primary literature do faculty provide students with, if any?
   3.4. What criteria do faculty utilize to select primary literature?

The findings to each research aim are presented as three studies in Chapters 2, 3, and 4, respectively.

Literature Search Methodology

To examine the depth and scope of research on primary literature conducted in the field of biology education, I performed a literature search using the Education Resource Information Center database (https://eric.ed.gov). The following keywords were used in the literature search: "Primary Literature" and "Undergraduate Biology," which returned 567 hits. Hits were filtered by "Undergraduate Studies" and reduced the number of articles to 269 hits. Each one of these articles was examined for usage of primary literature in undergraduate biology instruction. Studies examining primary literature implementation at the high school level or in other disciplines (e.g., physics) were excluded. After the initial selection, each article's references were examined for additional studies that examines primary literature at the undergraduate level.

Forty studies in total were compiled and are presented in Table 1. Each study's purpose, study format, and data sources/outcome measures are provided.

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CHAPTER 2: CHARACTERIZATION OF HOW EXPERT BIOLOGISTS READ PRIMARY RESEARCH LITERATURE

This chapter was adapted from the manuscript submitted to *CBE Life Sciences Education*: Lie, R., Guzey, S. S. (In review). Characterization of How Expert Biologists Read Primary Research Literature. Submitted to *CBE-Life Sciences Education*.

Abstract

Incorporating primary research literature into the classroom can offer opportunities to have students adopt disciplinary ways of thinking; however, empirical evidence of how biologists read primary literature is scarce. The purpose of this study is to describe and characterize literacy usage among biologists, specifically with regards to primary literature. We conducted semi-structured interviews with seven faculty members and had them describe their actions while reading a primary literature article. Among our participants, most reported reading such articles in a non-linear fashion, commonly skipping the introduction and/or methods or reading sections of the paper out of order. Using constant comparative analysis, we generated unique reading-related actions described by the faculty members. Through our analysis, we highlighted several reading-related characteristics common among most of the participants. Using Bloom's taxonomy of cognitive skills, we organized reading-related actions into cognitive domains (e.g., remember, understand). Actions aligned with evaluation were commonly expressed among participants and made up one third of total actions. We also identified factors that biologists cite when determining the credibility and validity of a primary research article. We discuss how the ways in which biologists read scientific texts can form the empirical basis of what it means to engage meaningfully with the discipline.

Introduction

Over the past decade, calls to action by multiple councils and organizations including the National Research Council (NRC, 2009), the American Association of Medical Colleges and Howard Hughes Medical Institute (AAMC-HHMI, 2009), and the American Association for the Advancement of Science (AAAS, 2011) have emphasized the need to reevaluate the ways in which undergraduate biology is taught. One such approach advocated by The Vision and Change report includes incorporating primary literature into coursework and teaching students to critically analyze primary literature (AAAS, 2011). To this end, many studies have emerged that have utilized primary literature to teach students various skills and strategies to engage with primary literature (e.g., Hoskins, Stevens, & Nehm, 2007; Gottesman & Hoskins, 2013).

Primary literature is an integral part of communication within a discipline and mediates the development of disciplinary knowledge. As noted by Hyland (2004), such "text[s] embody the social negotiations of disciplinary inquiry, revealing how knowledge is constructed, negotiated and made persuasive" (p. 3). It is no wonder that reading primary literature takes up a significant amount of time for researchers, with estimates as high as 23% of their total work time dedicated to reading (Tenopir & King, 2003). Given that reading primary literature is an increasingly important part of engaging with the discipline, it makes sense to introduce primary literature as a staple of undergraduate biology curriculum; however, what does critical analysis of such literature entail? Critical analysis of disciplinary literature not only requires a comprehensive understanding of content knowledge, but also necessitates awareness of disciplinary norms, conventions for communicating ideas, and ways of evaluating and challenging ideas within a discipline (Moje, 2008). It is therefore worth exploring how these ways of generating and negotiating disciplinary knowledge manifest in close readings of primary literature.

While a great number of studies have emerged using primary research literature as a means for faculty to teach scientific practices, many of these studies rely on anecdotal evidence and make tacit assumptions of how experienced readers approach primary literature (Hubbard & Dunbar, 2017). In examining the literature, we were surprised to find little empirical evidence characterizing how biologists engage with primary literature or other disciplinary texts for that matter. Even with valuable disciplinary literacy studies in other science disciplines (e.g., Bazerman, 1985; Shanahan, 2012), there are no studies in biology, to our knowledge, that examine the ways in which biologists make sense of primary literature. To craft more effective curricula and teaching pedagogies centered around primary literature that promote discipline-specific ways of knowing in biology, we found it valuable to empirically examine how scientists engage with primary research literature. In following study, we utilize an expert-reader model to explore the ways in which biologists critically read primary literature and identify and characterize the practices they employ while doing so.

Theoretical Framework

The foundation for disciplinary literacy incorporates three major areas of research: functional linguistics (Fang & Schleppegrell, 2010; Shanahan & Shanahan, 2008), theories addressing cognition and general content reading strategies (Moje, 2007; Shanahan & Shanahan, 2012), and novice-expert studies in reading (Bazerman, 1985; Pressley & Afflerbach, 1995; Shanahan, 2012; Wineburg, 1991). As highlighted by Shanahan and Shanahan (2012), disciplinary literacy is “an emphasis on the knowledge and abilities possessed by those who create, communicate, and use knowledge within the disciplines” (p. 8). Moje (2007) notes that knowledge and identity construction precede disciplinary literacy, suggesting that the acquisition of disciplinary literacy is associated with being an active participant within communities of practice. Collin (2014) describes, among others, that teaching disciplinary literacy involves the emphasis of unique features of professional and university literacies (i.e., how practicing biologists read and write). Therefore, a salient question of this line of research is: despite being written and spoken in the same language, why is literacy within a particular domain different from any other domain? Works by Burke (1966) and Rorty (1979, 1989) help to provide a framework to address this question.

Burke (1966) posits that the terminology we employ, either written or spoken, become the lens in which we view the world or the nature of reality. The nature of reality can be argued, but even with such argument, the terms and the ways in which the argument is written dictates how the discussion unfolds. Similarly, disciplines generate their own terminology and ways of constructing meaning. For example, the way a mathematician or chemist reads, understands, and communicates through their respective disciplinary texts are markedly different (Shanahan, Shanahan, & Misischia, 2011). In the study, researchers observed differences in how expert readers in different disciplines approached and contextualized, among other aspects, primary literature in their respective fields.

Rorty (1979) further explores this argument, introducing the concept of normal and abnormal discourse. In brief, normal discourse occurs when people subscribe to the same terminologies and conventions to produce discourse that is coherent and productive. In contrast, abnormal discourse takes place when people disagree about the conventions (e.g., terms, what qualifies as evidence). In such discourse, neither side can achieve truth or progress without reconciling differences in conventions. Subsequent work by Rorty (1989) further argues that participants outside of normal discourse cannot effectively contribute unless the participant adopts the normal discourse of the community.

Lemke (1990) builds upon this notion of normal discourse held among communities of scientists. To summarize, Lemke illustrated the ways in which the discourse of science, both written and oral, constitutes a specialized system of language that embeds theory, themes, and concepts that are not immediately salient to a novice. Therefore, learning science not only means to learn area content, but also to recognize themes and navigate between the various concepts within a discipline. Bruffee (1999) assimilated and applied these concepts to collaborative learning saying, “The professor’s goal is to help students learn fluency in that discourse, to make it become, for them, normal discourse” (p. 144). Following this reasoning, educators ought to help students assimilate into the normal discourse of a discipline. By having students adopt the normal discourse of the discipline, they can become members of such disciplinary communities.

Disciplinary literacy involves an “explicit understanding, articulation, and teaching of the normal discourse of legitimate participants within a discipline to students for whom the disciplinary normal discourse is nonstandard” (Reynolds & Rush, 2017, p. 201). In undergraduate biology, this not only includes teaching terminology and content, but also having students learn the conventions, norms, and practices within the discipline. This includes, but is not limited to, learning how to pose a research question, how to challenge disciplinary ideas, and how to evaluate evidence posed by their peers, among other things. Due to the importance of primary literature to practicing biologists, we found it worthwhile to explore how the act of reading such literature reflects upon experts’ ways of knowing within the discipline.

Promoting Disciplinary Literacy Through Primary Research Literature

For scientist, researchers, and academics, much of the written discourse and communication of research findings occurs through peer-reviewed publications. Within a specific discipline, communities of scholars have their own norms and conventions in which they adhere to when making sense of new knowledge (Lemke, 1990). In order to effectively participate within a discipline, students must develop an understanding of discipline-specific literacy practices that underlie knowledge creation. While studies over the past number of years have worked to ameliorate the difficulties that students encounter while reading primary literature, such work has primarily focused on the development of particular skills and/or strategies (e.g., Abdullah, Parris, Lie, Guzdar, & Tour; 2015; Ferenc et al., 2017; Gottesman & Hoskins, 2013; Hoskins et al., 2007; Krontiris-Litowitz, 2013; Round & Campbell, 2013; Segura-Totten & Dalman, 2013). While these studies are valuable in helping students develop skills and strategies to overcome the barriers in engaging with primary literature, we argue that most of these studies focus on approaches that more closely align with general reading strategies that are not discipline specific. As highlighted by Shanahan (2012), "disciplines have different ways of writing and speaking about the world. And because of this, discipline experts approach text with sets of expectations, reading strategies, and understandings that are firmly grounded in disciplinary knowledge" (p. 71). Currently, we have limited evidence characterizing how expert biologists approach primary literature.

Recent work by Hubbard and Dunbar (2017) begins to examine the literacy knowledge of expert biologists (in addition to undergraduate students, graduate students, and post-doctorates). Findings from this study highlight the importance of particular sections of primary literature articles. Specifically, expert readers (post-doctorates and academics) placed higher value in the

Results (figures and text) and Methods section in contrast to novice readers (2nd and 3rd year undergraduates; Hubbard & Dunbar, 2017). They also found that experienced readers recommended a selective approach to scientific reading. While this work provides some characterization of literacy practices of biologists, a more in-depth approach is necessary to better understand and identify disciplinary literacy practices in biology.

The purpose of this exploratory study is to describe and identify literacy practices within biology. By characterizing features of how expert biologists engage with and make sense of disciplinary texts, specifically primary literature, we hope to develop approaches to support and enhance literacy learning among biology undergraduates. Therefore, the study was guided by the following research questions: (1) How do expert biologists navigate through primary research literature articles? (2) What actions do experts take while reading primary literature and what are their characteristics? (3) What factors do biologists consider when determining the credibility of a primary literature article? (4) What are the difficulties that experts face while reading, if any?

Methods

Data Collection

We conducted semi-structured interviews with biology faculty members at a large midwestern research university to understand how expert biologists read primary literature. Using this approach allowed for flexibility to probe or clarify participants' responses outside of our standard interview protocol (Rubin & Rubin, 2011). The interview protocol is provided in Appendix A. Faculty participation was solicited via e-mail from three different areas of research within the Biological Sciences Department: cell and molecular biology, neurosciences and physiology, and ecology and evolutionary biology. All participants had both research and teaching appointments. A total of seven faculty members volunteered to participate in the study and were provided with informed consent (Appendix B). Also, participants were compensated upon the completion of the interview. Faculty were selected from a range of appointments from assistant professor to full professor positions. Average total research experience among participants was 25 years ± 4.4 years (Table 2). Faculty demographics are presented in Table 2. Prior to participation, all participants gave their informed consent. Interviews were audio recorded and subsequently transcribed. Participant information was de-identified and assigned a pseudonym for further analyses.

Faculty participants were asked to provide a copy of a primary research article in their field of expertise to help guide a portion of the interview. We reasoned that because expertise is domain specific (Hyland, 2004), it would be more accurate for participants to select their own primary research article. Throughout the course of a 40-minute interview, faculty participants were asked demographic information along with several open-ended questions to gauge their experiences with primary literature. Lastly, we asked participants to describe how they would approach reading a primary research article.

Data Analysis

Transcripts were analyzed in accordance with the aforementioned research questions, using both quantitative and constant comparative approaches, and utilizing an a priori coding framework. Quantification of reading order of major sections was calculated using distance vectors to determine if faculty read the paper linearly (i.e., in the order of presentation) or non-linearly. We utilized a Hamming distance vector to measure the linearity in their approach to reading the major section of the article: Abstract, Introduction, Results, Discussion, and Methods (Hamming, 1950). Hamming distance vector values were generated for each faculty member, which measures the distance between the individual's navigation pattern and the predetermined navigation pattern (i.e., the presented order of major sections; Figure 1). The distance vectors were normalized to the number of major sections (5) in a primary literature article. A normalized value of 1 indicates that the subject read the article completely out of order, and the value of 0 indicates the paper was read completely linear.

A

Paper Section	Vector #
Abstract	1
Introduction	2
Results	3
Discussion	4
Methods	5

B

Sections	Vector	Hamming Distance	Normalized Hamming Distance
Read in order	12345	0	0
Read out of order	13542	3	0.6
Skipped Methods	1234	1	0.2

Figure 1 Schematic of Hamming distance vector calculation. (A) Each major section of a primary literature article is assigned a vector number. (B) Example calculations based on readers’ navigation pattern through a primary article.

Table 2 Faculty demographic information.

Faculty Members	Research Area	Position	Years of Research Experience		Articles Read per Month (Average)	Normalized Hamming Distance	Paper Context
			Current Area	Total			
Damon	Cell & Molecular Biology	Associate Professor	14	27	10	0.4	Targeted reading
Caleb	Ecology & Evolutionary Biology	Professor	12	27	18	0.2	Targeted reading
Roberta	Cell & Molecular Biology	Assistant Professor	10	18	13	0.2	Directly related to research area
Jeffery	Neuroscience & Physiology	Professor	28	28	8	0.4	Journal club article
Candice	Cell & Molecular Biology	Assistant Professor	20	20	16	0.4	Directly related to research area
Diane	Ecology & Evolutionary Biology	Assistant Professor	25	25	14	0	Paper selected for student reading
Oscar	Cell & Molecular Biology	Associate Professor	20	30	20	0.6	Directly related to research area

Note. Normalized Hamming Distance represents the linearity in which faculty read primary literature. For more details, see data analysis section.

The implied cognitive level of each action expressed by faculty members was determined using Bloom's Taxonomy (Anderson et al., 2001; Bloom, Krathwohl, & Masia, 1956). This analytical framework was originally constructed to help educators construct learning objectives that promote meaningful learning. According to the framework, meaningful learning can be defined as the "knowledge and cognitive processes [people] need for successful problem solving" (Anderson et al., 2001, p. 65). These cognitive processes constitute a continuum that promote retention and transfer of concepts, which include: remember, understand, apply, analyze, evaluate, and create. The use of Bloom's taxonomy as a method to gauge the construction of assessment items has been well documented in biology education (e.g., Crowe et al., 2008). This usage is predicated on the belief that the construction of learning objectives and assessment items can elicit certain cognitive processes, which can enhance knowledge retention and transfer. Similar to Lie and colleagues' (2016) extension of the framework, we take this reasoning one step further and propose that actions performed while reading are indicative of specific cognitive processes employed by the reader. As such, reading actions described by participants were subsequently assigned a cognitive process that best aligned with the task. Researchers discussed and collaboratively determined the cognitive level of each action until a consensus was achieved. Actions that could not unambiguously be assigned a cognitive level were excluded from further analysis. Table 3 provides representative codes and faculty quotes for each cognitive level.

Table 3 Unique actions performed during critical reading of a primary research article expressed by faculty members. Actions are separated into two levels: major section within an article and broad overarching themes. Percentages indicate the amount of faculty participants performing at least one of the corresponding actions (n = 7).

Major Section	**Code**	**Sub-code**
Abstract	Probing (42.9%)	Identifying new information/key components
		Probing for interest
	Experimental outcomes (42.9%)	Evaluating reported outcomes
		Summarizing the study
	Tapping prior knowledge (71.4%)	Applying methods to my own research
		Connecting to prior knowledge
		Assessing relevancy to my research
		Predicting experimental approach
	Does not read (14.3%)	N/A
Introduction	Checking for logical reasoning (28.6%)	N/A
	Evaluating authors' hypothesis and prediction (14.3%)	N/A
	Checking references for further reading (14.3%)	N/A
	Does not read (57.1%)	N/A
Results	Examining experimental design (71.4%)	Predicting experimental approach Examining controls
		Evaluating experimental approach
		Predicting experimental outcomes
		Connecting experimental design to the research question
		Understanding experimental progression
	Examining data (100.0%)	Analyzing experimental data
		Evaluating consistency between text and figures
		Evaluating experimental data/figures
		Connecting quantitative data to biology
	Forming a conclusion (57.1%)	Using text to reinforce understanding
		Forming my own conclusions based on the data
		Developing a mental model
		Evaluating authors interpretation of data
	Tapping prior knowledge (28.6%)	Connecting methods to prior experiences

Table 3 continued

Discussion	Study evaluation (42.9%)	Evaluating authors' arguments
		Comparing my own conclusion to authors'
		Evaluating assumptions
		Evaluating scientific writing
		Resolving discrepancies between my own conclusions and authors'
		Evaluating study's limitations
	Big picture (57.1%)	Determining the implications of the study
		Determining the significance of the study
		Determine future experiments
	Check understanding (57.1%)	Identify new information/key components
		Understanding the study's rationale
		Understanding the novelty of the study
		Checking references for further reading
	Tapping prior knowledge (14.3%)	Applying information to my own research
Methods	Experimental design (28.6%)	Evaluate alignment of hypothesis and methodology
		Evaluate experimental design
		Evaluate data sources
	Methodology (14.3%)	Determine assumptions of methodology
		Evaluate statistical methodologies
		Understand analysis methods
	Clarifying information (details; 42.9%)	N/A
	Does not read (28.6%)	N/A

Institutional Review Board

The permission to conduct, record, and transcribe university faculty members' semi-structured interviews (IRB #1612018546) was obtained by the Purdue University Institutional Review Board.

Results

Characterization of Expert Reading of Primary Literature

To understand how expert biologists navigate primary literature, we first characterized participants' reading habits using quantitative approaches. Reading in the context of this study is defined as critical analysis of the article, compared to other forms participants described, such as scanning or referencing. Faculty reported reading an average of 14.1 ± 4.3 primary research articles per month. There did not appear to be any noticeable patterns associated with frequency of articles read and years of research experience (current area or total) or position (Table 2). We were curious to see if any patterns emerged regarding the order in which faculty members navigated each of the major sections (Abstract, Introduction, Results, Discussion, and Methods). The average normalized Hamming distance was determined to be 0.31 ± 0.20, meaning that the average faculty member either skipped 1-2 major sections or read 1-2 sections out of order. Normalized distance vector values are provided for each participant in Table 2. Upon closer examination, five of the seven participants regularly omit reading the Methods section or only viewed this section for clarification purposes. Additionally, four participants expressed that they normally do not read the Introduction of the paper, citing familiarity with the content area as the primary reason.

One interesting characteristic that we noticed in most participants is that after familiarizing themselves with the topic of the paper (i.e., read the abstract and/or introduction), they immediately proceeded to examine the figures in the results section, as opposed to examining the text. A few of these participants expressed that by doing so, it allows them to approach the data unbiased by the article's narrative. Two participants, however, explicitly stated that they usually read the text first, followed by the figures. It is interesting to note that these two participants' research focus aligned with Ecology and Evolutionary Biology, whereas the other participants' research areas are at the cellular level.

Our next step in characterizing how experts approach primary literature was having participants describe in detail how they read a primary research article in their field of expertise. We utilized constant and comparative coding methodologies to generate a list of actions performed by the biologists while reading primary literature. We provide an exhaustive list of all generated codes, organized according to major sections of a research article in Table 3. Forty-eight unique actions emerged from our analysis. Among the seven faculty members, we found that there was much less overlap in the actions than we originally anticipated, which led us to categorize these unique actions into broader, encompassing themes to create a multi-level coding scheme as shown in Table 3. This highlights that actions performed while reading are contextual and may be driven by factors such as field of study, years of research experience, available time, and intended purpose for reading, among others.

Cognitive Dimensions of Reading-associated Actions

We were interested in further organizing the actions expressed by our participants; to this end, we sought to determine the cognitive level of the reading-associated actions presented by faculty members. Using Bloom's Taxonomy of cognitive processes, we assigned a cognitive process (remember, understand, apply, analyze, evaluate, and create) to each action described by the faculty, where appropriate. Representative examples are provided in Table 4.

Table 4 Representative examples of actions while reading primary literature organized according to Bloom's Taxonomy of Cognitive Processes (Anderson et al., 2001; Bloom et al., 1956).

Cognitive Process	**Example Codes**	**Representative Example**
Remember	Identifying new information	"And so that's why I read the abstract. I make sure from the abstract – is there anything that it seems like I don't know. And from this abstract, no, it seemed straightforward." (Candice)
Understand	Determining implications of research	"And the discussion is important in a similar way, but also to try to figure it out the ... some of the implications people get out of their own data…" (Oscar)
Apply	Predicting experimental approach	"Usually for the abstract, you can kind of get a feel of the types of experiments that they do. So this is a cell culture paper so a lot of molecular genetic experiments, RNAi, and then Westerns." (Damon)
Analyze	Connecting quantitative data to the biology	"But I love the papers in which they use the stats to support the biological trends … Are they potentially, biologically interesting or not…" (Diane)
Create	Constructing my own conclusion	"And the point of my ... I see the title of each of the results sections associated with the figures. And then I look at the figures and try to make my own conclusions before I read what they are saying." (Candice)
Evaluate	Evaluating the alignment of the hypothesis and methodology	"…most importantly [I pay attention to] how they follow the hypothesis and the predictions to try to see whether there is a mismatch between the way the study was designed and what the authors predicted in the first place." (Caleb)

We first examined how the cognitive level of actions were distributed across the major sections of an article. As suspected, most of the actions reported by faculty took place in the Results and Discussion section (36.1% and 27.8% of total actions, respectively), suggesting that these two sections are where most time/effort is spent while reading; whereas the faculty collectively performed the least amount of actions in the Introduction and Methods (5.6% and 12.5%, respectively). Interestingly, actions aligned with the evaluate process were present and relatively constant throughout all sections of the article. In contrast, other actions aligned with other cognitive processes were either, prevalent only in a specific section(s). For example, analyze-related actions were predominantly expressed in the Results section (12.5% of total actions). Alternatively, actions associated with remember or create were infrequent throughout all the sections.

We also quantified and plotted each individual's cognitive profile (Figure 2) based on the distribution of cognitive processes of reading-associated actions. Among faculty participants, we observed several cases in which the cognitive processes of reading-related actions were skewed towards a particular area. For example, the actions Caleb described while reading primary literature heavily aligned with evaluation (77.8%), whereas 50% of the actions described by Jeffery were categorized as understanding - more than double of the group mean in both cases. We reason that the context in which the paper was selected and read influenced the depth of reading. For example, since Jeffery read his article for a journal club (Table 2), we suspect Jeffery was inclined to perform actions aligned with understanding while reading the article. In contrast, Caleb chose his article for a targeted purpose, which may have led him to perform mostly reading-actions aligned with the evaluate process. In Figure 3 and in the subsequent text, we provide a vignette of the actions described by Candice, the participant whose cognitive profile was most similar to the group mean.

Similar to most of her colleagues, Candice began her reading with the Abstract and expressed that she starts with connecting the information presented in the Abstract to her own research experiences, specifically narrating how the such information fit within her own research narrative. Candice also highlighted that her main objective was to identify any new or novel pieces of information. Next, like the majority of her colleagues, Candice reported skipping the

Introduction and directly proceeding into the Results, confidently citing her level of knowledge in the field to be sufficient.

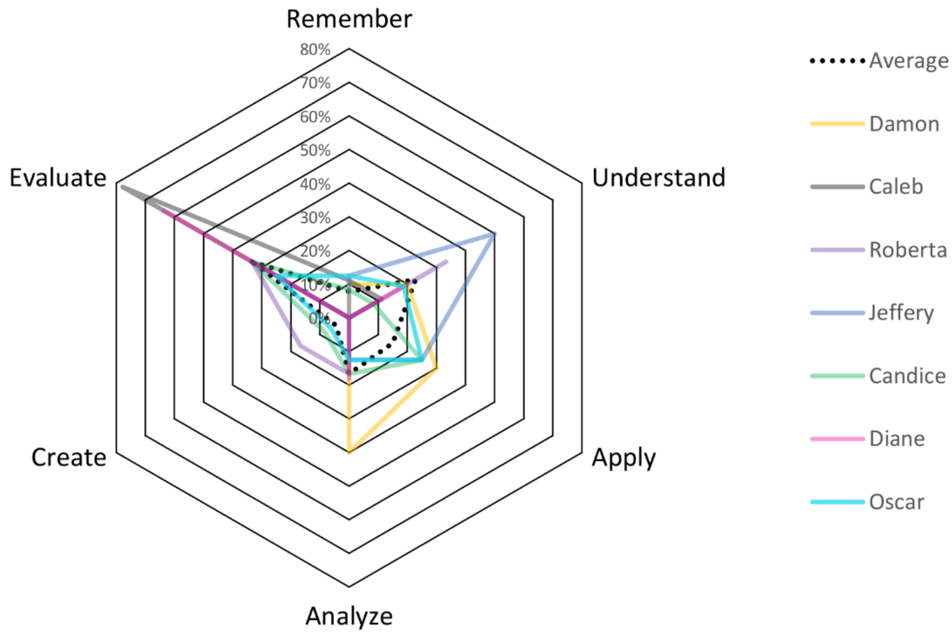

Figure 2 Cognitive profiles of reading-associated actions represented as percentage of total actions. Participants' reading actions were aligned with Bloom's Taxonomy of Cognitive Processes (Anderson et al., 2001; Bloom et al., 1956) and individually plotted. The dotted line represents the average profile among all participants.

Candice reported spending a majority of her time in the Results section. Interestingly, her actions in this section were quite diverse and included actions that aligned with apply, analyze, evaluate, and create processes. She began with predicting the experimental approach of the paper based on the title of each subsection. This is followed by examining each figure individually. As Candice described the experiments performed throughout the article, she drew upon her own experiences with these methods, describing how these techniques were used in her laboratory to answer similar but different questions. This practice was fairly common across faculty members, as the paper invoked researchers to reflect upon their past research experiences, to varying degrees. While examining each figure, Candice emphasized relating quantitative data to the biological phenomenon, explaining the biological implication of the graphical representations within each figure. After analyzing each figure, she evaluated whether or not the authors' experimental approach was sufficient to test the overarching hypothesis. Prior to moving towards the Discussion section, Candice reported forming her own conclusion based on the data presented (Table 4).

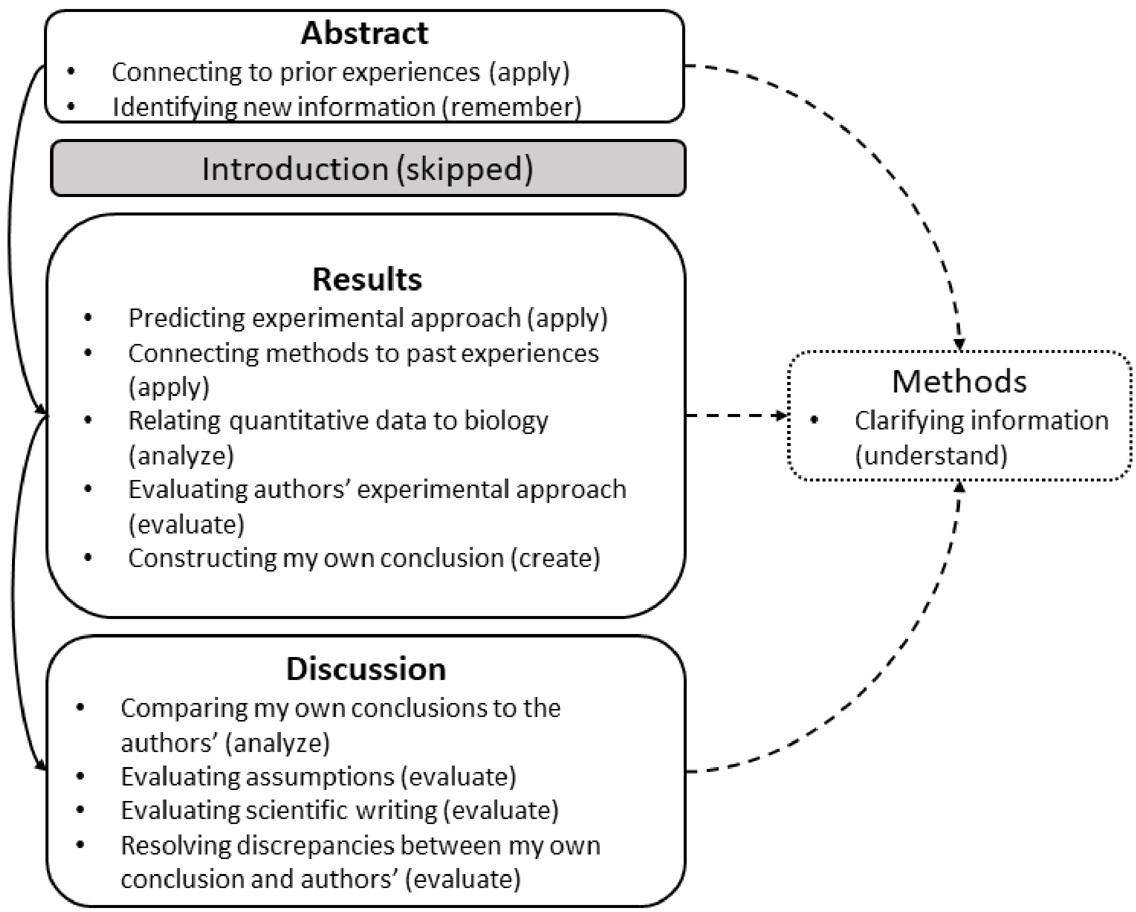

Figure 3 Representation of the actions related to reading primary literature as described by Candice. Cognitive levels of each action are provided in parenthesis. The solid arrow represents the navigation pattern among major sections of the paper, whereas the dotted line represents conditional reading patterns (e.g., reading for clarification purposes).

In the Discussion, Candice performs actions primarily aligned to the evaluate process, including evaluating the assumptions posed by the authors, evaluating the writing, and resolving any discrepancies between her own conclusion and the conclusions posed by the authors (Figure

3). Candice did not initially report reading the Methods section, but when probed she stated, “And wherever I feel there's a discrepancy, then I'll go back and then essentially read the whole paper Methods, the Results, and everything, and then see, ‘Okay. Reading that, did it change what my interpretation was?’” Here, we observed that the Methods was mainly used as a supplement and not necessarily accessed, as her expertise in the field was generally sufficient to understand the experimental design of the study. This response regarding the Methods was fairly common, as four of the seven participants reported either skipping the Methods or only looking for details or clarification purposes.

Interestingly, the faculty members that regularly examined the Methods (Caleb and Diane) cited contextual factors as the main reason for doing so. For example, Diane stated that, “There’s a big issue with pseudo-replication in my field, so I’m always attentive to if they are pseudo-replicating or [if] they are doing this carefully enough. Can I believe what they’re concluding?” It is interesting to note that both Caleb and Diane’s research area aligns with Ecology and Evolutionary Biology, which may suggest sub-discipline-specific reading characteristics.

What Constitutes Credibility?

To acquire a better understanding of how knowledge negotiation and construction takes place, we utilized constant and comparative analysis to identify and characterize the factors that play a role in determining the credibility of primary research literature. Faculty expressed an average of 3 factors that contributed to determining the credibility of a primary research article. A list of factors and corresponding examples are provided in Table 5. We identified three major categories of factors that affect credibility: corroboration, experimental setup and methodology, and sourcing. Corroboration describes considerations across texts or between text and one’s own knowledge (Wineburg, 1991). Setup and methodology refer to either the experimental design (or specific components), methodological approaches, or framing of the experiment. Lastly, sourcing refers to factors based on reputation, such as names of authors, laboratories, or journals (Wineburg, 1991).

Table 5 Factors that influence the credibility of a primary literature article. Participants expressed multiple factors in their responses. Percentages indicate the amount of faculty expressing one or more factors falling into one of the three overarching categories (n = 7).

Credibility Factors	**Representative Quotes**
Corroboration (71.4%)	
Prediction	"And the reason that I found these papers is because I expected something similar. I knew that there was some kind of connection between ACK and some type of unknown." (Damon)
Triangulation	"What I just said ... as I said I like to see more than one approach used to try to make a point. That doesn't seem to be the case of this paper. So that makes me more confident." (Oscar)
Validation of results	"They defined a specific signature, and that gave me a hint.…but my point is that I can cross reference this PAPV—has it been found elsewhere? The answer is yes." (Damon)
Setup and methodology (100.0%)	
Controls	"The controls are very, very important. This is why I like to look through the figures and interpret the data without reading their interpretations first. I like to just look at it, try to understand what they've done, and then see if it is fully controlled." (Candice)
Experimental design	"The quality ... the nature of the things used, as in any other discipline, there are some very old techniques and some more novel techniques and more stringent techniques; obviously the better the technique, the more confident I'm gonna be on this. But as I said, the more techniques they use, the better. It will make me more confident." (Oscar)
Hypothesis	"A clear hypothesis, a clear prediction, an experimental design that follows these two…These are three things that if all these criteria are met, not just one, all of them, then I tend to believe those results more…" (Caleb)

Table 5 continued

Quality of data	"…and then the overall quality of the data. We do a lot of imaging, so if the images look bad and they do some contradictions based on images, I'm wondering what they really measured." (Jeffery)
Sample size	"Well… it's like sample size, and I look particularly carefully at the biostatistics…" (Diane)
Statistics	"You know sometimes you see some papers that they claim to have found something, then when you look at them the differences are really marginal, the errors very low and it's not really worth my time sometimes." (Oscar)
Sourcing (57.1%)	
Authors	"I have to admit sometimes the authors, or the last author might play a role a little bit. Unfortunately, that's not something that should be taken into consideration, but in some cases when you see that the paper is coming from a big lab you might be a little more confident. But experience has shown us that that not necessarily is the case always." (Oscar)
Journal	"I'm gonna be honest, one of the first ones is the journal that it's published in. I put a lot of weight on the journal, the editors, the reviewers, and I think if it's a reputable journal then I'm more convinced that the science is probably going to be credible." (Roberta)
Other (14.3%)	
Access to raw data	"Are you giving me the raw data? I love that in the supplement you can, in many of the good journals, you'll find the entire image of a gel or a membrane or something, not just a crop part that's in the figure." (Roberta)

Most participants referenced some credibility factor related to sourcing. As highlighted by Damon, it is difficult to approach an article completely unbiased when you are aware of the reputation of a laboratory or research group. He mentioned, "You know that if [the article] is from some big lab, and there is a lot of reputation that goes before them, then you kind of put some weight on those papers." Similarly, Roberta mentioned that the journal also plays a non-trivial role in influencing credibility (Table 5)—particularly citing her trust in the rigor of peer review in reputable journals. While reputation of a name or journal can present certain biases, our participants also emphasized that they try to evaluate the merit of the article based on other factors, including design of the experiment.

All participants cited at least one factor that aligned with setup and methodology, with most participants citing two or more. Oscar probably best summed up the relationship of sourcing and setup and methodology:

> *I have to admit sometimes the authors, or the last author might play a role a little bit. Unfortunately, that's not something that should be taken into consideration, but in some cases when you see that the paper is coming from a big lab you might be a little more confident. But experience has shown us that that not necessarily is the case always.*

Oscar recognized the bias of sourcing, but also adds that it is not something that should be acknowledged when evaluating the scientific merit of an article. It is important to note that Oscar also cited factors related to both corroboration and setup and methodology, reinforcing the idea that while sourcing may provide some indication of quality, other aspects are essential in determining credibility and validity.

The last category, corroboration, was expressed by 71.4% of our participants. Here, participants cited the need for multiple approaches (Triangulation), validation of results, or results that align with previous bodies of knowledge (Prediction). Given that reproducibility and consistency with results can be an issue in biological sciences (Munafo et al., 2017), it is not surprising that most faculty expressed corroboration as a consideration for credibility.

What do Experts Perceive as the Most Difficult Aspect of Primary Literature?

As part of our ongoing effort to characterize the progression of learning to read primary scientific literature (Lie et al., 2016), we were curious to see if faculty faced any difficulty or challenges while reading. We asked participants, "What aspect of reading primary scientific literature in your field of expertise do you find most challenging, if any?" We intentionally asked participants to consider literature in their field of expertise, as prior studies have shown that expertise is domain specific (Hyland, 2004). We found that the majority (four) of professors expressed little to no difficulties with the content matter itself, while the other faculty members expressed contextual difficulties. For example, Candice reported that accessing the Methods section of the paper was the most challenging, as, "Many papers are made shorter and shorter, or the Methods have been moved into the supplemental information, and supplemental information is not always easily available." For Roberta, validating techniques across the literature was the most challenging. We suspect this is another contextual factor, as Roberta performs research in an emerging field of biology where new techniques are more frequently employed, compared to classical techniques. From our participants, we were unable to determine any other trends regarding perceived challenges in reading primary literature.

Discussion

Knowledge generation within a discipline operates according to particular practices and conventions for communicating, representing, and evaluating knowledge in the discipline. Additionally, developing disciplinary literacy is important in the construction of students' identities as they advance within a discipline (Moje, Overby, Tysvaer, N., & Morris, K., 2008). One possible method of developing disciplinary literacy at the undergraduate biology level is through the incorporation of discipline-specific texts, such as primary research literature (Shanahan et al., 2011). Such reading is known to be quite challenging for students (e.g., Hubbard & Dunbar, 2017; Lie et al., 2016; Round & Campbell, 2013), and various studies have explored instruction on how to read primary literature (e.g., Abdullah et al., 2015; Ferenc et al., 2017; Gottesman & Hoskins, 2013; Hoskins et al. 2007; Krontiris-Litowitz, 2013; Round &

Campbell, 2013; Segura-Totten & Dalman, 2013); however, it is important to differentiate whether these studies are promoting general reading strategies (i.e., transferable to other disciplines) or disciplinary literacy (i.e., practices and norms specific to a particular discipline). We acknowledge that development of both general reading strategies and disciplinary literacy are integral to learning a discipline; however, if the goal is to use primary literature to help biology students develop ways of thinking within the discipline, we need more empirical evidence of the norms and practices biologists employ while engaging with disciplinary literature. Engaging with a discipline's primary research literature is nested within that community's discourse and is subjected to their norms and values (Hyland, 2004). In the present study, we explored the characteristics of how expert biologists read primary literature in hopes that this information can be applied to helping build students' disciplinary literacy. We conducted this study using several approaches, including examining general reading characteristics (e.g., reading order), identifying reading-related actions, categorizing actions according to cognitive level, and determining factors that influence credibility.

In this study, we found that most faculty read research papers in a nonlinear manner and spent most of their effort engaging with the data, specifically the Results section. Furthermore, most of our faculty focused more on the figures or representations as opposed to reading the text. Our observations align with some of Hubbard and Dunbar's (2017) findings, which found that researchers considered the Results section (both the text and figures) to be the most important section of the paper. It is interesting to note that Hubbard and Dunbar's study (2017) also found the Methods section to be the next most important section after Results according to researchers. Surprisingly, we found that a majority of our faculty usually skipped the Methods section while reading, suggesting that importance of a section may not necessarily be aligned with time or effort spent reading a particular section.

Using Bloom's taxonomy as a framework to characterize reading actions (Anderson et al., 2001; Bloom et al., 1956), we were able to observe how reading actions potentially reflect biologists' identity and other contextual factors that affect how they read. We found that a large part of reading for faculty members was related to evaluation of data, evidence, and experimental design, among others. This suggests that faculty may view themselves as the arbiters of information, ultimately judging the credibility and quality of the science in the article. As Moje (2007) posits, identity construction precedes and plays a role in the development of disciplinary literacy. Our data suggests that faculty members' identity as practicing biologists help to inform their role as evaluators of scientific evidence and knowledge when they read primary literature. As Candice highlighted, "just because it's in print doesn't mean it's correct. And so that was one of the take home points - that you have to check up on things, verify things on your own." As we previously noted, we observed participants' actions aligned with evaluation were seen throughout all sections of the paper. Such judgements are based on criteria and standards that are formed through the interaction and negotiation within a disciplinary community (Hyland, 2004). The biologists we interviewed have developed their craft over the course of decades, immersed in the disciplinary discourse; they have become part of the disciplinary community and know the implicit conventions of what it means to be a scientist. By making these implicit conventions explicit throughout undergraduate biology curricula, we reason that students can grasp a more informed understanding of disciplinary thinking. This is an important factor to consider when constructing instructional strategies that rely on identity construction within the discipline.

Lastly, we were curious to see what factors played a role in determining a study's credibility among biologists. We found three major categories of factors expressed by participants: corroboration, setup and methodology, and sourcing. Prior work by Shanahan, Shanahan, and Misischia (2011) show that corroboration plays a large role according to historians and chemists, whereas mathematicians are more concerned about internal consistency. In our study, corroboration between the results from an article and other bodies of knowledge was fairly consistent among participants. Our participants also expressed that the influence of sourcing is different than mathematicians or historians, but quite similar to chemists (Shanahan, Shanahan, & Misischia, 2011). In brief, historians placed large importance on the author(s) and their perspectives, whereas mathematicians read without consideration of the author. Chemists were in between the two in that they "paid more attention to the source of information as a predictor of quality" (Shanahan, Shanahan, & Misischia, 2011, p. 409). Similarly, most of our participants view authors, laboratory, or journals indicate a certain level of quality or credibility; however, the most often cited factor was related to setup and methodology.

As suggested by Moje and colleagues' (2008) work with adolescent populations, educators help to shape the ways in which students develop discursive navigation and awareness within a discipline. Thus, it is important for biology educators to carefully consider the ways in which we invite and engage learners within a discipline. While primary literature may be difficult and frustrating for undergraduate students (Round & Campbell, 2013), it is important to immerse students in the language of the discipline in order to develop students' identities as biologist. As Moje (2008) states, "we need to reconceptualize subject area learning as a matter of learning new ways of knowing and practicing, not merely as a means to expose students to new ideas or bits of information" (p. 103).

From our study, we have learned that researchers and professors are highly evaluative and/or critical when reading a primary research article, yet our prior work suggests that students may not even be aware that evaluating plays a large role in engaging with primary literature (Lie et al., 2016). Providing instruction on what biologists value (e.g., corroboration across multiple studies/methodological approaches, connecting data/methods to past experiences) and how these values are reflected in their discourse can help students gain a better understanding of how biological knowledge is negotiated and constructed. Furthermore, expert researchers' reading strategies are dictated by contextual factors of their profession and research. Our investigation into what experts perceived as difficult corroborates this point, as difficulties brought up by the faculty were contextual, but were unrelated to the actual content. Past research has demonstrated that strategies identified in expert-reader models in other disciplines can lead to effecting teaching strategies (see e.g., Bazerman, 1985, Hynd-Shanahan, 2008). This exploratory study presents one of the first characterizations of how biologists examine primary literature and is something that will need to be examined in more detail in future studies.

Limitations and Future Directions

This study has several important limitations to consider. First, only seven disciplinary experts were recruited for this study. Furthermore, our participants read papers in several different contexts which limits the generalizability of the conclusions that can be made. This is an unavoidable limitation of the expert-reader approach; however, this paradigm is meant to identify and characterize potentially important insights of how reading takes place, rather than to make universally generalizable claims (i.e., biologists read texts in this manner). Much of our observations are exploratory and will need to be expanded upon in subsequent studies. The present study, nonetheless, highlights how disciplinary expertise, among other factors, guides biologists to make sense of primary literature.

Another limitation of our study is related to the level of depth the faculty members expressed their-reading related actions. We suspect that there are many finer grain details that were implied, but not explicitly mentioned. Therefore, we speculate that the actions expressed by faculty in this study to be the most salient or important actions that they consider while reading. To address this concern, we suggest utilizing a think-aloud protocol in future studies (Ericsson & Simon, 1984) for a finer grain analysis of the ways biology researchers approach these disciplinary texts. Our immediate step in this project, however, is to examine how inexperienced readers (i.e., undergraduates), approach primary research literature. In this manner, we can compare and contrast the ways in which novice and expert biologists approach reading such text. Such work can provide the necessary evidence to construct pedagogical approaches to help students develop literacy practices in biology.

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CHAPTER 3: CHARACTERIZATION OF HOW (COMPETENT) NOVICE BIOLOGISTS READ PRIMARY RESEARCH LITERATURE

This chapter was adapted from a manuscript in preparation.

Abstract

Incorporating primary literature into undergraduate biology classrooms can provide authentic opportunities to better understand knowledge generation within a discipline; however, students often face many difficulties and anxiety while engaging with such literature. The following study describes and characterizes literacy practices upper-level undergraduate biology students employ while reading primary research. We conducted semi-structured interviews with 19 students from a large midwestern research institution and prompted them to describe their actions while reading a primary research article. Students reported reading the articles in a linear manner, and often disregarded the methods section. Utilizing constant comparative analysis, we generated categories of reading actions based on students' descriptions, with most actions focused on obtaining a general understanding. Further organization of reading-related actions into Bloom's taxonomy of cognitive skills revealed that most reading actions were associated with remember and understand processes. Actions aligned with other cognitive domains (e.g., apply, create, and evaluate) were scarcely reported. We also examined factors that students cite when evaluating the credibility of an article. In light of these results, we discuss the implications for instruction of undergraduate biology education.

Introduction

Reform documents released by multiple councils over the past decade have advocated for a transformation in the way undergraduate biology is taught (AAAS, 2011; AAMC-HHMI, 2009; NRC, 2009). This wave of reform to biology education requires a shift from content-focused curricula to helping students “understand, generate, and communicate knowledge about the living world” (AAAS, 2011, p. 11). Given that knowledge production is increasing at a rate much faster than students can possibly learn (Geddes, Cannon, & Cannon, 2018), it is imperative that undergraduate education focuses on how to navigate and make sense of emergent knowledge. To this end, incorporating primary literature has been advocated as a means to enhance student understanding of knowledge generation within the discipline (AAAS, 2011). Furthermore, faculty have expressed the importance of teaching skills and practices that are associated with making sense of primary research literature (e.g., problem solving, critical thinking, interpreting data, reading and evaluating primary literature; Coil, Wenderoth, Cunningham, & Dirks, 2010).

Primary literature serves an essential role in the communication and establishment of disciplinary knowledge. As such, primary literature functions as a tool that mediates social interactions among disciplinary practitioners, as understanding its usage is necessary to engage in disciplinary discourse (Hyland, 2004). With scientists and medical researchers spending as much as 23-30% of total work time engaged in reading primary journals (Tenopir & King, 2003; Tenopir, King, & Bush, 2004) and on average reading upwards of 120-130 articles per year (Tenopir & King, 2002), undergraduate science education must better prepare students to engage in critical reading of such literature. Critical reading of disciplinary literature not only necessitates a deep understanding of content knowledge, but also requires knowledge of disciplinary norms, guidelines for communication, and how to evaluate and challenge ideas (Moje, 2008). Thus, teaching biology students the ways of generating and making sense of disciplinary knowledge requires a reconceptualization of learning.

Many studies have examined how targeted use of primary research articles can help develop students' understanding of research literature through various novel approaches (e.g., Abdullah, Parris, Lie, Guzdar & Tour, 2015; Farenc et al., 2018; Gottesman & Hoskins, 2013; Round & Campbell, 2013). While incorporating primary literature in undergraduate coursework can produce benefits even with minimal scaffolding (Liao, 2017), instructional approaches that develop disciplinary literacy practices are necessary to prepare students to become active participants in science communities. Many studies have assessed literacy and related process skills (e.g., Abdullah et al., 2015; Gottesman & Hoskins, 2013; Round & Cambell, 2013; Sato, Kadandale, He, Murata, Latif, & Warschauer, 2014); however, there is little empirical evidence examining the process of students' reading. Work by Van Lacum colleagues (2012) compared the ability of first-year undergraduates and expert readers to identify evidence and conclusions within a primary literature article, highlighting that students were less able to identify appropriate conclusions compared to experts. They provide several vignettes of how students read but did not perform any systematic analysis. Therefore, this study aims to explore the ways in which undergraduate biology students read primary literature. Prior work that has characterized how expert biologists engage with disciplinary literature reveal disciplinary ways of knowing and evaluating (Lie & Guzey, in review). By identifying the differences between the two populations, we aim to craft instruction that can help students to think and read as disciplinary participants.

Theoretical Framework

Disciplinary literacy stems from the fact that "each discipline possesses specialized genre, vocabulary, traditions of communication, and standards of quality and precision" (Shanahan & Shanahan, 2011; p. 395). Thus, the ways in which practitioners engage with disciplinary literature differs according to content area. The groundwork for disciplinary literacy is based on three areas of research including functional linguistics (e.g., Fang & Schleppegrell, 2010; Halliday, 1994), general content reading strategies (e.g., Moje 2007; Shanahan & Shanahan, 2012), and novice-expert reading studies (e.g., Bazerman, 1985; Pressley & Afflerbach, 1995; Wineburg, 1991). Disciplinary literacy is not to be confused with content area literacy, which "prescribes study techniques and reading approaches that can help someone to comprehend or to remember text better" (Shanahan & Shanahan, 2012, p. 8). Furthermore, content area literacy offers generic reading strategies that are akin to study habits (e.g., concept mapping, annotation), and are transferable from one discipline to another. In contrast, disciplinary literacy emphasizes the literacy practices unique to a specific discipline (e.g., what qualifies as valid evidence).

Works by Burke (1966) and Rorty (1979, 1989) provide a framework that begins to address how domain-specific communication affects professional literacies. Given that each discipline uses terminology in specific manners and orientation, such a use of language affects our world view (Burke, 1966). Language serves as the foundation in how we construct meaning, and subsequently establishes dialogue within communities. Thus, communities that engage in a particular endeavor develop unique uses of language to serve its purpose. As such, markedly different approaches to reading and understanding of disciplinary texts have been reported among linguists, mathematicians, historians, and scientists (e.g., see Bazerman, 1985; Reynolds & Rush, 2017; Shanahan, Shanahan, & Misischia, 2011). In order for individuals to have a fruitful exchange of information, discourse must be grounded with a set of underlying assumptions and conventions (e.g., terminology, determining what is relevant, what counts as evidence). This is coined as "normal discourse" by Rorty (1979). Participants operating outside of the normal discourse cannot hope to effectively participate nor contribute unless they take up the discourse of the community (Rorty, 1989).

The discourse in science constitutes a system of communication of theory, themes, and concepts that are not immediately apparent to novices (Lemke, 1990). Thus, learning to navigate within a discipline not only means learning content, but also developing the ability to recognize such themes and concepts within a discipline. Of course, this includes the discourse and literacy practices of the discipline. Yet, content area specialists have tended to teach content without the consideration to develop students' literacy skills (Siebert & Draper, 2008). If the goal of education is to invite students into participating in disciplinary communities, educators must help students become fluent in the discourse of such communities (Bruffee, 1993). In science, the definition of literacy is extended beyond words, as science texts often contain graphical representations and mathematical modeling (Lemke, 2001), which is essential to making sense of the information. Developing students' understanding of disciplinary literacy is not an easy task, as this demands an "explicit understanding, articulation, and teaching of the normal discourse of legitimate participants within a discipline to students for whom the disciplinary normal discourse is nonstandard" (Reynolds & Rush, 2017, p. 201). In the context of undergraduate biology education, this means having students learn the conventions, norms, and practices employed by biologists, in addition to content knowledge and terminology.

The goals of this research are to identify and describe literacy practices within biology. By comparing previous work that characterized features of how expert biologists make sense of disciplinary texts (Lie & Guzey, in review) with students, we can develop instructional approaches to target and support literacy practices of biology students. Thus, the following study was guided by the following research questions: (1) How do upper-level biology students navigate through primary research literature? (2) What actions do students perform while reading and what role do these actions play in students' sense-making? (3) What factors do students consider when determining the credibility of a primary research article? (4) Lastly, how do these qualities compare to expert readers?

Methods

Data Collection

We conducted semi-structured interviews with biology undergraduates at a large midwestern research university to better understand how novice biologists read primary literature. This approach provided flexibility to probe or clarify participants' responses outside of our standard interview protocol (Rubin & Rubin, 2011). The interview protocol is provided in Appendix C. We solicited student participation via e-mail and/or in-class solicitation from two different areas of research within the Biological Sciences Department: cell and molecular biology, and neurosciences and physiology. Additionally, we recruited students of junior or senior standing, as we reasoned that this population had prior experience with reading primary literature. A total of 19 students volunteered to participate in our study and were provided their informed consent (Appendix D). Furthermore, students were given compensation upon the completion of the interview. Information such as year of study, major, career trajectory, and laboratory experience was collected. Demographics of student participants are provided in Table 6. Prior to participation, all participants gave their informed consent.

Table 6 Student participant demographics.

ID	Year	Major	Career Trajectory	Total # of papers read (self-reported)	Laboratory experience (months)	Level of Research Participation[+]	Normalized Hamming Distance Vectors
1	Senior	Brain & Behavioral Sciences	*	40 (total)	12	Low	0
2	Senior	Neuroscience & Physiology	*	40 (total)	18	Low	0
3	Senior	Biology	Physician's Asst. Degree	80 (total)	15	Medium	0
4	Junior	Biochemistry	Medical School	10 (total)	*	Low	0.2
5	Senior	Cell	Graduate School	10 (total)	9	Medium	0
6	Senior	Biochemistry & Microbiology	MBA	100 (total)	36	High	0
7	Senior	Biology Education	Graduate School	30 (total)	-	No Experience	0.2
8	Senior	Engineering (Biology Minor)	Nonprofit Startup	10 (total)	-	No Experience	0.8
9	Junior	Biology	Graduate School	4-6 (monthly)	12	Low	0
10	Senior	Neurobiology	Medical School	20 (total)	12	Medium	0.8
11	Junior	Biology	Graduate School	1 (monthly)	0	No Experience	0
12	Senior	Ecology and Evolutionary Biology	Environmental Education	> 100 (total); 10 (monthly)	12	Medium	0.2
13	Senior	Biochemistry	Medical School/Ph.D. (dual degree)	> 300 (total); 20-30 (monthly)	18	High	0.2
14	Senior	Biology	Graduate School	8 (monthly)	30	High	0.2
15	Senior	Animal Sciences	Veterinary School	100 (total)	12	Low	0.2
16	Senior	Nutrition Sciences & Psychology	Medical School	100 (total)	24	Medium	0.6
17	Senior	Biochemistry	Genetic Counseling	200 (total)	24	High	0.6
18	Senior	Biology	Healthcare (vague)	3-4 (monthly)	12	Low	0.4
19	Senior	Genetics	Healthcare (vague)	20 (total)	18	Medium	0.2

Notes: ***** indicates that the question was either omitted, not answered, or ambiguous. [+] Refer to Table 7 for coding scheme.

Interviews were audio recorded and subsequently transcribed. Participant information was de-identified, randomized, and assigned an identification number for further analyses.

Student participants were asked to provide a copy of a primary research article in their area of study to help guide a portion of the interview. A majority of students brought articles related to the coursework of one of their classes, whereas several students brought articles tied to their research experiences. Throughout the interview, participants were asked demographic information along with several open-ended questions to gauge their experiences with primary literature. We asked participants to describe their approach to reading a primary research article, using the article they brought as a reference.

Data Analysis

Transcripts were analyzed in accordance with the aforementioned research questions, using both quantitative and constant comparative approaches, and utilizing an *a priori* coding framework where appropriate. Levels of laboratory participation were devised based on reported levels of autonomy and involvement in intellectual involvement (Table 7). Researchers discussed and assigned levels of research participation based on consensus. Quantification of reading order of major sections was calculated using distance vectors to determine if students read the paper linearly (i.e., in the order of presentation) or non-linearly. We utilized a Hamming distance vector to measure the linearity in their approach to reading the major section of the article: Abstract, Introduction, Results, Discussion, and Methods (Hamming, 1950; Lie & Guzey, in review). Normalized Hamming distance vectors were generated for each student, which measures the distance between the student’s navigation pattern (i.e., reading order) and the predetermined navigation pattern (i.e., the presented order of major sections). The distance vector was normalized to the number of major sections (5) in a primary literature article, where a normalized value of 1 indicates that the subject read the article completely out of order, and the value of 0 indicates the paper was read linearly.

Table 7 Student levels of participation in a research laboratory.

Level of Participation	**Description**	**Representative Examples**	**# of students**
No Experience	-No research experiences	N/A	3
Low	-Students performs experiments -No involvement in planning experiments -Little to no autonomy in experimental design -Student may be involved in other aspects of the lab (i.e. dish washing, maintenance)	I'm an undergraduate lab assistant. I started off doing menial things until I can do, learn the ropes for other stuff. But now I'm helping my grad student with her project, doing a lot of what she's doing as well. (S09)	6
Medium	-Student performs experiments and provides some degree of input -Able to influence the direction of the research project -Student expresses some degree of project ownership	So I did that for a summer, and then I worked in a lab again for another semester finishing up that project. I got to see the project from the beginning where we were stimulating bone growth in mice for a couple weeks, and we had to dissect the mice and extract the tibias and then we had to micro CT them and analyze those micro CTs. (S10)	6
High	-Student has complete or near complete autonomy over their project and experiments -Student is engaged with lab activities (i.e. journal club, lab meetings) -Student expresses a strong sense of ownership over their work	Yeah. Actually, originally, stuff wasn't working, so I found an alternative technique and I got the go ahead on that, and I went with it. I'm not ... I have a high degree of autonomy, I would say, as far as moving around in lab, doing stuff. As far as large project goals, depends. (S13)	4

For a majority of our interview data, we utilized constant comparative analysis to determine the salient themes that emerged from student participants' description of how and why they read primary literature the way they do (Strauss & Corbin, 1997). We first "pre-coded" transcripts to identify portions of the interview that corresponded to each research question and then identified codable units - words, utterances, sentences, or short phrases that embody underlying themes (Boyatzis, 1998; Layder, 1998). Generation of codes to describe reading actions was done in an iterative manner by two researchers. We identified an average of 6.4 ± 1.9 actions throughout students' account of how they read primary literature. We divided our analysis by common sections of a primary research article (Abstract, Introduction, Results, Discussion, and Methods), and selected all possible actions for further analysis. A similar procedure was used to analyze the factors students consider when determining the credibility of a study. Many of the generated codes fell into three overarching categories (corroboration, setup and methodology, and sourcing) that were previously generated (Lie & Guzey, in review). Generated codes and corresponding examples are presented in Table 8.

Table 8 Reading actions and representative examples organized by major reading sections.

Reading actions	**Representative examples**
Abstract	
Obtaining a general overview	I always read the abstract first, because that gives you a pretty good summary. (S12)
Identifying new information/ key components	I always go through the very first part of it and highlight some of the more ... kind of like, the terminology. Like the enzymes and the proteins used. (S07)
Identifying study's rationale	…first I started with abstract, then I highlighted the purpose of the study…(S16)
Probing for interest	It more or less goes through the finding of the paper that I might be interested in…(S04)
No mention/does not read	N/A
Introduction	
Identifying terms/concepts/jargon	Then you get into the introduction, and there was a lot of technical wording and acronyms. You can look at it, there's all these acronyms left and right. (S12)
Understanding background information	…knowing the introduction really helps, just to give you the background information. (S17)
Skimming/identifying main points	I never read the intro too much in depth, because I feel like most of the intro will also be covered in the conclusions. (S06)
Checking references for further reading	…when I do read introductions, I think it's a good way to find other papers that are similar, because they usually reference other papers. (S10)
Identifying research question/hypothesis	…in the introduction, what the question was and why that's important, basically. (S09)
No mention/does not read	N/A
Results*	
Using text to reinforce understanding	Usually I read the text first. I pretty much go by how the journal has set it up. They obviously have read the paper and they're putting it in a way that's gonna be easy to read. (S12)
Analyzing experimental data	Usually just understanding trends or they usually interpret what's in the figure into words and make sure I can see that in the figure and understand what's going on. (S14)
Identifying key features	But when I go into the results about the exact action, like what's happening, that's when I get more highlight heavy, pay attention a little bit more. And I still do the same thing through the results. (S07)
Evaluating experimental approach	After I read the results, I take stuff back to evaluate if that's still possible based on what they're saying… (S09)
Understanding experimental progression	I noted that this was one of their main reasons for doing this experiment and trying to determine if they could do it. (S11)
Connecting results to methods	So, that was really helpful if you wanted to like connect back to the materials and methods and see what the exact results of that experiment was… (S05)

Table 8 continued

Forming my own conclusions based on the data	I kind of formed an opinion after looking through the graphs and figures…(S08)
Multiple read throughs	I think a second or third or fourth read through, for me at least I would probably understand the results better. (S05)
Skimmed figures	I mainly look at the image in passing. I would say the images are not my main focus when I'm reading an article like this. (S15)
Discussion	
Identifying the study's implications	Usually I'd look at implications at the very end. This one has relevant implications to me. (S13)
Understanding the study (general)	They do actually end up summarizing it pretty well. That's honestly what gives you the best idea about what they found in the paper. (S12)
Identify new information/key components	Then, when I finally got to the discussion, I again highlight the key points that they found… (S11)
Checking for understanding	I read the discussion before I even went back and looked at that other figure, because it helps to know what information they're getting from the results and interpreting them. (S12)
Comparing my own conclusions to authors'	That kind of shows what they found and what they think about it and I kind of see based on the results if I agree with that or not. (S18)
Critiquing the study	The biggest thing I am looking for is the discussion [is] what I think could have been done differently. (S18)
Identifying the significance of the study	… it's helpful to know why this research is important and that's what I look for in the discussion. (S19)
Evaluating authors' arguments	I think how plausible is - what they did, based on what I know. (S09)
Relate discussion to methodology	I read the first experiment of methods, and then I go to find the discussion part and how they explained um, the first method, and then I kind of related it to the discussion back and forth. (S02)
Methods	
No mention/does not read	N/A
Perfunctory	Because this is how the paper is structured, I go step by step. (S02)
Applying information to my own research	I was looking at the methods because I've had some success in my project, so I'm also gonna be moving forward with this kind of strategy. (S13)
Connecting data to methods	… there's one where they're talking about how they specifically made, basically it was a model brain they built from stem cells. They were saying how they did that. So I was looking for what they did… (S09)
Evaluate methodology	… so the big things I look for in this, in the materials and methods is how they concuss them and then how they look and evaluated that. (S18)
Understanding experimental process	So I really tried to read and understand where they're going, why you are doing those things. (S06)

Note. Codes are listed in order of most to least expressed by students. * Due to an abundance of unique codes in this section, only codes expressed by two or more students are presented.

The implied cognitive level implied by each action expressed by participants was determined using Bloom's Taxonomy (Anderson et al., 2001; Bloom Krathwohl, & Masia, 1956). Coding of the cognitive level of each action was based on previous applications of Bloom's Taxonomy (Lie, Abdullah, He, & Tour, 2016; Lie & Guzey, in review). Researchers discussed and collaboratively aligned each action with a cognitive level (remember, understand, apply, analyze, evaluate, and create) until a consensus was achieved. Actions that could not unambiguously be assigned a cognitive level were excluded from further analysis. Table 9 provides representative codes and examples for each cognitive level.

Table 9 Representative reading actions aligned with Bloom's taxonomy of cognitive processes (Anderson et al., 2001; Bloom et al., 1956).

Cognitive Process	Example Codes	Representative Example
Remember	Identify terms/concepts/jargon	One of the first things I did when I read the first paragraph, is I noticed they used a lot of acronyms. As I continued reading, I realized I couldn't remember what the acronyms were, so I made sure to highlight the acronyms that they were using so it was easy for me to find. (S11)
Understand	Understanding the study (general)	They do actually end up summarizing it pretty well. That's honestly what gives you the best idea about what they found in the paper. (S12)
Apply	Generating different applications of methodology	For example, if I could replicate it or I could use that for something that I'm doing for example, that's another thing that I would look for. Just more applications. (S19)
Analyze	Examining controls	I might read over the description and the results to like, see what controls they were using. (S04)
Create	Developing a mental model	…at the end, they gave us a relatively useful pathway… they used a Map-kinase inhibitor knowing that that plays a role in growth cone turning or collapse. (S04)
Evaluate	Evaluating authors' arguments	I think [about] how plausible is - what they did, based on what I know. (S09)

Institutional Review Board

The permission to conduct, record, and transcribe university students' semi-structured interviews (IRB #1612018546) was obtained by the Purdue University Intstitutional Review Board.

Results

Student Demographics

Student participants had varying degrees of exposure to primary literature with some students reported having read as little as 10 primary articles in total, and some students reported reading greater than 300 primary articles (Table 6). A majority (84.2%) of students reported either currently or previously involved in novel research. Students' descriptions of research participation varied drastically, with some students reporting only being involved in performing experiments, whereas other students expressed having near complete autonomy over their experiments. We designated student laboratory participation into low/medium/high categories based on student descriptions (Table 6). A coding rubric with representative examples are provided in Table 7. Additionally, a majority of students expressed that they were planning to pursue postgraduate studies.

Students also described their background on receiving instruction on reading primary literature. Of the 19 student participants, six students reported that they never received explicit instruction of any kind on how to read a primary article. Of the remaining 13 students that did receive some degree of instruction, seven students described instruction that we describe as procedural instruction, which provides a step-wise approach to reading the primary literature that suggests the reading order of the major sections in a primary article and/or points out certain features (Lie & Guzey, unpublished). For example:

> *So, she said read the abstract and then go through the methods, and not necessarily the experimental methods, but the results. And read through the results. Then get, skim the laboratory methods, and then once you have a good idea, then go back and start over again.* (Student 7)

The remainder of students received more in-depth instruction that resembles an apprenticeship model. As one student describes:

> *Because me and my mentor who I work under would read the same article, and she'd have notes, and then I'd get a fresh, clean one, and then we'd compare notes, and dissect each thing. Like, why did you find this of importance versus why did she find those things…* (Student 6)

Students that described this in-depth form of instruction received it in contexts outside the classroom, such as laboratory experiences and journal clubs.

Characterization of Students' Reading of Primary Literature

We examined student reading patterns by analyzing the order in which students read each major section of a primary article using distance vector analysis. Mean normalized Hamming distance was found to be 0.24 ± 0.27, which means that the average student either skipped approximately one section of the article or read one of the sections out of order in the manner presented. The former was more common, as half of the students reported omitting the Methods section. Individual distance vectors are provided in Table 6. Other sections of the paper were examined by all or almost all students.

We were interested in how students engaged with the primary article, specifically what actions they took to understand the research article. To this end, we had participants describe how they read a primary research article, using a research article they have recently read as a guide. A little over half (57.9%) of the students brought articles that were assigned reading for a course, whereas the remainder used papers they personally selected, either for a research project for a course, laboratory research, or purely out of interest in a topic. A list of reading actions performed by students was generated using constant comparative coding methods and is presented in Table 8. A total of 48 unique actions emerged from our analysis of participant responses.

Students mainly expressed that the goal of reading the abstract and introduction sections was to obtain a general understanding of the background and the research approaches and identify aspects of the paper that were unfamiliar to them. Some students were more intentional and mentioned that they were looking at specifics, such as the study's rationale or the research question/hypothesis; however, the general trend we observed was that much of the participants tended to be vague or non-specific in their reading actions. Similar trends were observed in the

Results section, as the most common action was *using text to reinforce understanding*. Student descriptions aligned with this code tended to rely on the authors' analysis of the data to either "follow along" or reaffirm their own analysis. As one student (S01) describes:

> *I looked at the graphs before I started reading the results, um and I didn't completely understand them, and so I read the results in depth. Otherwise, I probably wouldn't have read them as in depth, if I would have completely understood the graphs to begin with.*

This example highlights that understanding and interpreting graphical representations of data pose challenges to students and as a result, they rely on the authors' interpretations. This section also generated the most diverse codes due to the number of codes that were expressed by only one participant. Examples include *connecting methods to prior experiences*, *examining controls*, and *predicting experimental outcomes*.

Similar to the Introduction, students' actions while reading the Discussion were associated with obtaining a more general understanding or summary from the text. Student 14 highlights that they read this section looking to check their general understanding: "So it's mostly trying to understand or trying to make sure that what they got from the results, I could see that as well. So if they're making connections or interpreting results, did I notice that in the results." Other students similarly rely on the authors' interpretation and summary of the experiment to affirm their understanding of the study as a whole. Very few students articulated actions that went beyond obtaining a general understanding; however, some of these actions that were observed include *critiquing the study* and *evaluating authors' arguments*. Lastly, approximately half of the students expressed that they typically do not read the Methods section. Of the remaining students, some read it without much purpose or intent (*perfunctory*), whereas several students thought of applying some of the techniques to their own research work.

Cognitive Dimension of Students' Reading-associated Actions

Due to the diversity of expressed actions, we were interested in further organizing reading actions. We noticed that the actions described by students reflected different categories of cognitive processes (e.g., remember, understand, apply, analyze, evaluate, and create) proposed by Bloom and colleagues (1956) and revised by Anderson and colleagues (2001). Using Bloom's taxonomy of cognitive processes as a coding framework, we aligned each reading action with a cognitive level. Representative examples are provided in Table 9.

A majority reading actions aligned with the understand cognitive processes (54.2%; Figure 4). Some examples include: *obtaining a general overview, understanding background information,* and *using text to reinforce understanding*. The next most common category of cognitive process were actions that aligned with remember (20.1%), followed by analyze (17.2%). Actions aligned with remember typically involved recognition of terms, jargon, and pieces of information (both known and unknown). Students frequently expressed highlighting or annotating the article to ease the cognitive load imposed by jargon and acronyms. As expected, actions that aligned with analyze were observed almost exclusively in the Results section, with the most common action being *analyzing experimental data*, which tended to capture non-specific references to students examining the data and figures. Examples of more specific actions that were less frequently expressed include *forming my own conclusions based on the data* and *examining controls*. Actions aligned with apply, create, and evaluate were fairly sparse among students and across the different sections.

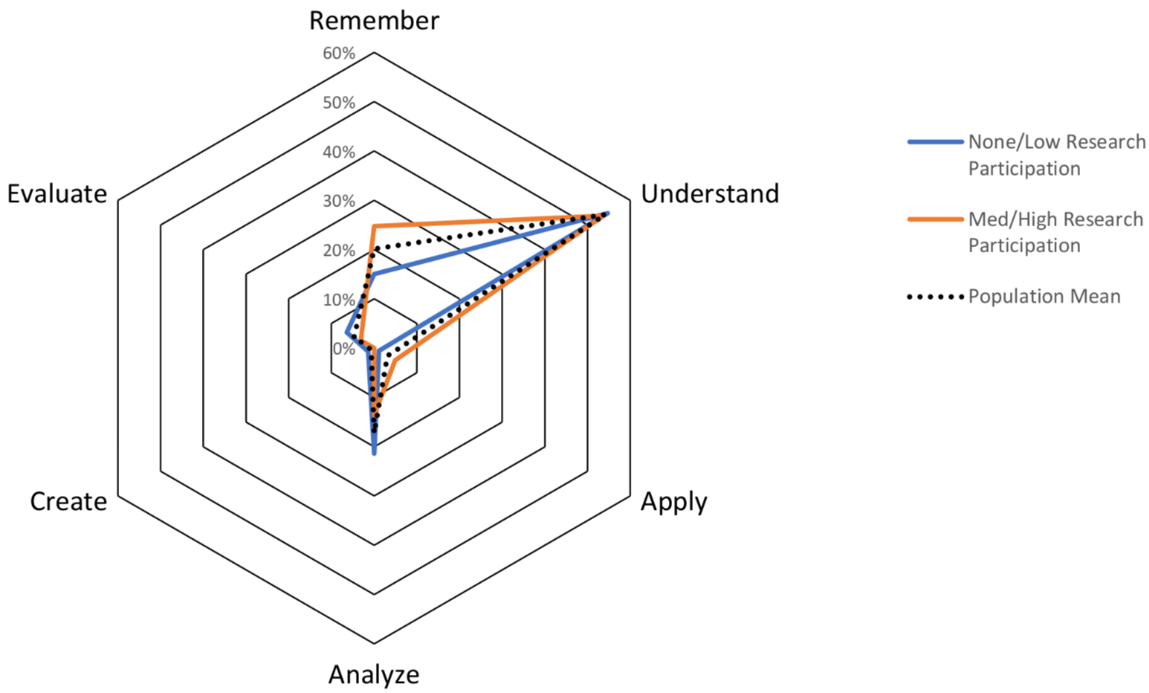

Figure 4 Cognitive profiles of reading-associated actions represented as percentage of total actions. Participants' reading actions were aligned with Bloom's Taxonomy of Cognitive Processes (Anderson et al., 2001; Bloom et al., 1956). The dotted line represents the average profile among all participants. Students with no/low levels research participation and medium/high levels of research participation are displayed in blue and orange, respectively.

A majority reading actions aligned with the understand process (54.2%; Figure 4). Some examples include: *obtaining a general overview*, *understanding background information*, and *using text to reinforce understanding*. The next most common category of cognitive process were actions that aligned with remember (20.1%), followed by analyze (17.2%). Actions aligned with remember typically involved recognition of terms, jargon, and pieces of information (both known and unknown). Students frequently expressed highlighting or annotating the article to ease the cognitive load imposed by jargon and acronyms. As expected, actions that aligned with analyze were observed almost exclusively in the Results section, with the most common action being *analyzing experimental data*, which tended to capture non-specific references to students examining the data and figures. Examples of more specific actions that were less frequently expressed include *forming my own conclusions based on the data* and *examining controls*. Actions aligned with apply, create, and evaluate were rarely observed.

We were also interested to see if level of research participation affected student's reading actions. Due to a limited sample size, we grouped students with no research experience and low levels of research participation together and also grouped students with medium and high levels of research participation. No significant differences were apparent between the two groups of students (Figure 4).

How Do Students Determine Credibility?

We also examined how students make sense of data, claims, and assertions put forth in articles by asking what factors students consider in determining the credibility of primary research articles. Students cited an average of 2.4 ± 1.1 factors that were considered in evaluating the credibility of an article. Among students' responses, we identified three broad categories of factors that influence credibility: *corroboration*, *experimental setup and methodology*, and *sourcing*. *Corroboration* includes sub-codes that describe consideration across sources or between the text and one's own knowledge (Wineburg, 1991). *Setup and methodology* broadly represent components of experimental design, methodological approaches, or related considerations. *Sourcing* captures factors that are based on reputation (e.g., authors, laboratories, journals; Wineburg, 1991). Sub-codes that did not align with these three categories were placed in the "other" category.

The one of the most cited factors for determining credibility fell under *experimental setup and methodology*, where 68.4% of student participants expressed one or more factors within this category (Table 10). The most commonly expressed sub-code was *experimental design*, which broadly describes responses that reference the alignment between methodological approaches and the research question. In the example provided in Table 10, Student 04 makes an unspecified reference to “test every condition that reasonably made sense.” Other responses that fell under the *experimental design* sub-code were similarly vague. Some students were more specific in their responses, citing specific components such as controls, sample size, ethical considerations, and variables.

Table 10 Factors students cite in determining credibility of a research article and representative examples.

Credibility Factors	**Representative Examples**
Corroboration (15.8%)	
In-text sourcing	One factor I guess I look for first is looking at the references that people make… So, if they're trying to do things back in the '90s, I doubt that all of the information might be completely accurate to today. They might be using outdated data. (S11)
Prediction	But it’s interesting idea and I also kind of came into reading this paper convinced that there were other systems involved… So I would say it convinced me further… (S01)
Setup and methodology (68.4%)	
Amount of data	I think it had a lot of data in it, as well as taking from different sources… That kind of validates it for me. (S08)
Controls	So they had a very, very well defined control group of the mice that were not given any type of change… (S07)
Completeness of the study	I thought that if you're going to talk about the mechanism so much and in such great detail, you should talk about the structure of it. And they did not… I see where they're going with it, but it's not quite enough. (S06)
Ethical considerations	Yeah, you can do it, but it doesn't mean that it's the right thing. More knowledge needs to be there before you attempt to do something like this. You need to know exactly what other effects could come about from removing deleterious genes from the population. (S19)
Experimental design	…they tested every condition that reasonably made sense. (S04)
Sample size	… the sample size was really small, it was only 9 people, so I wouldn’t say that it could be something that could be broadly applied. (S01)
Triangulation	For each conclusion there's multiple ways they obtained a result… Yeah, there was just lots of different ways they proved the result. (S13)
Variables	Yeah… I think in the measures that they took was pretty convincing… (S01)
Sourcing (68.4%)	
Authority bias	Most of the articles that I've read have been articles that have been presented to me to read, so I don't question the credibility because I assume the professor that's told me to read it knows it's credible. (S19)
Authors	The amount of people that are listed in the authors. When it's a primary literature and I only see two people, and they are from a university that I've never heard before, it's just like hmm. (S16)
Citations (by others)	I usually use google scholar … you can see how many times a specific source has been cited by another author, another researcher, so I usually base it off of how many citations they have. (S03)
Journal	If you have a Cell or a Nature paper, that's gonna be way different than something else where you might need to be more skeptical. (S13)

Table 10 continued

Other (31.6%)	
Figure presentation	I think it's also really helpful, again, with the graphs and all that. That kind of validates it for me. (S08)
Narrative	Like I said, they set it up in a pretty good way. They set it up well for the narrative of what they're trying to figure out… (S12)

A majority of students also considered factors related to *sourcing* to determine the credibility of an article. Within this broad category, *authors* and *journals* were the most commonly expressed. Many students conflated the reputation of the journal that published the article with credibility. As Student 14 puts it, “If it’s a good journal, the name of the journal can give it credibility.” Similarly, Student 2 conflates funding and peer-review with reliability, saying “Because it’s published in [journal name] and they get funding, and it’s already been published so I think they are more reliable. No? It’s not right?” Two other sub-codes that fell into this category include *authority bias* and *citations* (by others). *Authority bias* refers to the tendency to allot credence based on the authority of a figure, unrelated to its contents (Milgram, 1963). The corresponding example in Table 10 highlights the implicit assumption about the quality or credibility of an article that students may have when assigned by an authority figure, such as the instructor of a course. Other authority figures students referenced include post-docs, graduate students, and researchers in general. Lastly, number of citations by other articles was another metric students cited as factor that helped them to determine credibility. This factor draws parallels to previously mentioned sub-codes, as citations referencing an article serves as an implicit approval by other practicing scientists in the field.

The third category, *corroboration*, was the least cited credibility factor among students. Within this category were two sub-codes: *in-text sourcing* and *prediction*. Students citing *in-text sourcing* attempt to negotiate how the current finding fit within the framework of established knowledge or other research. *Prediction* takes into account one’s own knowledge and compares it to what is asserted in the article. Factors that did not align with the three major groups were *figure presentation* and *narrative*, which were placed in the 'Other' category. We also examined if there were any differences in factors related to credibility among students with high levels of research participation compared to other students, however, there was no discernable differences.

Discussion

Efforts to reform undergraduate biology education have focused on transitioning from content-driven, traditional teaching practices to an emphasis on building an understanding of how knowledge is generated within the discipline (AAAS, 2011). Knowledge generation operates according to discipline-specific practices and conventions for communicating and evaluating knowledge (Moje, 2008). As such, incorporating primary literature into the classroom can help to advance students' literacy skills and promote ways of thinking and sense-making that align with the disciplinary practices. Reading primary literature, however, can be very challenging for students (e.g., Hubbard & Dunbar, 2017; Lie et al., 2016; Smith, 2001). In this study, we examined the characteristics of how junior and senior biology students read primary literature in hopes that this information can be applied to developing undergraduate curricula that can promote disciplinary literacy. The study examined several aspects of reading primary literature, including students' navigation patterns, characterizing reading actions, and determining how students determine the credibility of a study.

We found that students tended to read research papers fairly linearly (i.e., in the order of presentation) and often skipped the methods section. Unlike experts who were much more selective in their reading of primary research (Hubbard & Dunbar, 2017; Lie & Guzey, in review), students typically lacked the prerequisite background knowledge which compels them to read the Introduction. These findings align with Hubbard and Dunbar (2017) work that highlights that undergraduates assign a higher importance to the Introduction section compared to more experienced scientists. Methods was the least important section according to undergraduates, which aligned with our observations that the Methods were either ignored or read in a perfunctory manner. In contrast, expert readers tended to examine Methods for evaluative (e.g., examining sample size, data sources, etc.) or clarification purposes (Lie & Guzey, in review).

Students' actions revealed that the main goal of their actions was to obtain a general understanding of the experiment, as many of the actions lacked specificity. In contrast, experts' reading actions tended to be highly specific and contextual, as they approached the article with an *a priori* framework for dissecting the article that took into account such contextual factors (i.e., purpose of reading a particular article) and experience with certain methodologies (Lie & Guzey, in review). Further characterization of students' reading actions utilizing Bloom's taxonomy revealed that student actions aligned primarily with understand and remember. Additionally, our data suggests that students rarely engage in evaluative practices, among others, despite it being a competency that faculty expect students to accomplish upon graduation (Lie & Guzey, unpublished). In contrast, expert readers' cognitive profiles tended to be much more diverse, with their actions more equally distributed among evaluate, understand, analyze, and apply. While it is unreasonable and unrealistic to expect students to read at the level of experts, instruction that only focuses on emphasizing understanding may lead to the misconception that published studies provide factual, rather than tentative knowledge. Therefore, it is necessary to supplement instructional approaches that only focus on understanding with instruction that trains students how to engage in evaluative reading.

According to Moje (2008), identity construction as a practitioner of a discipline precedes and contributes to the development of disciplinary literacy. As such, we reason that instruction that cultivates students' science identities can help influence literacy practices. Prior work suggests that students' not engaging in evaluative actions may stem from either lack of awareness of performing evaluative actions or lack of knowledge of types of weaknesses/errors/flaws that can occur (Farenc et al., 2017; Lie et al., 2016). Therefore, explicit and scaffolded instruction on how to evaluate research literature ought to be considered to help develop students employ more evaluative modes of reading (Farenc et al., 2017).

Despite not expressing evaluative actions during their narration of reading the article, when students were prompted to provide factors that contributed to determining an article's credibility, students cited several aspects related to the experimental setup and methodology. This demonstrates that some students are aware of some the features of the paper that require evaluation, but may not regularly engage in evaluating them. While some students may know how to go about evaluating an article, it may be more appropriate to say that it is performed in a post hoc manner. Additionally, it is surprising that many students relied on sourcing to determine the credibility of an article. While name recognition can be an indicator of quality, expert biologists primarily evaluate the credibility primarily based on the experimental setup and methodology and corroboration with the body of literature (Lie & Guzey, in review). These findings suggest that name recognition of the journal and/or author(s) exert considerable influence over students; however, we are skeptical as to whether students with limited research participation are knowledgeable about the reputation of specific authors or research groups. Thus, instructors must be careful not to pedestalize journals, authors, and research groups (either implicitly or explicitly) and emphasize that published articles are means of communication and knowledge building rather than authoritative works. Lastly, students hardly expressed factors aligned with corroboration, as we suspect that students may not have a firm grasp of the content and/or are not familiar with the body of related literature.

This study reinforces the notion that students do not regularly engage in evaluative actions while reading primary literature (Lie et al., 2016). Previous studies have demonstrated that primary literature can be implemented in a variety of ways to address process skills, nature of science, etc.; however, these studies, if enacted as a stand-alone curriculum, are likely insufficient to address the spectrum of competencies students must develop to engage with disciplinary discourse. Therefore, instruction of disciplinary reading practices is necessary to not only help students understand how knowledge is generated, but also if such knowledge is to be accepted. If the goal of undergraduate education is to enable students to generate, negotiate, and communicate knowledge, coordinated instruction utilizing primary literature that spans throughout students' undergraduate coursework is necessary.

Limitations and Future Directions

This study has several important limitations to consider. First, the study took place in a singular institution, which limits the generalizability of the conclusions to different contexts. Our observations are exploratory in nature and will need to be expanded upon in subsequent studies, with particular interest in examining how instruction that promotes evaluation relates to other constructs, such as science identity. Furthermore, while we were able to compare the cognitive levels of students' actions across different levels of research participation, we did not measure the proficiency of such actions. For example, while two students may describe performing actions such as *evaluating experimental approach*, we cannot comment about the depth and rigor of such evaluation. While we did not observe differences in actions at the cognitive level between the students with no/low and the medium/high levels of research participation, perhaps there may be differences in the degree to which similar actions were accomplished. Further research into examining the relationship between students' literacy practices and literacy proficiency is a subject of interest.

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CHAPTER 4: SUMMARY OF THE NOVICE-EXPERT GAP IN LITERACY PRACTICES

Introduction

In the tradition of novice-expert reader studies, one of the research approaches that informs the disciplinary literacy framework, we examined the gaps in how these two populations engage with primary literature. From the limited studies in the field of biology education that examine the novice-expert reader gap, we are aware of several patent differences. Research by Van Lacum and colleagues (2012) demonstrates that experts are better able to identify rhetorical structures (i.e., components of arguments, including grounds and claims) as compared to novice readers. More recently, work by Hubbard and Dunbar (2017) shows that readers value different sections of a research article according to stages in their career. Given that disciplinary literacy includes awareness and knowledge of the values of a disciplinary community (Hynd-Shanahan, 2013; Shanahan & Shanahan, 2012), it is important to recognize and foster an understanding for why a particular section holds importance among experts. In this chapter, we synthesize evidence from Chapters 2 and 3 that illustrate the gaps in disciplinary literacy among novice and expert readers.

Navigation Patterns

Part of reading primary literature is the ability to navigate through the various sections in a manner that is conducive to extracting important and relevant information. Our first question was to examine the navigation patterns among novices and experts as they read such articles. Using distance vector analysis, we found that both populations engaged in selective reading and navigation patterns tend to be more linear. Experts often omit the Introduction, citing that they have adequate levels of prerequisite knowledge to effectively engage with the study. In contrast, nearly all novices reported reading the Introduction, due to the lack of prerequisite knowledge. These observations align with the findings of Hubbard and Dunbar (2017), which report that more expert readers (academics) rate the Introduction as the least important section of a paper, whereas novices rate it as most important. Opposite to reading the Introduction, almost half of novice readers report omitting the Methods, with several other students reading the section in a perfunctory manner. Experts, on the other hand, read the Methods as needed, fluidly going back and forth between the Results or Discussion and the Methods section. Given these differences in how novices navigate literature compared to experts, scaffolded instruction that is mindful of the novices' approach to reading must be considered.

Table 11 Summary of expert and novice biologists' primary literature navigation patterns.

Expert Readers	**Novice Readers**
Selective reading; almost linear navigation (0.31 ± 0.20)	Selective reading; almost linear navigation (0.24 ± 0.27)
Majority omitted Introduction	Almost all read Introduction
Most read Methods "as needed"	47% omitted Methods

Reading Actions

While there have been many studies that have examined students' abilities and proficiency in process skills related to analyzing primary research literature, there is limited evidence describing how they read. Furthermore, there is even less regarding how experts read. While Van Lacum and colleagues (2012) provide several vignettes illustrating how novice readers approach a primary article, no systematic analysis was performed. Here, we synthesize our findings of how experts and novices go about reading an article.

Among both populations, we identified 48 unique reading actions each based on their self-reported process of reading. Substantial amounts of actions were expressed in the Results section; however, the types of actions were markedly different between the two populations. We found experts' actions to be diverse and highly specific (i.e., participants expressed actions with such specificity that they rarely overlapped with other participants). The specificity of such actions suggest that faculty had an *a priori* framework or organization scheme that informed how they will read. In contrast, students' actions were focused on obtaining a general understanding, as many expressed a reliance on the authors' interpretation of the data, rather than personally interpreting the data. This is highlighted as *Using text to reinforce understanding* was the most common action among students in the Results. To illustrate this point, Student 12 said, "Usually I read the text first. I pretty much go by how the journal has set it up. They obviously have read the paper and they're putting it in a way that's gonna be easy to read." The student hints at absolving responsibility of personally interpreting and analyzing the data, and instead places trust in the authors' interpretation. This is particularly problematic, as this way of reading primary literature does not constitute the authentic literacy practice of experts, who independently evaluate and validate the presented data and information.

Given the diversity and abundance of reading actions expressed by participants, we further organized reader actions using Bloom's Taxonomy (Anderson et al., 2001; Bloom, Krathwohl, Masia, 1956). This framework allowed us to categorize reading actions according to cognitive processes. We observed that experts' actions were distributed among multiple cognitive domains, particularly the processes of evaluate, understand, apply, and analyze. Furthermore, it seems that faculty's purposes for reading tended to skew reading actions towards specific processes (e.g., Jeffery and Damon; Figure 2). In contrast, novices' actions were less diverse and skewed towards the understand cognitive process, followed by remember and analyze (Figure 5), regardless of research participation (Figure 4). Furthermore, novices rarely engage in the evaluate process, which represents a sizeable amount of expert readers' actions.

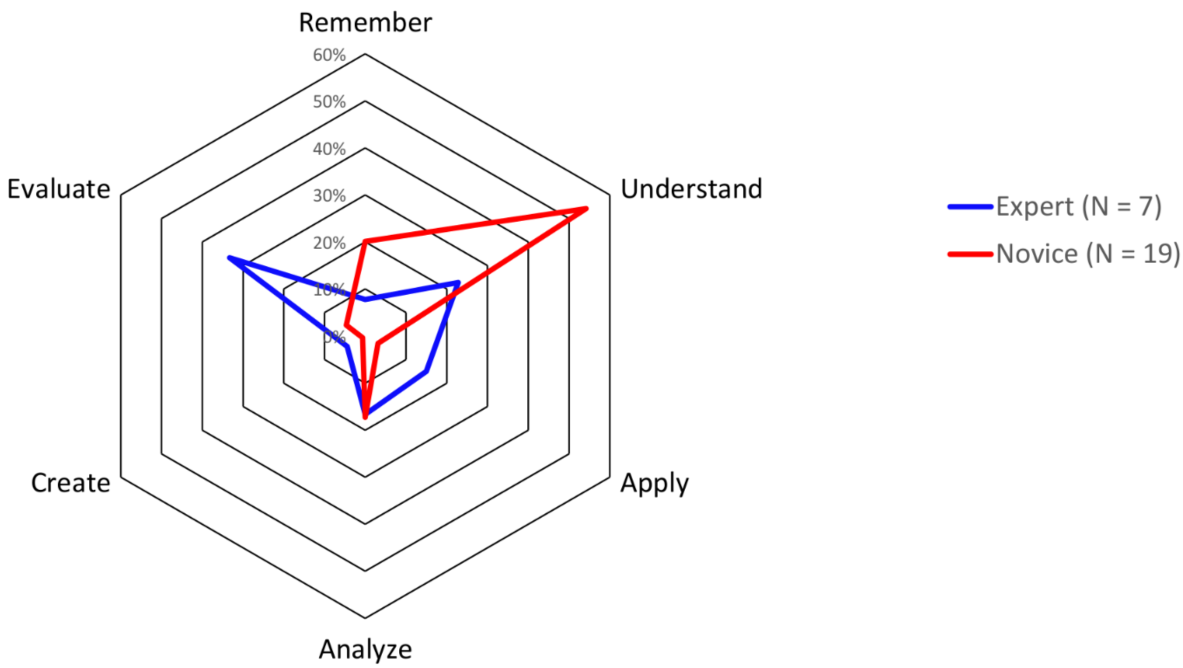

Figure 5 Comparison of cognitive profiles of reading-associated actions represented as percentage of total actions. Participants' reading actions were aligned with Bloom's Taxonomy of Cognitive Processes (Anderson et al., 2001; Bloom et al., 1956).

Determining Credibility

Given that disciplinary literacy includes what counts as evidence, how arguments are generated, important features, and determining values (Hynd-Shanahan, 2013), evaluating the credibility and examining the factors that impart validity of a study is an important exercise while reading primary articles. In Chapters 2 and 3, we examined the factors that expert and (competent) novice biologists consider when determining the credibility of an article. Three overarching factors emerged from both populations: corroboration, setup and methodology, and sourcing. As presented in Figure 6, nearly all experts cited factors related to corroboration, all cited one or more factors related to setup and methodology, and roughly half cited sourcing factors. In contrast, very few novices cited factors related to corroboration, as many are likely to not have expertise or knowledge of the broader literature. Novices also cited factors related to setup and methodology and sourcing equally. The types of factors related to setup and methodology were fairly similar among novices and experts (e.g., sample size, controls, study design), with the exception of experts citing specific contextual factors such as the quality of the data and statistical analysis performed. While similar proportions of novices and experts cited sourcing as a credibility factor, there were marked differences in how these factors contributed to credibility.

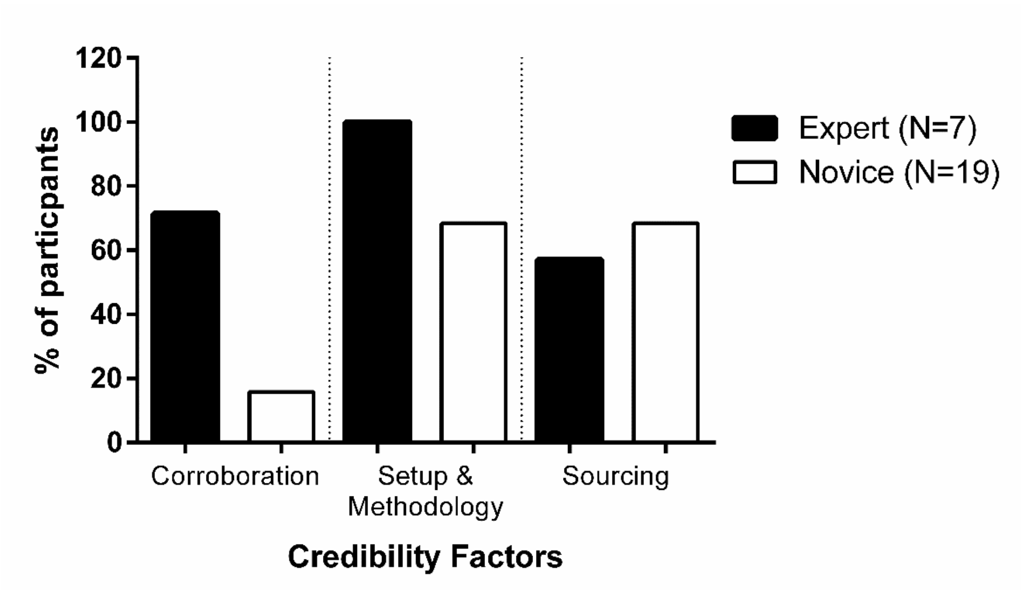

Figure 6 Comparison of self-reported factors that expert and novice biologists consider to determine the credibility of a primary literature article.

We observed that experts tend to rely on sourcing as an indicator of quality, whereas novices tend to rely on the authority of sourcing and an indicator of credibility. The following comment from Oscar illustrates this point:

> *I have to admit sometimes the authors, or the last author might play a role a little bit. Unfortunately, that's not something that should be taken into consideration, but in some cases when you see that the paper is coming from a big lab you might*

> *be a little more confident. But experience has shown us that that is not necessarily the case always.*

Here, Oscar admits that name recognition may prompt consideration of an author's previous track record; however, the merits of the study should stand, without the influence of the author(s). Other experts expressed similar caveats when referencing sourcing.

In contrast, Student 02 invokes the authority of the journal to justify the credibility of an article: "Because it's published in [journal name] and they get funding, and it's already been published so I think they are more reliable." This illustrates a common misconception of the role of primary literature. Rather than being a medium for argument and communication, the student perceives the publication in a reputable journal as validity and therefore factual. Another example of sourcing serving as authority is seen by Student 19, where they admit, "Most of the articles that I've read have been articles that have been presented to me to read, so I don't question the credibility because I assume the professor that's told me to read it knows it's credible." This highlights a factor that mentors and educators may fail to consider – the implied power of authority. Here, the student has an underlying assumption that their mentor and instructors only recommend reputable articles to read.

Discussion

While we observed several similarities in reading among novice and expert readers including selective reading and determining credibility, the process of how each population engaged with primary literature was markedly different (as summarized in Figure 7). The gap from novice to expert readers highlight the skills and actions that are disciplinary in nature. For example, many of the participants brought in articles that were read in several different contexts (e.g., journal club, targeted analysis, updating knowledge base, etc.). As such, we suspect that such context influences how they approach that particular article. It is important to recognize that reading articles for different purposes invoke different cognitive processes, allowing the reader to engage in a many unique literary practices. Students may not receive this opportunity to read literature in different contexts, which may help to explain why students' reading actions heavily are uniformly distributed. As highlighted by our expert population, part of disciplinary literacy is to engage in diverse modes of reading and in read primary literature in various contexts. We suspect that students in our study (and in general) may not receive many opportunities to engage primary literature in diverse contexts. Instead, we speculate students mainly engage with primary literature with an intent to simply understand the content.

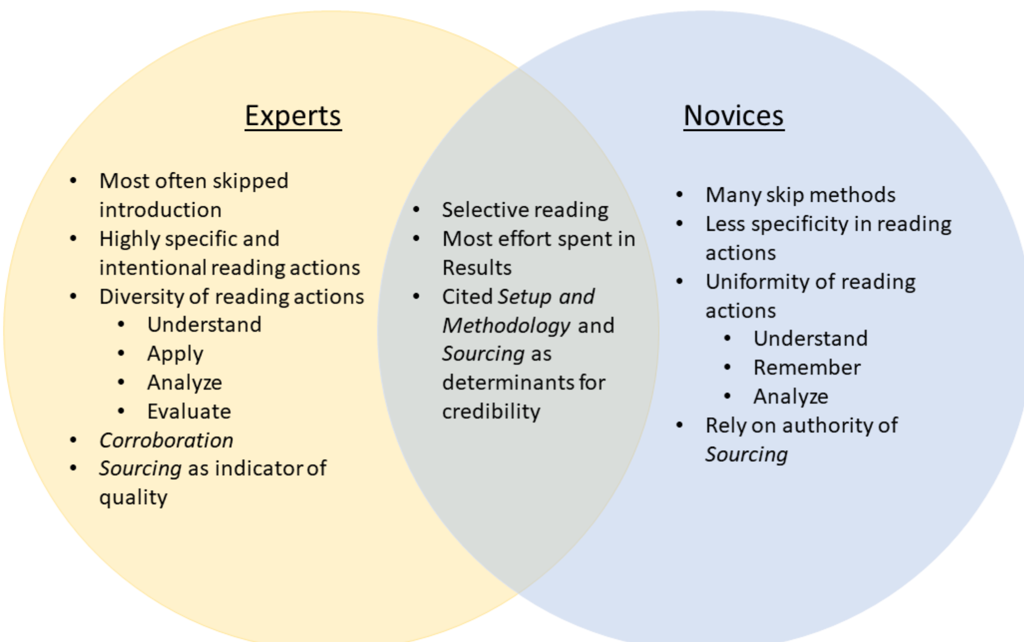

Figure 7 Venn diagram summary of similarities and differences among novice and expert biologists reading primary literature.

Lastly, the differences we observed in the credibility factors that both populations cite indicate fundamental misconceptions of the role of primary literature. Instead of viewing primary literature as a work that mediates knowledge creation (Hyland, 2004), our work suggests that students view such literature as pieces of factual knowledge, akin to reading a textbook. As such, it is important for instructors to be cognizant of these misconceptions that students may hold when implementing primary literature into the classroom. If the goal is to have students critically engage with such literature, instructors must provide support that encourages students to move beyond understanding.

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CHAPTER 5: EXAMINING UNDERGRADUATE FACULTY MEMBERS' LIERACY TEACHING PRACTICES

This chapter was adapted from a manuscript in preparation.

Abstract

Instruction in undergraduate biology classrooms utilizing primary literature offers many opportunities for students to engage in authentic science practices; however, many factors prevent faculty from adopting such teaching practices (e.g., time, workload). In the following study, we examined the practices of seven biology faculty members at a large midwestern research institution, regarding the implementation of primary literature into their classrooms. Faculty agreed that students should be competent in performing reading-related tasks that align with understand and evaluate cognitive domains. We examined the relationship between these beliefs and teaching practices and found that a majority of instructors describe practices aligned with instructive beliefs, with two others describing practices that align with responsive beliefs. Despite the expectation for students to be evaluative while reading, few faculty members describe instruction that explicitly target evaluative thinking, with most faculty focused on understanding ways of thinking about experimentation. Lastly, we describe how faculty selected articles for classroom usage. Taken together, these results highlight several factors that biology faculty must consider in order to effectively develop students' literacy practices.

Introduction

Calls to reform undergraduate biology education have emphasized that traditional approaches to teaching undergraduate biology are inadequate to meet the challenges of the 21st century (AAAS, 2011; AAMC-HHMI, 2009; NRC, 2009). One of the biggest concerns is that the increasing rate of knowledge accumulation currently exceeds the rate in which students can acquire new knowledge (Geddes, Cannon, & Cannon, 2018). Thus, the *Vision and Change* report highlights that the future of the labor force "must become adept at making connections among seemingly disparate pieces of information, concepts, and questions, as well as be able to understand and evaluate evidence" (AAAS, 2011, p. 3). In order to help students develop these competencies, efforts have been made to reimagine science education as promoting an understanding of how knowledge is generated, negotiated, and communicated, rather than traditional approaches that focus on knowledge transfer. As such, this approach requires students to examine knowledge creation and communication at its source - i.e., primary literature.

Scientists report that a significant amount of their time is spent reading primary literature, with estimates ranging from 23-30% of their work time spent examining primary research articles (Tenopir & King, 2003; Tenopir, King, & Bush, 2004). Despite this fact, many faculty members express that this is a skill that they do not teach enough, due to several factors including time, workload, and the need to cover content (Coil, Wenderoth, Cunningham, & Dirks, 2010). As a result of the underutilization of primary literature, "many science majors reach their junior and senior years fearing and being intimidated by having to read and interpret primary literature" (Smith, 2001, p. 466). As such, a multitude of studies over the past two decades have proposed instructional approaches to teach students how to better read primary articles and the accompanying skills (e.g., experimental design, data interpretation, conducting a literature search, etc.). Therefore, we were interested in exploring how faculty at a large undergraduate research institution incorporate primary research articles into undergraduate biology curricula and what instructional support they provide they provide students to help develop literacy skills.

Developing Disciplinary Literacy

In order to navigate the increasing amount of available knowledge, students must be able to recognize the unique practices of a particular discipline. Disciplinary literacy emphasizes the unique literacy practices within a discipline, such as what counts as evidence, how arguments are constructed, important features, the degree of confidence in recent findings, etc. (Hynd-Shanahan, 2013). Scholars have argued that learning within a subject area not only includes developing content knowledge, but more importantly understanding the operating norms and practices for knowledge production and communication (Bain, 2000; Gee, 2001; Lemke, 1990; Moje, Peek-Brown, Sutherland, Marx, Blumenfeld, & Krajcik, 2004; Shanahan & Shanahan, 2008). Thus, developing students' disciplinary literacy is paramount to understanding how knowledge is generated and negotiated (e.g., Bain, 2000; Moje, 2008; Shanahan & Shanahan 2013); which in turn can help students not only identify accepted knowledge within a discipline, but also enable them to evaluate and potentially challenge such knowledge (Bain, 2006). Despite the need to develop students' disciplinary literacy practices, many instructors express challenges or hesitations in addressing it. As Moje (2008) summarizes, critics of teaching literacy practices state that it "place[s] an unfair burden of teaching reading on them when they should be teaching content" (p. 98); however, given that traditional teaching practices (i.e., transfer of knowledge) are inadequate to address the challenges of the 21st century, we must reexamine the ways of how undergraduate biology is taught to include literacy practices.

Instructor's Beliefs and Practices

Science educators' beliefs about teaching and learning has been an area of exploration over the past number of decades, as beliefs are thought to guide teaching practices (e.g., Nespor, 1987; Pajares, 1992). Beliefs stem from personal experiences, vary in strength, and tend to be resistant to change (Block and Hazelip, 1995; Nespor, 1987). Beliefs about teaching influence pedagogical decisions and translate into instructor's practices in the classroom, thereby affecting student learning (Fang, 1996; Richardson, 1996). At the university setting, research has shown there to be interactions between faculty member's instructional beliefs and practices (e.g., Henderson, Beach, & Finkelstein, 2011); however, there is much debate regarding the extent to which beliefs influence classroom practices (Kane, Sandretto, & Health, 2002).

Previous researchers have characterized teaching beliefs – on one end of the continuum are instructor-focused beliefs and on the other end are student-centered beliefs (Luft & Roehig, 2007; Moore et al., 2015). Shifts along the continuum towards more student-centered beliefs are likely to be accompanied by student-centered practices (Henderson et al., 2011). Student-centered approaches to teaching have many downstream effects, identity development being one of them. Scholars examining identity constructs have reported a link between teaching practices and the development of students' science identities. Carlone (2003, 2004) found that student-centered teaching practices are much more effective for fostering science identity development, particularly among women and women of color. It is also important to note that development of identity precedes disciplinary literacy – i.e., students' development of science identities is a prerequisite to engaging in literacy discourse within a discipline (Moje, 2008). As such, student-centered approaches are necessary to effectively support undergraduate disciplinary learning and science identities.

Despite this importance of student-centered teaching practices, researchers and councils point out that undergraduate biology education has yet to fully adopt such practices (e.g., AAAS, 2011). Promoting change among college faculty is a difficult task due to barriers such as training, time, incentives, and struggles between a scientist's professional identity (Brownell &

Tanner, 2012). As such, institutional support is critical to help facilitate change, along with approaches that address faculty beliefs. As an example, a staff development program developed by Ho and colleagues (2001) that aimed to change teachers' belief systems resulted in changes towards student-centered beliefs and led to enhanced and long-term changes in teaching practices. Given the relationships among teaching beliefs, teaching practices, and students' identity and disciplinary literacy development, we were interested in examining how has primary literature has been implemented in undergraduate classrooms.

Implementation of Primary Literature at the Undergraduate Level

One popular approach to implementing primary literature into undergraduate classrooms has been journal club-style discussions (Barker, 2010; Glazer, 2000); however, the quality and fidelity of implementation can vary based on a number of factors. In addition, there are other factors to consider as to why a journal club-style approaches alone are likely to be insufficient to teach critical reading. As noted by Farenc and colleagues (2018) journal articles are becoming much more specialized that students may spend more time attempting to understand, instead of practicing critical analysis. Second, journal selection in journal clubs tend to skew towards journals that have been through rounds of peer review, leaving little opportunity for students catch errors. Over the past few decades, a number of researchers have proposed and evaluated novel instructional approaches.

Many of these studies have mainly aimed at ameliorating the difficulties that students encounter while reading primary literature. Furthermore, many of these studies chiefly express the intent to develop students' science process skills (e.g., Abdullah, Parris, Lie, Guzdar & Tour, 2015; Ferenc et al., 2018; Gottesman & Hoskins, 2013; Hoskins et al., 2007; Krontiris-Litowitz, 2013; Round & Campbell, 2013; Segura-Totten & Dalman, 2013). Among these studies, several have reported positive gains in students' understanding of science practices (Carter & Wiles, 2017; Gottesman & Hoskins, 2013; Hoskins et al., 2007), confidence in reading primary literature (Abdullah et al., 2015; Sato, Kadandale, He, Murata, Latif, & Warschauer, 2014; Kozeracki, Carey, Colicelli, & Levis-Fitzgerald, 2006), science literacy (Krontiris-Litowitz, 2013), data analysis skills (Abdullah et al., 2015; Round & Campbell, 2013), and promoting the understanding of the nature of science (Carter & Wiles, 2017; Gottesman & Hoskins, 2013), among others.

In light of the abundance of studies proposing novel approaches to primary literature, we were curious to examine current biology faculty's beliefs and practices on the usage of primary literature in undergraduate classrooms. The following study was guided by the following research questions: (1) What primary literature-related competencies should undergraduate biology students possess upon completion of a 4-year program according to faculty with research and teaching appointments? (2) What are the characteristics of faculty members' self-reported teaching practices with primary literature into their curriculum and how do these described practices align with developing students' disciplinary literacy skills? (3) What explicit strategies on reading primary literature do faculty provide students with, if any? and (4) What criteria do faculty utilize to select primary literature?

Methods

Data Collection

Semi-structured interviews were conducted with biology faculty at a large midwestern research university to understand how faculty view the role of primary literature in undergraduate curriculum. This methodological approach afforded some flexibility to probe or clarify participants' responses outside of the standard interview protocol (Rubin & Rubin, 2005).

The interview protocol is provided in Appendix A (second half of the protocol). We solicited participation via e-mail from three areas of research within the Department of Biological Sciences: cell and molecular biology, neurosciences and physiology, and ecology and evolutionary biology. We also selected participants that had both teaching and research appointments, as we reasoned that both experiences play an integral role in how primary literature is integrated at the undergraduate level. Participants provided their informed consent prior to participation (Appendix B) and were compensated upon interview completion.

Seven faculty members volunteered to participate in the study and were compensated upon the completion of the interview. Participants were at various points in their careers, with appointments ranging from assistant professor to full professor appointments. Average total research experience among participants was 25 ± 4.4 years and average teaching experience (as instructor of record) was 10.4 ± 4.9 years. Faculty demographics are presented in Table 12. Prior to participation, all faculty members provided their informed consent. Interviews took approximately 40 minutes where faculty were asked to provide demographic information along with several open-ended questions to investigate 1) what primary literature-related competencies they expect from students graduating from the Department of Biological Sciences; 2) how primary literature is integrated into coursework; 3) what explicit strategies do faculty provide to students, if any; 4) the selection criteria for primary literature articles. Interviews were audio recorded and subsequently transcribed. Participant information was de-identified and assigned a pseudonym for subsequent analysis.

Table 12 Faculty demographics.

Faculty Members	Research Area	Position	Years of Research Experience	Years of Teaching Experience*
Damon	Cell & Molecular Biology	Associate Professor	27	13
Caleb	Ecology & Evolutionary Biology	Professor	27	15
Roberta	Cell & Molecular Biology	Assistant Professor	18	3
Jeffery	Neuroscience & Physiology	Professor	28	15
Candice	Cell & Molecular Biology	Assistant Professor	20	5
Diane	Ecology & Evolutionary Biology	Assistant Professor	25	9
Oscar	Cell & Molecular Biology	Associate Professor	30	13

*Years of teaching as instructor of record.

Data Analysis

Transcripts were analyzed using constant comparative approaches to determine the salient themes that emerged from faculty participants' responses to each question (Strauss & Corbin, 1990). We first "pre-coded" transcripts to identify portions of the interview that correspond to each research question and then identified codable units - words, utterances, sentences, or short phrases that embody underlying themes (Boyatzis, 1998; Layder, 1998). These codable units were then assigned preliminary codes that captured the essence of the statements. The finalization of codes was done in an iterative manner by two researchers, where codes were negotiated until consensus was met. Codes generated for each research question in this way are provided in Tables 12, 16, and 17.

Identifying Primary Literature-related Competencies

We first utilized constant comparative approaches to examine what primary literature-related competencies biology students should develop upon completion of a biological sciences program. After finalizing the codes, we noticed that each competency aligned with different levels of cognitive processes according to Bloom's Taxonomy (Anderson et al., 2001; Bloom, Krathwohl, & Masia, 1956). This framework posits that meaningful learning takes place through engaging in a range of cognitive processes (remember, understand, apply, analyze, create, and evaluate). As such, learning objectives that addresses multiple domains of cognitive processes are more effective in supporting the acquisition and transfer of knowledge (Anderson et al., 2001). Given the importance of establishing learning objectives in curriculum development, we utilized Bloom's Taxonomy as a coding framework to map each competency expressed by faculty, based on previous applications (e.g., Crowe et al., 2008). Researchers discussed and collaboratively assigned cognitive levels to each competency until consensus was achieved. Table 13 provides a mapping of competencies to cognitive level.

Table 13 Primary literature-related competencies for undergraduates and representative examples expressed by faculty.

Category of Competencies	**Representative Examples**
Remember	"I think they should know how to read it with regards to reading the abstract, the introduction, knowing that when they're in the introduction if there's things they don't understand to go and search for them with some limited amount of time. You don't want to be digging too deep, enough to kind of get them to 60 or 70% take home from that paper." (Roberta)
Recall the features of a paper*	
Understand	"Like, what happened – what were they trying to achieve? What was the question? Why does it matter? How did they do it, just briefly – not even with a lot of detail." (Diane)
Infer experimental progression	
Summarize the main findings*	
Summarize background information	

Table 13 continued

Apply	
Perform a literature search*	"Anyways, I think first of all students should be able to read research papers - be able to use all these wonderful resources to find papers that can help them." (Damon)
Analyze	
Distinguish relevant information*	"The second thing is to extract information, which I'm afraid I don't see that ability in most students. People can read a conclusion, but to really find information that's useful" (Damon)
Draw conclusions from data	
Integrate findings into a larger context	
Create	
Generate a follow-up question*	"And then finally I think the biggest thing is to probably come out of it starting to think of another question. And that's the hardest thing." (Roberta)
Evaluate	
Evaluate arguments	"Again, what's really the difference in your results and conclusion? They have a critical attitude to a paper… in every paper there's a weakness." (Jeffery)
Check for experimental consistency	
Assess value of an article	
Determine the validity of data	
Critique the study*	

Note. Competencies are organized according to levels in Bloom's Taxonomy of Cognitive Processes (Anderson et al., 2001; Bloom, 1956). * indicates the codes corresponding to the representative examples.

Examining Teaching Practices Associated with Primary Literature

We utilized the Teacher Beliefs Interview (TBI) instrument to classify each faculty members' teaching practices with regards to primary literature (Luft & Roehrig, 2007). While the TBI rubric was originally designed to gauge teacher beliefs about teaching and learning, we repurposed it to classify faculty members' described practices, along the continuum of student- and teacher-centered teaching. Furthermore, this application of the framework seems reasonable considering several studies have reported a link between teachers' beliefs and teaching practices, where one helps to inform the other and vice-versa (e.g., Norton, Richardson, Hartley, Newstead, & Mayes, 2005). Teaching practices can be classified into the following categories, listed from more teacher-focused to student-focused: traditional, instructive, transitional, responsive, or reform-based. Traditional practices place emphasis on the delivery or transfer of information from the instructor to students (e.g., lecturing). Instructive practices emphasize providing students with opportunities to learn through experiences and activities. Transitional practices aim at building the student-teacher relationship and providing a learning environment that is supportive for students. Responsive practices promote collaborative learning opportunities among students, their peers, and the instructor. Lastly, reform-based beliefs emphasize students guiding their own learning based on individual needs and interests, where instructors mediate student knowledge (Luft & Roehrig, 2007). We repurposed the TBI rubric as an analytical framework for characterizing faculty members' self-reported teaching practices with primary literature.

Luft and Roehrig (2007) and Lee (2019) provided several examples of responses that describe teaching beliefs (and to some extent, self-reported teaching practices) in accordance with the TBI, and these descriptions and examples served as the basis for our coding rubric. Descriptions and representative examples from our participants are provided in Table 14. Faculty members typically expressed multiple ways of implementing primary literature in their classes, ranging from using figures from an article during a lecture, to having students help select primary articles based on interest or class discussions. Because each faculty member tended to describe multiple ways of implementation, each unique teaching practice was coded individually.

Table 14 Teaching practices categories, description and representative examples (adapted from Luft & Roehrig, 2007).

Category	Description	Representative examples
Traditional	Transmission of information to students; teacher focused	"So I use primary literature to inform the contents of that class. Now, how often during the semester I expect students to read primary literature" (Caleb)
Instructive	Teacher provides learning experiences/activities for students; teacher focused	"…we typically read two papers. One is an assignment, the other one I use kind of as a discussion to discuss 50 students, and to go through figures and discuss some of these issues I mentioned. The other one is a homework assignment for them." (Jeffery)
Transitional	Focus on developing student-teacher relationship	"…right after the first midterm, … I give them a survey of is it working for them or is it not. What are the pros and cons of my teaching style? What do they like? What do they not like? We still have two-thirds of the semester left, so we can fix things so that we can make it the most productive class for us." (Candice)
Responsive	Focus on collaboration (with peers), feedback, and/or knowledge development; student focused	"And we were discussing this, and the students always get interested in these kinds of things. And then they were asking me if primates did it, or if in humans it was related to our current conditions… So the following class I found some papers and a review that looked at all of these actually…" "…for instance, when they try to think of their alternative hypothesis – two minutes talk to your partner – what other explanations do you have for this? And a few people volunteer – they write it on index cards and I pick them up…and I take the most common misconceptions and I bring them up the next day…" (Diane)
Reform based	Focus on facilitating student-driven learning; student focused	N/A

Institutional Review Board

The permission to conduct, record, and transcribe university faculty members' semi-structured interviews (IRB #1612018546) was obtained by the Purdue University Institutional Review Board.

Results

Goals for Literacy Competencies

We asked faculty members to describe what primary literature-related competencies should biology students develop upon graduation. Based on faculty responses, we generated categories of competencies utilizing constant comparative approaches. Participants expressed an average of 3.1 ± 1.3 competencies. Among these, we observed that each competency aligned with differing levels of cognitive processes, leading us to utilize Bloom's Taxonomy as a coding framework to determine the cognitive levels of each task (Anderson et al., 2001; Bloom et al., 1956). A list of competencies, organized by cognitive process, is presented in Table 13. Nearly all faculty members were explicit in their expectations for students to be able to engage the literature with understand- and evaluate-related competencies. Aside from these two cognitive processes, other categories were inconsistent among faculty.

Overall, faculty expectations for student competencies were quite heterogeneous. On one end of the spectrum, Diane expressed that students should be able to *Summarize the main findings* (understand) at the bare minimum (Table 15). As she stated:

> *…it would be great if you could give [students] a paper and they could basically show you… what happened – what were they trying to achieve? What was the question? Why does it matter? How did they do it, just briefly – not even with a lot of detail.*

However, she later expressed that “most [students] are not able to do it”. In contrast, several of her colleagues expected significantly more from students, with many suggesting students ought to be able to evaluate the study as a whole, or particular aspects.

Table 15 Category of tasks related to primary research literacy, according to Bloom’s Taxonomy, that students should be able to do upon the completion of a bachelor’s degree in Biology according to faculty. Shaded boxes indicate explicit tasks relating to each Bloom’s level.

Faculty Participant	Remember	Understand	Apply	Analyze	Create	Evaluate
Damon		■	■	■		
Caleb						■
Roberta	■	■			■	■
Jeffery	■	■	■			■
Candice		■		■		■
Diane		■				
Oscar		■	■	■		■

In the following example, Candice describes her expectations for students, which we coded as evaluate (*Assess value of an article* sub-code):

> *But [students] should, over time, be at a point where for most literature, even if it's not directly related to your field, for most literature you should be able to, very quickly, just going through journals, be able to read the abstract, look at your figures, and essentially know if it's a good paper or not or whether you believe it or not.*

Here, the main point was for students to evaluate the credibility or value of the article by briefly examining several sections. Similar competencies like these were expressed by her colleagues, as other codes tended to be more or less specific (e.g., *Determine the validity of data*, *Critique the study*).

Described Classroom Implementation of Primary Literature

To complement our initial research question, we were curious of how faculty members' self-reported teaching practices with primary literature aligned with their expectations, with regards to student learning. We found that a majority (57.1%) of faculty members' described teaching practices with primary literature aligned with the Instructive teaching practices, whereas two faculty members' described implementations aligned with Responsive practices (Table 16). None of the faculty's descriptions of aligned with Reform-based beliefs. Described implementation of primary literature coded as Instructive practices were similar in that they centered around some kind of activity or assignment. As Oscar describes, "we typically read two papers. One is an assignment, the other one I use kind of as a discussion to discuss with 50 students, and to go through figures and discuss some of these issues I mentioned." Other faculty members similarly provided assignments or in-class activities that functioned as a type of formative assessment.

Table 16 Faculty beliefs and practices mapped onto TBI categories.

Faculty Participant	Traditional	Instructive	Transitional	Responsive	Reform based
Damon		[cross-hatch]			
Caleb	[gray]	[cross-hatch]			
Roberta	[cross-hatch]				
Jeffery		[cross-hatch]			
Candice		[gray]	[gray]	[cross-hatch]	
Diane	[gray]	[gray]		[cross-hatch]	
Oscar	[gray]	[cross-hatch]			

Note. Cross-hatch pattern indicates highest level of student-centered practices and light gray shading indicates other expressed practices.

While Candice and Diane also had assignments and/or in-class activities, their practices emphasized collaborative sense-making - a key feature of Responsive beliefs. For example, Candice has students work with their peers in groups to examine a primary article in a journal club format. She makes it explicit that students of a particular group are responsible for guiding their peers through the evaluation of the assigned study. On the other hand, Diane collaborates with students to further develop their knowledge. In the representative examples of Responsive beliefs (Table 14), Diane is influenced by students' interest and questions, leading to change the contents of subsequent classes. Similarly, in the second example (Table 14), the students' misconceptions of developing an alternative hypothesis to a given study informs the following class. In this way, her students' interests and/or misconceptions help to shape future instruction.

Explicit Instructions for Reading Primary Literature

Since primary literature can be implemented in the classroom in a variety of ways and to varying degrees, faculty encounter students in their classes with varying degrees of experience with primary literature. We were therefore interested if faculty provide explicit paper-reading strategies, if any, and if so, what those are. Of the seven participants, only one faculty reported that they did not provide any explicit reading strategies (Damon). Among those who did report doing so, we found four overarching categories of instruction expressed by faculty members: *Ways of thinking about experimentation*, *procedural instructions*, *general reading strategies*, and *content-related instruction*. Representative examples of each category of instruction are presented in Table 17.

Table 17 Explicit reading-related instruction provided to students.

Categories of Instruction	% of faculty	Representative examples
Ways of thinking about experimentation	57.1	"…I set up, I give them how an experiment is done, give the flow chart, and then say, "Okay. What would you predict if you did this experiment?"… And we make predictions." (Candice)
Procedural instruction	42.9	"We tell them to go through the abstract and read the introduction to learn what is the context, what is the significance of the research, what is the background of the group as to into this field, and what is the hypothesis that is being moved forward in this paper." (Oscar)
General reading strategies	14.3	"I also suggest to them if the figures are not well labeled, to do some labeling for their own purpose. So it's easier to understand the figure or maybe late to explain it to somebody else if you have to do that in a journal." (Jeffery)
Content-related instruction	14.3	"That being said, in the class I would put together a brief introduction of the paper if there were things that were essential that we didn't cover a few days before in textbook part of the lecture." (Roberta)
No explicit instruction provided	14.3	N/A

Instruction coded as *ways of thinking about experimentation* was the most prevalent among participants, which we defined as instruction that emphasized features of experimental design or practices (e.g., difference between a hypothesis and prediction, predicting experimental outcomes). *Procedural instructions*, the second most common category, provide a step-wise approach to reading the primary literature that suggests the reading order of the major sections in a primary article (e.g., abstract, introduction, etc.) and points out certain features. *General reading strategies* refer to advice that help to organize student thinking that could be applied to many different contexts (e.g., annotate the figure, draw a concept map, etc.). Lastly, *content-*

related instruction provides any ancillary information related to disciplinary content to provide the context for the study.

Paper Selection Criteria

Lastly, we inquired about the factors that influence how faculty selected primary articles into the course, as we reasoned that article choice helps to align primary literature-related activity with learning goals and outcomes. Paper selection criteria and representative examples are shown in Table 18. Unsurprisingly, one of the top selection criteria faculty expressed was that the content of the article had to be directly related to the contents of the course. The other top selection criterion was the *quality of the study*, specifically exemplary studies (as opposed to flawed or poorly written). As Roberta describes:

> *I typically shied away from papers I didn't think were good - and maybe that's not a great thing 'cause I think it's good for students to see them - but for this particular class I think because of the time constraints, I really wanted them to see what the good literature was…*

While she does acknowledge that flawed or poorly written papers could provide a valuable learning experience, time was a limiting factor that ultimately limited her from incorporating both types of papers.

Table 18 Paper selection criteria expressed by faculty.

Criteria	% of faculty	Representative examples
Content directly related to the course	57.1	"And it's about some topics that we have been discussing during the course as well." (Oscar)
Quality of the study (exemplary studies)	57.1	"I really wanted them to see what the good literature was that was supplying the information in the text." (Roberta)

Table 18 continued

Novelty of the study	42.9	"I like them to be seminal advances in the field, like something that changed our thinking or a new finding. And I understand every published thing is a new finding, but something that really brought to light something that nobody had ever seen before." (Candice)
Date of publication (more recent)	42.9	"I may be using one for two, maybe three years. I like to pick one that's relatively recent…" (Jeffery)
Teach new technique(s)	28.6	"[The papers] are really good examples of the methods that the students have to use for the research that they're supposed to be doing…" (Caleb)
Popular topics	28.6	"[Paper selection] mostly gravitates to stem cells, some kind of neurodegenerative disorder, CRISPR, optogenetics, some kind of micro RNA" (Damon)
Appropriate difficulty	28.6	"So the papers were selected based on somewhat of an ease…" (Roberta)

Other criteria for selecting primary articles that was expressed by multiple participants included the novelty of the study. As highlighted in the example provided on Table 18, participants that expressed this criterion wanted to provide an example of studies that altered conventional thinking within a discipline, offering a chance to observe creativity in science. A similar number of participants also expressed the date of publication, specifically more recent ones, to be an important factor. Faculty expressed that relating the contents of the course with current trends in the field was an important feature of teaching the course. Other criteria that were less frequently expressed include papers that offer an opportunity to teach new techniques, articles on popular topics in biology, and whether or not the article is of an appropriate difficulty.

Discussion

Learning within a discipline not only includes developing content knowledge, but also understanding the practices for the knowledge creation and communication (Bain, 2000; Moje, 2008). Given that primary literature serves as one of the major vehicles for communicating and negotiating ideas within disciplinary communities, developing science identities and literacy skills that allow students to engage in discourse is a necessary component of disciplinary education. Prior studies have highlighted that engaging with primary literature is challenging for students (e.g., Hubbard & Dunbar, 2017; Kozeraki et al., 2006; Lie et al., 2016; Round & Campbell, 2013). Many studies have explored instruction that target a variety of skills and concepts, including experimental design, data analysis, nature of science, among others (e.g., Abdullah et al., 2015; Ferenc et al., 2017; Gottesman & Hoskins, 2013; Hoskins et al. 2007; Krontiris-Litowitz, 2013; Round & Campbell, 2013; Segura-Totten & Dalman, 2013); however, there is no clear consensus which is approach is best (Segura-Totten & Dalman, 2013). In this study, we describe several aspects of biology faculty's implementation of primary literature in a large research university.

Consensus of Understand and Evaluate-related Competencies

Our work highlights the competencies related to reading primary literature that undergraduates should develop by the time they graduate, as expressed by biology faculty. According to disciplinary experts in the study, these competencies clustered around understanding and evaluation processes, whereas competencies related to other cognitive levels were in much less agreement. Many pedagogical approaches have addressed the initial barrier of understanding-related difficulties students encounter while reading primary literature, such as the CREATE strategy which develops the understanding of a particular field of research (Gottesman

& Hoskins, 2013; Hoskins et al. 2007) or Figure Facts, which promotes a data-centered approach to understand primary article (Round & Cambell, 2013). Faculty's consensus on evaluation-related competencies are in alignment with the idea of developing scientific skepticism, in that many of the participants highlighted evaluation of the validity, credibility, or importance of the study as an expected competency for students to develop. These findings overlap with prior work surveying science-practice skills, which include problem solving and critical thinking, interpreting data, graph construction, and communication (Coil et al., 2010). In order to promote student reading that moves beyond understanding, approaches are necessary that encourage students to proactively engage in evaluation-related competencies. Prior work suggests that scaffolded instruction in a course dedicated to reading primary literature can increase awareness of performing evaluative actions while reading (Lie et al., 2016); however, many undergraduate curricula do not have the luxury of implementing such a course. Therefore, an alternative approach would be to provide sequential instruction spanning across students' undergraduate experience.

Faculty Mainly Engage in Instructive Practices

Efforts to reconceptualize undergraduate education have emphasized the transition from traditional, teacher-centered instruction to student-centered instruction to expand opportunities for student to engage in sense-making (AAAS, 2011). To this end, we examined faculty members' self-reported teaching practices in how they implemented primary literature into their classrooms. We report that most faculty participants described practices that align with Instructive beliefs. Such instruction with primary literature includes assigning homework, administering assessments, or holding discussions that mirror a journal club. While emulating a journal club may stimulate discussion among students (Barker, 2010), other work suggest that discussion alone may not be sufficient to teach critical reading of primary articles (Farenc et al., 2018). Two faculty members described Responsive beliefs as demonstrated by their collaborative approaches (student-student and student-teacher) incorporating primary literature. These two instructors not only held discussion, but also worked with the students to inform future instructional practices.

Prior research has shown that teaching practices are guided and informed by beliefs (e.g., Fang, 1996; Kane et al., 2002); as such, facilitating change towards student-centered instruction may require faculty to reflect on their beliefs, practices, and student learning outcomes. By incorporating student-centered approaches that emphasize the process of knowledge creation, faculty can help in the development of students' professional and science identities (Carlone, 2003, 2004), which can help to enhance student motivation (Kiefer, Ellerbrock, & Alley, 2014). Furthermore, development of science identities is thought to enhance students' disciplinary literacy practices (Moje, 2008). Further research is necessary to examine the association between more student-centered teaching practices involving primary literature and the development of students' science identities.

Use of Explicit Instruction

Developing literacy skills to engage in a content area's discourse can place over many years across hundreds of articles. Many of our participants cited time as a major limiting factor for instruction or activities related to primary literature, therefore explicit instruction on how to approach such articles can play an important role in mitigating time requirements. Most of our faculty provided some degree of explicit instruction, with most being related to experimentation (e.g., checking for controls, predicting experimental outcomes); however, none of the participants reported instruction related to evaluation despite it being a major competency.

Researchers have suggested that explicit teaching of strategies employed by expert readers can not only enhance students' comprehension (e.g., Pressley & Afflerbach, 1995), but also evaluation of scientific literature (Farenc et al., 2018); however, explicit instruction tends to be associated with teacher-centered approaches, which may undermine or contradict student-centered teaching practices. Yet, given the complex nature of primary literature, explicit instruction or scaffolding in introductory courses can help to curb anxiety and frustration students commonly face (Kozeracki et al, 2006). Therefore, it is recommended that a combinatorial approach that incorporates explicit instruction followed by student-centered approaches be implemented to teach students how to read primary literature.

Strategic Selection of Papers Based Primarily on Positive Factors

Another important consideration for implementing primary literature in a meaningful way is to select articles that are aligned with student learning outcomes. The top selection criteria participants cited include, content, quality, and the novelty of the study. While these are reasonable selection criteria, exposing students only to studies that are novel or of exceptional quality limits valuable learning opportunities. Muench (2000) highlights three potential learning outcomes that make use of different types primary literature, including: understanding a scientific paper, critiquing experimental design and/or designing follow-up experiments, and relating scientific findings to social and environmental contexts. Several examples of intentional paper selection include: using flawed manuscripts to provide contexts that allow students to practice skills related to evaluation (Abdullah et al., 2015; Ferenc et al., 2018), incorporating multiple studies with contradictory outcomes or conclusions (Abdullah et al., 2015), or following a series of publications to highlight the intellectual progression of ideas (Hoskins et al, 2007). The risk of selecting exceptional studies may limit the development of scientific skepticism or critical evaluation, as students holding a naive understanding of the role of primary research articles may accept them as fact, rather than arguments to establish scientific consensus (Lie & Guzey, unpublished). Prior work (Lie & Guzey, in review) highlights that the expertise biologists display when reading primary literature is a result of years of reading hundreds of primary articles, if not more, in a wide variety of contexts (e.g., targeted research purposes, examining methodology, peer review, acquisition of new knowledge); therefore, it is important to provide opportunities that allow students to experience reading primary literature in a wide array of contexts.

Taken together, these results highlight a need to develop undergraduate curricula that offers continuity across courses that effectively scaffold the development of students' literacy skills and practices. As highlighted by Henderson and colleagues (2011), best practice curricular materials and "top-down" policy-making are ineffective in developing change, whereas effective change strategies are aligned with changing the belief of individuals and/or involve long-term intervention strategies that fit into the existing structure of a college or university. Therefore, future strategies that facilitate changes in faculty beliefs about teaching literacy practices is required. This can prove to be challenging (Nespor, 1987), as it requires a reconceptualization of undergraduate biology education; however, recent work by Kenyon and colleagues (2019) suggest that professional workshops are able to facilitate change and even produce downstream impacts.

Limitations and Future Directions

This study contains several limitations to consider, the first being sample size. We consulted only seven faculty, which limits the generalizability of the conclusions; however, this exploratory approach is intended to reveal insight into the characteristics of incorporating primary literature into undergraduate biology education. While our observations are not generalizable, we suspect that the described characteristics may be similar to other research-intensive universities. Furthermore, we relied on faculty self-reporting their teaching practices with primary literature, rather than conducting in-class observations. This can be problematic, as self-reported teaching practices do not necessary align with actual teaching practices. As such, in-class observations may be conducted to determine the alignment between self-reported and actual teaching practices. Our findings provide a clearer roadmap to further explore undergraduate competencies related to reading primary literature, possible selection criteria for primary literature usage in the classroom, and how teaching beliefs and practices can help to provide better support for students' learning.

Future work to further identify and establish a consensus of student competencies related to engaging with primary literature will help to align paper selection and instructional approaches. In conjunction with previous research on the topic of primary literature, we posit that faculty must reconceptualize the long-term goals of undergraduate biology education with regards to literacy competencies and discourse within the discipline. We suggest viewing student literacy competencies as a type of skill progression - a series of skill elements of increasing difficulty (Reiken, 1985). Such a framework can organize skill progression across different stages at the post-secondary level (e.g., instruction related to comprehension is given before instruction related to evaluation).

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CHAPTER 6: CONCLUSIONS AND FUTURE IMPLICATIONS

Dissertation Focus

Reimagining undergraduate biology education as supporting students' ways of knowing within the discipline, rather than an accumulation of facts, necessitates the development of skills that will allow students to engage in data analysis, evaluation of evidence, and scientific communication – skills necessary to engage with biology of the 21st century (AAAS, 2011; AAMC-HHMI, 2009; Alberts, 2009; NRC, 2009). As such, having students examine primary literature, the forefront of where knowledge is presented and negotiated, is increasingly important (AAAS, 2011; Coil, Wenderoth, Cunningham, & Dirks, 2010). Despite this importance of developing biology students' literacy skills, many still describe the task as difficult upon or after graduation from a 4-year institution (e.g., Lie, Abdullah, He, & Tour, 2016; Smith, 2001).

This is due to the complex nature of primary literature that not only requires a certain level of content knowledge, but also requires proficiency in data analysis, understanding disciplinary representations of data, experience with scientific prose, and knowledge of experimental design, among other facets. As a result, students inundated with all these unfamiliar concepts commonly express anxiety and frustration (Kozeracki, Carey, Colicelli, & Levis-Fitzgerald, 2006). Disciplinary literacy describes the unique literacy practices within a discipline, including what counts as evidence, how arguments are generated, important features, common parlance, etc. (Hynd-Shanahan, 2013). In order to develop students' disciplinary literacy, they must first understand the operating norms and practices for knowledge generation and communication (Bain, 2000; Gee, 2001; Lemke, 1990; Moje, Peek-Brown, Sutherland, Marx, Blumenfeld, & Krajcik, 2004; Shanahan & Shanahan, 2008).

A multitude of studies have emerged over the past several decades that have proposed novel approaches to teach students how to read primary literature and/or related literacy skills. Some of these specifically address how to read primary literature (e.g., Abdullah, Parris, Lie, Guzdar, & Tour, 2015; Clark, Rollins, & Smith, 2014; Murray, 2014; Van Lacum, Ossevoort, & Goedhart, 2014) or use primary literature as a vehicle to develop certain process skills (e.g., Abdullah et al., 2015; Hoskins, Stevens, & Nehm, 2007; Round & Campbell, 2013). However, many of these studies rely on tacit assumptions or anecdotal evidence of how students read (Hubbard & Dunbar, 2017). Thus, to address the challenge of developing biology students' literacy practices, further empirical evidence on how biologists and students read primary articles is necessary.

Currently, only a couple studies characterize novice and/or expert reading of primary literature (Hubbard & Dunbar, 2017; Van Lacum, Ossevoort, Buikema, & Goedhart, 2012). Van Lacum and colleagues (2012) compared the ability of novice (first-year undergraduates) and expert readers to identify evidence and conclusions within a primary literature article. Students tended to be much more liberal in their identification of conclusions in comparison to expert readers. Hubbard & Dunbar (2017) highlight the differences in perceived importance among the different sections of an article across different career stages. This dissertation further extends knowledge of novice and expert biologists' literacy practices and examines current teaching practices associated with primary literature.

Summary of Dissertation Findings

In order to characterize disciplinary literacy practices, we employed an expert-novice reader paradigm in which we identified and characterized the ways in which these two populations engaged with primary research literature. We utilized a semi-structured interview format and had participants narrate their process of reading a primary research article of their choosing. This was important to consider in the case of expert readers, as expertise is discipline specific (Alexander & Judy, 1988; Hyland, 2004). Follow up questions and probes were utilized to promote participants to elaborate their thinking processes (Rubin & Rubin, 2011). A total of seven faculty and nineteen students from a large midwestern research institution were interviewed.

We first characterized general aspects of how participants read the articles, including reading pathway analysis utilizing Hamming distance vectors. Both students and experts tended to read articles in a selective manner (i.e., excluded particular sections), where students often did not read a study's Methods. In contrast, most experts refenced the Methods as needed to check on specific components of experimental design (e.g., data sources, controls) and commonly skipped the Introduction. Furthermore, students tended to read linearly in the order major sections were presented, whereas faculty moved between sections to access information as needed. These observations align with and provide further contextual evidence of reading habits highlighted by prior researchers of student and experts' selective reading habits (Hubbard & Dunbar, 2017; Van Lacum et al., 2012).

Further characterization of reading habits led us to examine the reading actions taken by expert and novice populations. We noticed that the experts' described actions tended to be much more specific than students. Faculty expressed a similar number of unique actions to students, despite only seven faculty being interviewed compared to nineteen undergraduates. This difference in specificity and diversity of reading actions make sense, considering experts have years, if not decades, of experience reading articles in various contexts. We posit that such diverse experiences and contexts have allowed experts to develop an *a priori* analytical framework that help to explain why they chose to perform certain actions. In contrast, students mainly described actions that were aligned with reading understanding. This typically meant relying on the text to help guide interpretation of data and development of conclusions presented by the authors.

Given the diversity of actions expressed by both populations, we sought to more concisely characterize such actions, which led us to align reading actions with cognitive levels according to Bloom's taxonomy (Anderson et al., 2001; Bloom, Krathwohl, & Masia, 1956). Expert readers displayed much more versatility in their reading actions. Their actions were reasonably distributed among understand, apply, analyze, and evaluate domains of cognition. In contrast, students' actions were overwhelmingly centered around actions aligned with understand, followed by remember. This was evident even among students with medium and high levels of research participation. How can we expect students to develop evaluative skills if they do not bother to engage in evaluative practices? This finding extends prior work by Lie and colleagues (2016), which suspected that students may not consider evaluative practices, due to lack of knowledge of how to go about doing so.

Additionally, we investigated what factors expert and novice readers cite when evaluating the credibility of an article. Three major categories of factors were found: corroboration, experimental setup and methodology, and sourcing. Experts most commonly cited factors related to the experimental setup and methodology, followed by corroboration, and sourcing. In contrast, students overall cited less factors, with equal amounts of students citing experimental setup and sourcing, and very few citing factors related to corroboration. While experts may use sourcing to indicate a certain level of quality, they ultimately rely on the other two factors to determine the merits of an article. In contrast, many students relied on the authority of sources to imply validity of research. This is particularly problematic, as students fall prey to the argument from authority fallacy, which is contradictory to the nature of science (Milgram, 1963). As noted by Moje (2008), identity construction precedes the development of disciplinary literacy. Thus, our observations may suggest that students' science and/or biology identities are underdeveloped, which might help to explain why they neglect to engage in evaluative literacy practices.

In addition to characterizing literacy practices, we examined faculty's expectations and teaching practices surrounding primary research literature. Most faculty agreed that students ought to be competent in skills aligned with understand and evaluate, whereas other skills were in less agreement. It is important to note that skills related to evaluation have an implicit relationship with skills of other cognitive levels – i.e. determining the validity of an author's claim (evaluate) may involve examining data (analyze). Thus, we reason that skills aligned with these two cognitive levels are perceived as most important by faculty. In examining faculty's teaching practices, we found that a majority's described teaching practices with primary literature in undergraduate courses resembled instructive practices, which aligns with more student-centered teaching. Two of our participants displayed more student-centered teaching practices, which involved collaborative work among students or working with students to inform future instruction.

Lastly, selection criteria of articles can greatly influence learning objectives and student learning experiences (Muench, 2000). As such, we were curious to examine the factors faculty considered in choosing primary literature articles. Most faculty tended to choose papers based on the novelty and quality of the study, skewing towards exemplary studies. This can be problematic, as only presenting exemplary papers may serve to promote the authority of published articles. As such, it is important to consider incorporating articles that contain flaws and errors that will allow students to engage in peer review and hone skills associated with evaluation, among others. Ferenc and colleagues (2017) take this one step further and have students write intentionally flawed manuscripts, followed by a process of peer review. Abdullah and others (2015) suggest assigning two articles that arrive at different conclusions, which compels students to compare and negotiate inconsistencies. Scientists must regularly make sense of sub-optimal, flawed, or conflicting information, yet students rarely receive the opportunity to engage in such sense-making.

Efforts over the past decade by AAAS and other organizations to redefine biology education can be seen particularly among biology education researchers; however, the extent of such impact as it concerns faculty and departments is unclear (AAAS, 2018). In examining biology faculty (none of which are involved in biology education research) at a large midwestern research institution, we found that most instructors rely on practices that more closely align with teacher-focused approaches when teaching with primary literature. Furthermore, evidence from our novice reader population highlight that students do not regularly engage primary literature critically, despite this importance of this skill (AAAS, 2011). These findings, while limited, suggest that the core message of biology education reform documents have limited penetrance at the faculty and department level at the institution we conducted research at. As such, further work is necessary to effectively disseminate the works inspired by recent calls to reform.

Implications for Undergraduate Biology Education

This dissertation provides empirical evidence that highlights the expert-novice gap in literacy practices related to reading primary literature that can help to inform approaches to have students engage in disciplinary literacy practices. Furthermore, we examined teaching practices related to primary literature at a large midwestern research intensive university. To address this gap and promote reading beyond understanding, instructors must consider teaching practices that not only support authentic science practices, but also are student-centered. As highlighted by Carlone (2003, 2004), science identities are enhanced through student-centered teaching practices. Recent work by Barbarà-i-Molinero and colleagues (2017) found that factors including "social experience, educational context, perceived congruence with the profession, demographic characteristics, professional image, professional experience, personal development, and self-engagement" influence professional identity development in higher education. Given that development of professional science identities precedes disciplinary literacy (Moje, 2008), student-centered practices are necessary to facilitate disciplinary learning (i.e., how knowledge is constructed within a discipline); however, this is not an easy task to accomplish.

As highlighted by Brownell and Tanner (2012), numerous barriers impede faculty change, including training, time, incentives, and struggles between a scientist's professional identity, among others. Furthermore, biology instructors tend to prioritize personal or anecdotal evidence related to teaching decisions, rather than empirical evidence (Andrews & Lemons, 2015). Thus, what recourse is available to facilitate pedagogical change in the way primary literature is implemented? A review of the literature by Henderson, Beach, and Finkelstein (2011) reports that implementation of change strategies, particularly "best practice" curricular materials or "top-down" policy making, tend to be ineffective. In contrast, change strategies that involve changing beliefs of individuals or long-term interventions proved to be much more effective.

Recent work by Kenyon and colleagues (2019) examining the effects of a faculty workshop promoting the CREATE method have shown consistent and reproduceable effects in cognitive (e.g., experimental design) and affective (e.g., self-efficacy) domains; however, it is unclear if this method promotes evaluative reading practices in students. Furthermore, work by Segura-Totten and Dalman (2013) found there are not many differences in student outcomes when compared to equally scaffolded, traditional journal-club approaches to teaching with primary literature. Thus, more work is required to elucidate the best approach to influence teaching practices that promote students to engage in literacy practices that move beyond understanding. Additionally, it would be of great value to examine how such instruction influence students' professional identities and how it relates to literacy practices.

Scope of Future Research

The work presented here has established the groundwork for future studies regarding primary literature instruction. From this work, we know that students rarely move beyond simply understanding the contents of primary articles, which can lead to potential issues such as accepting arguments from authority or accepting peer-reviewed work as fact. Furthermore, students rarely engage in corroborating between bodies published knowledge, as they may not have had opportunities that encouraged them to do so. We acknowledge that developing disciplinary literacy takes place over many years, and standalone interventions are unlikely to result in long term outcomes (Henderson et al., 2011). As such, we recommend the development of a skill progression of literacy competencies that span across an undergraduate biology curriculum. Considering current advances in this area of research, future efforts can also synthesize existing research on primary literature instruction to construct sequential, scaffolded instruction that not only addresses understanding of content, but also promotes engaging in evaluative actions.

Additionally, it would be of interest to examine the link between students' science identities and literacy practices. As previously pointed out, students with high levels of research participation did not display drastically different modes of reading primary literature; yet, one would assume that such students would have a more developed science identity. Furthermore, this work points out that most students cite sourcing as grounds for validity, which may stem from the lack of confidence or the lack of knowledge of how to critique or evaluate published works. To our knowledge, there is a lack of research investigating how novel instructional approaches involving primary literature affect students' science identities. We hypothesize that encouraging students to engage in the practice of evaluating and critiquing scientific works can aid in the development science identities.

Finally, given that approaches that focus on promoting instructors' beliefs about teaching seem to be most effective in influencing teacher practices (Henderson et al., 2011), it would be worthwhile to devise a faculty development program that disseminates and incorporates the findings of this research. Yerrick and colleagues (1997) argue that having instructors examine their underlying beliefs regarding teaching and how that affects students' learning outcomes can lead to changes in classroom instruction. As such, having faculty reflect upon their teaching beliefs and practices can promote opportunities to help students engage in disciplinary ways of reading. Such effort would address the calls to action by the multiple organizations advocating for changes in the ways undergraduate biology is taught (AAAS, 2011; AAMC-HHMI, 2009;

NRC, 2009). Therefore, this work highlighting the gaps in literacy practices and instruction foregrounds future efforts to address the challenges of biology of the 21st century.

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APPENDIX A. FACULTY INTERVIEW PROTOCOL

Below is the faculty interview protocol used in the study.

Participant's Demographics and Background:

1. What sub-discipline of biology are you currently conducting research in?
2. How many years have you spent working in your field of research? In biology as a whole?
3. On average, how many scientific papers do you read on a monthly basis?
4. Would you describe your primary reason/motivation for reading scientific papers?
5. When reading primary literature, approximately how much time do you spend looking at figures as opposed to reading the text?
6. What aspect(s) of reading scientific papers in your field of expertise do you find most challenging? Can you provide any specific examples?

Participant's Process of Reading

7. What paper did you bring today (have them read title, year, first author)? Can you tell me the context of this how you chose this paper?
8. Can you briefly summarize the findings of the paper or point out something your found interesting?
9. Would you describe your strategy when reading a scientific paper for the first time? You may use the paper that you brought with you to guide your thought process.
10. What features of the paper made it either easy or difficult to understand?
11. Did you find the study convincing? Can you tell me how you came to that conclusion?
12. What are your criteria for judging the credibility of a paper?

Teaching with Primary Literature

13. Would you describe how you learned to read primary scientific literature?
14. How many years, if any, have you served as an instructor for a biology course?
15. Can you briefly describe the courses that you teach?
16. What is your primary student population of the classes you teach?
17. Do you use primary literature in your class(es) to teach?
    a. If so, which one(s) and how often?
    b. Would you describe how you implement primary literature into your class(es)? (Whole paper, just figures, models?)
    c. Can you describe your selection criteria for choosing papers to use in your class?
    d. Do you explicitly teach strategies on how to read scientific papers to your students? If so, please describe the instruction/activities you provide.
18. What aspect(s) of reading scientific papers do you believe undergraduate students, who have little experience with scientific literature, find most challenging and why?
19. As students become more experienced in reading primary literature, how do you think their perceived difficulty changes?
20. How do you think students can improve the skills associated with reading primary literature? Are there any activities that would support them in this aspect?
21. Can you describe the primary literature-related skills a student should have upon completing a 4-year biology degree?

APPENDIX B. RESEARCH PARTICIPANT CONSENT FORM (FACULTY)

RESEARCH PARTICIPANT CONSENT FORM

Understanding difficulties and approaches to reading scientific literature

Selcen Guzey

Department of Biological Sciences

Purdue University

What is the purpose of this study?

This study is designed to understand how students and experts approach primary scientific literature. Scientific papers offer valuable learning opportunities both inside and outside of the classroom. Currently, not much has been investigated on the difficulties that students and experts face when reading scientific papers.

In order to qualify to participate in this study, you must meet the following criteria: have taught an upper-level, undergraduate biology course and must currently be currently conducting research in a biology discipline.

What will I do if I choose to be in this study?

This study will require you to participate in a single interview session. The interview will be audio recorded for transcription purposes.

How long will I be in the study?

The study will only be comprised of a single interview lasting approximately 30-45 minutes.

What are the possible risks or discomforts?

All research carries risk. The standard for minimal risk is that which is found in everyday life. Some risk that may be present in the study are loss of time for participants, boredom, mental fatigue, or frustration that may arise due to interview questions.

Are there any potential benefits?

There are no immediate benefits to be gained by the individual however this study aims to understand the difficulties associated with reading scientific literature in order to develop effective instructional practices.

Will I receive payment or other incentive?

Faculty will receive a $10 gift card to their choice of Starbucks, Amazon, or ITunes.

Will information about me and my participation be kept confidential?

Yes. Information (emails and files containing scheduling) linking transcripts to study participants will be destroyed after the study is completed. Throughout the study, any confidential information will be stored in a location only accessible to investigators working on the project. The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight.

What are my rights if I take part in this study?

Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact Selcen Guzey [email].

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu)or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.,
West Lafayette, IN 47907-2114

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

____________________________________ ______________________

Participant’s Signature Date

____

Participant’s Name

____________________________________ ______________________

Researcher’s Signature Date

APPENDIX C. STUDENT INTERVIEW PROTOCOL

Participant's Demographics and Background:

1. Can you tell me your year and major?
2. What would you say is your career goal?
3. Are you involved in any laboratory research? For how long? Can you briefly describe your role?
4. In this study, we are examining several aspects regarding undergraduate students' experience with primary scientific literature in biology. Approximately how many scientific papers have you read?
5. How have you previously been exposed to reading scientific papers?
    a. If the participant has been exposed to primary literature in their coursework:
        i. Can you tell me which classes included primary literature?
        ii. Of these classes, did any explicitly teach how to read them?
    b. If the participant has read primary literature independently
        i. Can you tell me a little more about why you read?
6. Did any of these experiences provide any explicit instruction on how to approach scientific literature?
7. If the student chose more than 1 option in the previous question: Which one of these do you think provided the best learning opportunity to read scientific papers? Can you please elaborate as to why?
8. What would you consider to be the most challenging aspect of reading scientific papers? Are there any specific examples that you can think of?

Participant's Process of Reading

9. What paper did you bring today (have the student read the name, year, and first author)? Can you tell me the context of how you chose this paper?

10. Can you briefly summarize the findings of the paper or point out something you found that was interesting?
11. Would you describe your strategy when reading a scientific paper for the first time? You may use the paper that you brought to guide your thought process.
12. Can you describe what made this paper easy or difficult to understand?
13. Approximately how much time do you spend examining the figures as opposed to reading the text?
14. Did you find the study convincing? Can you tell me how you came to this conclusion?
15. What do you look for in a paper to determine its credibility?
16. When coming across something unfamiliar, (ie. terminology, experiments, methods, etc.) what strategy do you normally use to better understand the topic?
17. Would you have read the paper any differently in a different context (e.g. class, lab meeting, etc.)?

APPENDIX D. RESEARCH PARTICIPANT CONSENT FORM (STUDENT)

RESEARCH PARTICIPANT CONSENT FORM

Understanding difficulties and approaches to reading scientific literature

Selcen Guzey

Department of Biological Sciences

Purdue University

What is the purpose of this study?

This study is designed to understand how students and experts approach primary scientific literature. Scientific papers offer valuable learning opportunities both inside and outside of the classroom. Currently, not much has been investigated on the difficulties that students and experts face when reading scientific papers.

In order to qualify for the study, you must have either junior or senior standing and have experience with reading peer-reviewed scientific literature.

What will I do if I choose to be in this study?

This study will require you to participate in a single interview session. The interview will be audio-recorded for transcription purposes.

How long will I be in the study?

The study will only be comprised of a single interview lasting approximately 30-45 minutes.

What are the possible risks or discomforts?

All research carries risk. The standard for minimal risk is that which is found in everyday life. Some risk that may be present in the study are loss of time for participants, boredom, mental fatigue, or frustration that may arise due to interview questions.

Are there any potential benefits?

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Will I receive payment or other incentive?

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Will information about me and my participation be kept confidential?

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The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight.

What are my rights if I take part in this study?

Your participation in this study is voluntary. You may choose not to participate or, if you agree to participate, you can withdraw your participation at any time without penalty or loss of benefits to which you are otherwise entitled.

Who can I contact if I have questions about the study?

If you have questions, comments or concerns about this research project, you can talk to one of the researchers. Please contact Selcen Guzey [email].

If you have questions about your rights while taking part in the study or have concerns about the treatment of research participants, please call the Human Research Protection Program at (765) 494-5942, email (irb@purdue.edu)or write to:

Human Research Protection Program - Purdue University
Ernest C. Young Hall, Room 1032
155 S. Grant St.,
West Lafayette, IN 47907-2114

<u>Documentation of Informed Consent</u>

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research study, and my questions have been answered. I am prepared to participate in the research study described above. I will be offered a copy of this consent form after I sign it.

Participant’s Signature   Date

Participant’s Name

Researcher’s Signature   Date

VITA

Richard Lie

Purdue University

Department of Biological Sciences

EDUCATION

Doctor of Philosophy, Biology - Purdue University, 2019

Concentrations: Biology Education, STEM Integration

Dissertation Topic: Disciplinary Literacy in Biology Education - Examining Primary Literature

Master of Science, Biology - University of California, San Diego, 2014

Concentrations: Cellular Neurobiology, Cell Biology

Thesis: Multipotent neural progenitor cells exhibit enhanced neurite outgrowth on adult myelin: Implications for neural regeneration

Bachelor of Science, Human Biology - University of California, San Diego, 2012

ACADEMIC POSITIONS AND TEACHING APPOINTMENTS

Adjunct Faculty, Department of Life Sciences

Ivy Tech Community College, 2016, Jan 2019 - present

Courses Taught:

APHY101 - Anatomy and Physiology I (2 semesters)

APHY102 - Anatomy and Physiology II (1 semester)

Graduate Teaching Assistant, Department of Biological Sciences

Purdue University, Jan 2018 - Dec 2018

Courses Taught:

BIOL135 - First Year Biology Laboratory (2 semesters)

Teaching Assistant, Division of Biological Sciences

University of California, San Diego, Sep 2011-Jun 2014

Courses Taught:

BILD1 - The Cell (2 quarters)

BILD2: Multicellular Life (2 quarters)

BIMM110: Molecular Basis of Human Disease

BIPN102: Mammalian Physiology II

BICD100: Genetics

BICD134: Human Development and Reproduction.

PROFESSIONAL EXPERIENCE

Purdue University

Research Assistant, Department of Curriculum and Instruction - Project UPDATE

Aug 2018 – Aug 2019

Supervisor: Brenda Capobianco, Ph.D., bcapo@purdue.edu

- Developed and evaluated biology content assessments for pre-service teachers.

- Performed linear modeling to assess the effect of engineering integration in pre-service science courses.

Research Assistant, Department of Engineering Education – EngineeringTEAMS

Sep 2016 – May 2018

Supervisor: Tamara Moore, Ph.D., tamara@purdue.edu

- Developed grades 4-8 design-based science curricula based on the Next Generation Science Standards.
- Conducted conversational analysis of students and teachers enacting design-based science curricula resulting in 2 publications.
- Employed linear modeling to assess the effect of design-based science curricula on students' attitudes and learning resulting in a publication.
- Developed and participated in professional development program for grades 4-8 STEM teachers.

University of California, San Diego

Laboratory Technician, Department of Neuroscience

July 2014 – June 2015

Supervisor: Mark Tuszynski, MD., Ph.D., mtuszynski@ucsd.edu

- Investigated the effects of myelin-associated proteins on neural stem cells (1 publication).
- Mentored three undergraduate students in cell and tissue culture, molecular biology, and physiological techniques.

- Collaborated with colleagues at the University of California, Los Angeles on RNA sequencing project.
- Performed molecular biology and cell culture techniques.

Research Assistant, Division of Biological Sciences - Biology Education

Sep 2013 – Aug 2015

Supervisor: Ella Tour, Ph.D., etour@ucsd.edu

- Examined learning outcomes of a primary literature-based course resulting in a publication.
- Performed mixed-method analysis of students' perception of primary scientific literature resulting in a publication.

Undergraduate & Graduate (M.S.) Researcher, Division of Biological Sciences

Oct 2011 - June 2014

Supervisor: Mark Tuszynski, MD., Ph.D., mtuszynski@ucsd.edu

- Collected data to investigate the effects of adult CNS myelin on neural stem cells in spinal cord injury model.
- Developed and optimized a medium-throughput neurite outgrowth assay for an in-vitro genetic screen.
- Conducted histological analysis of neural tissue.

UNIVERSITY SERVICE

Purdue University

President, Biology Graduate Student Association, 2017 - 2019

Treasurer, Discipline Based Education Research – Graduate Student Group, 2016 - 2018

Social Chair, Biology Graduate Student Association, 2016 - 2017

Convener, Purdue International Biology Education Research Group (PIBERG), 2016

HONORS/AWARDS

Teaching Academy Graduate Teaching Award, Purdue University, 2019

Biology Teaching Assistant Award, Dept. of Biological Sciences, Purdue University, 2018

PGSA Travel Grant Award, Purdue Graduate Student Association, 2018

Honorable Mention, Graduate Research Fellowship Program, National Science Foundation, 2016-17

Case Study Conference Scholarship, University at Buffalo, Dept. of Biological Sciences, 2015

Andrews Fellowship, Purdue University, Dept. of Biological Sciences, 2015

PT Gilham Award, Purdue University, Dept. of Biological Sciences, 2015

Excellence in Teaching Award, University of California San Diego, Div. of Biological Sciences, 2014

Magna Cum Laude, B.S., University of California San Diego, Revelle College, 2013

Provost Honors, University of California San Diego, Revelle College, 2010-12

PUBLICATIONS

(* denotes equal contribution)

Lie, R., Guzey, S. S. (In review). Characterization of How Expert Biologists Read Primary Research Literature. Submitted to *CBE-Life Sciences Education*.

Aranda, M. L.*, **Lie, R.***, & Guzey, S. S. (2019). Productive thinking in middle school science students' design conversations in a design-based engineering challenge. International Journal of Technology and Design Education, 1-15.

Lie, R.*, Aranda, M. L.*, Guzey, S. S., & Moore, T. J. (2019). Students' Views of Design in an Engineering Design-Based Science Curricular Unit. Research in Science Education, 1-21.

Lie, R., Guzey, S. S., & Moore, T. J. (2018). Implementing Engineering in Diverse Upper Elementary and Middle School Science Classrooms: Student Learning and Attitudes. Journal of Science Education and Technology, 1-14.

Schleisman, K. B., Guzey, S. S., **Lie, R.**, Michlin, M., Desjardins, C., Shackleton, H. S., ... & Dubinsky, J. M. (2018). Learning Neuroscience with Technology: a Scaffolded, Active Learning Approach. Journal of Science Education and Technology, 1-15.

Poplawski, G. H.*, **Lie, R.***, Hunt, M., Kumamaru, H., Kawaguchi, R., Lu, P., ... & Tuszynski M.H. (2018). Adult rat myelin enhances axonal outgrowth from neural stem cells. Science Translational Medicine, 10(442), eaal2563.

Aranda, M. L.*, **Lie, R.***, Guzey, S. S., Makarsu, M., Johnston, A., & Moore, T. J. (2018). Examining Teacher Talk in an Engineering Design-Based Science Curricular Unit. Research in Science Education, 1-19.

Lie, R., Abdullah, C., He, W., & Tour, E. (2016). Perceived Challenges in Primary Literature in a Master's Class: Effects of Experience and Instruction. CBE-Life Sciences Education, 15(4), ar77.

Abdullah, C., Parris, J., **Lie, R.**, Guzdar, A., & Tour, E. (2015). Critical Analysis of Primary Literature in a Master's-Level Class: Effects on Self-Efficacy and Science-Process Skills. CBE-Life Sciences Education, 14(3), ar34.

CONFERENCE PRESENTATIONS

Guzey, S. S., Peralta, Y., Song, W., Harwell, M., Moore, T., & **Lie, R.** (2018, April). The impact of intense professional development on student STEM achievement and attitudes towards STEM. Poster presented at the annual meeting of the American Education Research Association, New York City, NY.

Lie, R., Guzey, S. S., Moore, T., & Aranda, M. (2018, April). Engineering design-based science curriculum and instruction. Paper presented at the annual meeting of the American Education Research Association, New York City, NY.

Lie, R., Aranda, M., Guzey, S. S., Akarsu, M., & Moore, T. (2018, March). Classroom discourse and student learning in an engineering design-based science unit. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Atlanta, GA.

Aranda, M., Guzey, S. S., **Lie, R.**, & Moore, T. (2018, March). Hybrid disciplinary discourses within a science and engineering unit. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Atlanta, GA.

Aranda, M., **Lie, R.**, Guzey, S. S., Akarsu, M., Johnston, A., & Moore., T., (2018, January). Examining teacher talk in an engineering design-based science curricular unit. Paper

presented at the annual meeting of the Indiana STEM Education Conference, West Lafayette, IN.

Poplawski, G.H., **Lie, R.**, Lu P., Hunt, M., Robinson, J., Kawaguchi, R., Coppola, G., Geoffroy, C., Zheng, B., & Tuszynski, M.H. (2015, October). Adult Myelin Stimulates Neurite Outgrowth From Neural Progenitor Cells. Poster presented at the annual meeting of the Society for Neuroscience, Chicago, IL.

Poplawski G.H., **Lie R.**, Lu P., Geoffroy C., Zheng B., Coppola G., Geschwind D., & Tuszynski M.H. (2014, November) Adult Myelin Stimulates Neurite Outgrowth From Neural Progenitor Cells. Poster presented at the annual meeting of the Society for Neuroscience, Washington, DC.

Abdullah, C., **Lie, R.**, Parris, J., & Tour, E. (2014, July). Student's evolving attitudes towards primary literature after taking a course that focuses on analysis of and evaluation of primary literature. Poster presented at the annual meeting of the Society for the Advancement of Biology Education Research, Twin Cities, MN.

Lie, R., Poplawski, G.H., & Tuszynski, M.H. (2012, June). Utilizing automated screening methods in order to identify regeneration-associated genes. Poster presented at the University of California, San Diego, Division of Biological Sciences, Student Research Showcase, La Jolla, CA.

MASTER'S THESIS

Lie, R. (2014). Multipotent neural progenitor cells exhibit enhanced neurite outgrowth on adult myelin: Implications for neural regeneration (Master's Thesis). Ann Arbor: Proquest/UMI. (Publication No. 1558896)