Participation in Biology Education Research Influences Students' Epistemic Development

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ABSTRACT

Knowledge construction is an essential scientific practice, and undergraduate research experiences (UREs) provide opportunities for students to engage with this scientific practice in an authentic context. While participating in UREs, students develop conceptualizations about how science gathers, evaluates, and constructs knowledge (science epistemology) that align with scientific practice. However, there have been few studies focusing on how students' science epistemologies develop during these experiences. Through the analysis of written reflections and three research papers and by leveraging methods informed by collaborative autoethnography, we construct a case study of one student, describing the development of her science epistemology and scientific agency during her time participating in a biology education URE. Through her reflections and self-analysis, the student describes her context-dependent science epistemology, and how she discovered a new role as a critic of scientific papers. These results have implications for the use of written reflections to facilitate epistemic development during UREs and the role of classroom culture in the development of scientific agency.

INTRODUCTION

As students enter professional careers, they will need to apply their understanding of science to new contexts and construct new knowledge to solve complex problems. To prepare students for such careers, policy makers have highlighted the need to steer student learning toward an understanding of how scientific knowledge is constructed and what counts as knowledge in science, also known as science epistemology (National Research Council, 2007, 2013; American Association for the Advancement of Science, 2011). To pursue the goal of developing students' science epistemologies, we must first understand epistemic development in students as they participate in authentic science experiences (Sandoval, 2012).

One example of these authentic science experiences are undergraduate research experiences (UREs), in which students engage with research practices to use data and evidence to construct new knowledge within a specific scientific field (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017). There is extensive work describing science, technology, engineering, and mathematics (STEM) student gains in understanding the process of science while participating in UREs (e.g., Thiry *et al.*, 2005, 2012; Lopatto, 2004, 2007; Hunter *et al.*, 2007), but there is little work describing what epistemic gains may result from student participation in a URE. There are a variety of UREs, and the quality of the educational experience for the student varies based on the costs, research topic, mentoring, and student expectations of the URE (NASEM, 2017). As such, the types of UREs students participate in likely have an impact on their epistemic gains. UREs that focus on biology education (BioEd UREs) provide a

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unique opportunity for researchers to study epistemic development in undergraduate researchers, because these experiences allow undergraduate researchers to study how others engage with biology knowledge through the use of authentic research practices. We hypothesize that as undergraduate researchers analyze how other students construct knowledge about biology, there will be opportunities for these undergraduate researchers to reflect upon their own knowledge construction. Through these reflections, undergraduate researchers in BioEd UREs will gain a deeper understanding of biology epistemology.

The goal of this paper is to describe one student's (M.W.) epistemic development through her participation in a BioEd URE and how these changes manifested in her written course work. Because this paper describes a study within a study, we will specifically refer to the URE in which M.W. was an undergraduate researcher as the "BioEd URE," and the case study in which we investigate M.W.'s epistemic development as the "case study." M.W. is a coauthor along with her URE mentors, D.L. and D.D.-R. All authors consented to using their initials throughout the article rather than pseudonyms. We begin with an overview of recent research investigating science epistemology, highlighting key outcomes as well as the research approaches, because this work 1) informed the development of the URE project to which M.W. contributed and 2) provides a framework to explore M.W.'s epistemic development as she participated in the URE. Next, we provide a description of the URE project to give context to M.W.'s experience. Then, we present a discussion of M.W.'s experience and evolving science epistemology, taking an approach informed by collaborative autoethnography in which M.W. provides a response to the analysis conducted by D.L. and D.D.-R. Finally, we conclude with a discussion of the implications of this work for future research on science epistemology and approaches to support students' developing science epistemologies within formal learning environments, such as the classroom and research lab.

BACKGROUND LITERATURE

Supporting the Development of Students' Science Epistemologies

Epistemology, or the beliefs and approaches around the acquisition, justification, and generation of knowledge, is a core aim of science inquiry (Longino, 2002). Science epistemology establishes the standards for evaluating, justifying, and generating knowledge within science. Students may gain a tacit understanding of epistemology while engaging with the processes of scientific knowledge generation; however, this understanding may be incomplete or inaccurate (Linn *et al.*, 2015). To ensure that students understand how science generates knowledge, it is important to discuss epistemology while students engage with the process of evaluating, generating, and constructing scientific knowledge (Sandoval, 2005).

Students are exposed to authentic scientific processes during UREs. Many studies have reported that participation in UREs increases student understanding of the processes of science through exposure to authentic scientific practice (Seymour *et al.*, 2004; Thiry *et al.*, 2005, 2012; Lopatto, 2007; Linn *et al.*, 2015). However, it is unclear whether these experiences help students understand the epistemic foundations of science (Hunter *et al.*, 2007). Studies investigating the impact of UREs on the development of student epistemology present mixed results. In their review of 53 studies on UREs, Sadler *et al.* (2010) found that, while some studies reported that students developed an understanding of uncertainty in science and the importance of scientific discourse, other studies reported little or no change in students' beliefs about how science constructs knowledge.

Practitioners across scientific disciplines from primary school through higher education have implemented classroom interventions to support the development of students' science epistemologies. The effectiveness of these interventions has been measured quantitatively with Likert-style surveys and qualitatively with open-ended survey items and interviews. For example, in one intervention, undergraduate biology students engaged in analysis of published literature wherein they considered, read, elucidated hypotheses, analyzed and interpreted results, and thought of the next experiment in a process termed C.R.E.A.T.E. (Hoskins *et al.*, 2011). In a pre–post survey assessment, students rated their own understanding about the nature of scientific knowledge significantly higher in the posttest compared with the pretest (Hoskins *et al.*, 2011). In another intervention, pre-service elementary school teachers in a geology class participated in a science as storytelling program as a way to teach introductory science students about scientific knowledge (Bickmore *et al.*, 2009). In this program, students treated science as a form of storytelling with rules that align with scientific practice. Students' conceptions of science and attitudes toward science were evaluated through surveys that were supplemented by open-ended responses. These pre-service teachers exhibited a better understanding of the creative and tentative aspects of science epistemology and had better attitudes toward science at the conclusion of the course compared with the beginning (Bickmore *et al.*, 2009). These studies demonstrate the effectiveness of interventions for improving student understanding of science epistemology, but the assessments only report the outcomes of the interventions, leaving us to ask the questions of "how" and "why" students' epistemic understanding changed.

Several qualitative studies also point to the importance of explicitly discussing epistemology in the classroom for epistemic development. In their study of 8- to 10-year-old children, Ryu and Sandoval (2012) found that students' epistemologies developed through collective argument, whereby students negotiated epistemic standards for acceptable justifications and appropriated these standards into their argument construction. These results parallel the critical contextual empiricism framework, which describes scientific knowledge construction as a social process whereby standards for knowledge validity are negotiated in a public forum (Longino, 2002). Work by McDonald (2010) points to the importance of explicit instruction in nature of science (NoS) for supporting the development of student understanding of epistemology. During the intervention, pre-service teachers discussed and reflected upon epistemic probes, reflective prompts that directed their attention toward relevant NoS aspects of the lesson (McDonald, 2010). These results suggest that metacognitive tasks such as reflection play an important role in supporting the development of student epistemologies.

Studying Biology Epistemology

The emerging epistemology research in biology education has focused on assessment of the effectiveness of teaching interventions using surveys. Student responses on surveys following the implementation of an active-learning intervention in a large classroom showed that students saw knowledge in biology as a collection of facts transferred from professor to student (Walker *et al.*, 2008). Supporting this finding are survey results that indicated student perceptions of science epistemology became more novice-like (e.g., memorizing is a primary way of knowing) during an introductory biology class (Semsar *et al.*, 2011). However, not all assessment of science epistemology resulted in a shift toward novice-like views. Survey results from community college students, first-year students, and advanced students in 4-year colleges exhibited enhanced understanding of science epistemology after exposure to pedagogy involving analysis of scientific literature (Hoskins *et al.*, 2011; Gottesman and Hoskins, 2013; Kenyon *et al.*, 2016). While these survey results present a generalized view of biology students' epistemologies, qualitative studies present a nuanced view of epistemology that brings context into play.

Surveys inherently assume that student epistemologies exist as coherent cognitive structures that can be accessed through questioning (Hofer, 2004). However, researchers have found that student epistemologies exist instead as a disparate set of resources (Elby and Hammer, 2001; Hammer *et al.*, 2005) that is often tacit (Hofer, 2004). Therefore, surveys, which provide limited opportunity for elaboration, may not capture the nuance and context surrounding students' perceptions of science epistemology (Watkins and Elby, 2013). Indeed, a qualitative study by Watkins and Elby (2013) focusing on one student's interview about her views on mathematics in biology found that she held diverse, contextual views about the role of equations in understanding biology.

Qualitative studies in K–12 have made important contributions to our understanding of biology epistemology. For example, researchers who interviewed students between nine and 15 years of age about genetics found that these children's understanding of genetics consisted of discrete, disconnected units rather than coherent frameworks organized around biological theory (Venville *et al.*, 2005). This analysis was made possible by the authors' attention to both the ontological (individual concepts) and epistemological (interconnectedness of the concepts) aspects of genetics understanding (Venville *et al.*, 2005). The ways in which students unify discrete biological concepts into a coherent framework is also influenced by their learning goals. By studying discourse within a high school classroom, researchers found that students applied different biology concepts to their arguments, in some cases applying these concepts to specifically complete the task at hand (doing the lesson), while in others to gain a deeper understanding of the topic (doing science) (Jimenez-Aleixandre *et al.*, 1999). These differences in reasoning highlight the importance of students' goals within particular contexts and their effects on how students apply biological concepts to their epistemic thinking.

Theoretical Framework

Epistemology has been conceptualized by researchers in many different ways: as a set of developmental stages (Perry, 1990; Kuhn, 1991; Baxter Magolda, 1992; King and Kitchener, 1994), a coherent set of beliefs (Hofer and Pintrich, 1997; Schommer-Aikins *et al.*, 2005) such as the NoS (Lederman, 2007), and as a set of cognitive practices activated in specific contexts (Louca *et al.*, 2004; Chinn *et al.*, 2014). We chose to conceptualize epistemology as a set of contextual cognitive and metacognitive practices using the epistemic thinking framework (Barzilai and Zohar, 2014), given the findings that student epistemologies are context dependent.

The epistemic thinking framework separates epistemology into two aspects: epistemic cognition (thinking about information) and epistemic metacognition (thinking about knowing). The cognitive aspect is informed by the AIR model for epistemic cognition (Chinn *et al.*, 2014), which separates epistemology into epistemic aims, ideals, and reliable processes to ensure these ideals have been met (Chinn *et al.*, 2014). "Aims" refer to the objective of the cognitive task, such as determining whether information is accurate (Chinn *et al.*, 2014). "Ideals" refer to criteria that must be met for an explanation to be accepted as knowledge, for example, ensuring the methods used were appropriate for answering the research question (Chinn *et al.*, 2014). "Reliable processes" are cognitive practices that are used to achieve epistemic ends (i.e., knowledge or understanding), such as considering multiple perspectives before making a decision (Chinn *et al.*, 2014). Reliable processes have also been referred to as "epistemic practices" (Kelly, 2008). Taken together, the aims, ideals, and reliable processes of epistemic cognition are the ways that students gather, justify, evaluate, and construct knowledge in a particular discipline like biology.

Epistemic metacognition is an individual's awareness of the knowledge, skills, and experiences related to that individual's thinking and learning. Much like metacognition, epistemic metacognition is divided into three subcategories: epistemic metacognitive knowledge (EMK), individuals' knowledge about how they and others conceptualize knowledge; epistemic metacognitive skills (EMS), the different ways people evaluate, monitor, or plan how to reach an epistemic aims/ends; and epistemic metacognitive experiences (EME), what people are aware of or feel as they are working toward an epistemic aim (Barzilai and Zohar, 2014). Just as metacognition has been shown to affect the way biology students approach learning (Stanton *et al.*, 2019), we hypothesize that epistemic metacognition will affect the way that students approach scientific knowledge. Using this theoretical framework, we aim to address the following research questions: 1) In what ways does one student's (M.W.) participation in a biology education research URE affect her epistemic development? 2) How, if at all, are these changes manifested in her written course work?

METHODS

The goal of our study was to explore M.W.'s epistemic development within the context of a BioEd URE and her biology course work. We used a case study approach combined with M.W.'s autoethnographic descriptions, which allowed us to consider M.W.'s epistemology within the context of the BioEd URE and her biology course work. Through this combination of methods, we present a description of M.W.'s epistemic development, incorporating our analysis of her course work and experiences in the BioEd URE with her own perspective of the experiences.

Study Context: The BioEd URE

M.W. joined a BioEd URE investigating undergraduate biology students' thoughts about scientific knowledge in the Spring of 2018. In this experience, M.W. was an undergraduate researcher, D.L. was a graduate researcher, and D.D.-R. was the principal investigator. The aim of the BioED URE was to answer the research question: How do students participating in a scientific argumentation–focused introductory biology course construct arguments in a literature review compared with students participating in a lecture-based introductory biology course? As part of the BioEd URE, we collected student research papers from two sections of an introductory biology course and analyzed the papers to identify students' arguments and reasoning to explore students' science epistemology. M.W. took this introductory biology course and completed these research paper assignments in the Fall of 2016 and Spring of 2017.

In order for M.W. to effectively analyze the research papers for science epistemology, she needed to be well versed in epistemic theory. As such, D.D.-R. and D.L. included readings, weekly discussion, and written reflections on epistemic theory in M.W.'s BioEd URE. In particular, we assigned M.W. readings on the AIR model for epistemic cognition (Chinn *et al.*, 2014) and the epistemic thinking framework (Barzilai and Zohar, 2014). Once she was familiar with these theoretical frameworks, M.W. began analyzing participants' scientific arguments within their course research papers. This analysis included the construction of a codebook through both emergent and a priori coding. Throughout this process, our research team held weekly meetings to discuss general research practices and engage M.W. in reflection on how the epistemic theories related to her own thoughts about scientific knowledge in the context of her experiences. The integration of reflection was informed by the work of Kalman (2007) and was included to support M.W.'s thinking about the epistemic theories we discussed. Over the course of one semester, we asked M.W. to write nine reflections. The specific prompts grew out of the discussions about science epistemology during our lab meetings. In her second reflection, M.W. writes:

> When I started this project, the whole idea of epistemic cognition seemed very far-fetched and abstract. I didn't really understand how it was possible to study such internal thoughts of other people by simply reading their papers. This is still a challenge for me now because I find it hard to put myself in others' shoes and try to understand their intentions when writing these papers. How can we really find out the truth about how "people know what they know?" This question still stumps me.
>
> When [D.D.-R.] asked me about how I was reacting to trying to understand our research, I told him it was making me second guess my past writing. For example, do I really blindly trust all scientific sources on the internet simply because they are published? And even if and when I do this, does it actually affect my writing on a deeper level?
>
> I decided to skim through my own biology lab [research] papers from last year to see how my own writing compares to the papers that we have been reading and coding thus far. One thing that I noticed about my papers was that I explained a lot of the background information in my own words and used a citation at the end of the paragraph that supported my explanation of the scientific mechanisms. For example, I wrote down the process of the cell cycle and explained it in my own words, then searched for a source that re-iterated what I said in my paper.

These insightful reflections on her own epistemology led us to reorient our research lens onto M.W.'s epistemic development. Consequently, her written reflections became an important part of the data set for the present study.

In addition to carefully designing training around epistemic theories for M.W., we (D.D.-R. and D.L.) also strove to create a community where M.W. felt comfortable challenging our interpretations, which was important to maintaining research quality for the original BioEd URE study. To create this community, we mirrored the four norms of an ideal scientific community outlined by Longino (2002) in her description of critical contextual empiricism:

1. Providing venues for criticism gives researchers a place to critique ideas so that only the most well-supported ideas are accepted as knowledge.
2. Uptaking criticism allows researchers to evaluate ideas based on criticism and make changes to these ideas when appropriate.
3. Recognizing public standards and using these standards to evaluate ideas helps a community maintain the quality of its knowledge.
4. Maintaining tempered intellectual equality ensures that voices within the community are heard, while ensuring that the influence of the voices are tempered by each individual's expertise.

We provided a *venue for criticism* of ideas in the form of research meetings, where we modeled the *uptake of criticism* and how to make appropriate changes to data interpretations in response to that criticism. During these research meetings, we also discussed the *public standards* of research quality in the context of both quantitative biology research and qualitative biology education research. We maintained *tempered intellectual equality* by considering all ideas presented and explaining our reasoning and theoretical justification when necessary.

All of the aspects described, including the specific training on epistemic theories and the community mirroring Longino's (2002) four norms, are part of the context under which we (all authors) seek to understand M.W.'s epistemic development. The other part of the context that undergirds M.W.'s BioEd URE experiences is her progression through her biology course work, which is briefly mentioned by M.W. herself in the quote presented earlier. We will provide more details about these courses and the research papers she writes in later sections.

Research Quality Framework

The quality framework (Q3) developed in engineering education (Walther *et al.*, 2013; Sochacka *et al.*, 2018) provided the language to describe and guide our thinking on key research quality issues throughout our data collection and analysis for our case study. Q3 separates interpretive research quality issues into six constructs: theoretical, procedural, communicative, pragmatic, and ethical validity, and process reliability (Table 1).

Ethical validation was an especially important aspect of this study because of the inclusion of M.W. as a researcher/participant. The guiding questions presented by Sochacka *et al.* (2018) shaped our thinking on how to equitably engage M.W. as a researcher, ensure that our analysis did justice to her lived experience, and temper our own biases so that they did not unduly

TABLE 1. The Q3 research quality framework

Quality construct	Construct definition
Theoretical validation	The theory generated from the analysis is representative of the social reality under study.
Procedural validation	The research design ensures that knowledge built from the project aligns with the social reality being studied.
Communicative validation	The ways in which data and analyses are effectively communicated between members of the research group, discipline, and beyond.
Pragmatic validation	The theoretical framework(s) used in this study are compatible with the social reality under investigation.
Ethical validation	The ways in which the researchers consider the underlying human elements that govern the influences between researchers and participants.
Process reliability	The processes used in this project are dependable and consistent.

influence M.W. or the interpretations we present. We will use the language described in Table 1 to discuss other affordances and challenges to the aspects of research quality throughout this paper.

Participant as Researcher

Given the nature of this study and to ensure that M.W.'s voice was appropriately represented, the BioEd URE research team (D.D.-R., D.L., and M.W.) contacted their local Institutional Review Board (IRB) for guidance. Following an IRB-approved procedure, M.W. provided written consent to be identified as a researcher participant (IRB approval no. 2016-244). As an identified researcher participant, M.W. contributes her insights throughout this paper, displayed in italics. To address the quality aspects of communicative and theoretical validation, and to ensure that her voice is preserved, we elected to keep her commentary separate rather than incorporating her comments into the narrative of the paper. As such, "we" represents the combined voices of D.L., D.D.-R., C.K., and C.F. This way, readers can differentiate between the researchers' analyses and can experience M.W.'s self-analysis in her own words. As a part of ethical validity, each author is referred to by initials in this paper to maintain intellectual equality among the researchers. Each researcher's involvement in the project is described in Table 2.

Participant Description

At the time of the study, I was a sophomore microbiology major and sociology minor. I was also an honors college student, taking honors biology and chemistry courses at Clemson University. Due to my microbiology major, I took very specific courses on microbes, but also took broader biology courses such as cell biology and immunology. My sociology minor allowed me to take classes about social topics like deviance, drug abuse, and the family. I was not interested in sociology until I came to Clemson and took an introductory sociology class to fulfill a requirement, which inspired me to take more classes. This interest in sociology broadened my interests to include social science in addition to my traditional "hard" science classes (i.e. biology and chemistry).

I previously participated in undergraduate research my freshman year. I worked in a life sciences lab and learned basic skills, such as how to grow cells in culture and count cells accurately, in order to design and implement my own experiment. The experiment I worked on consisted of investigating the effects of fruit and vegetable extracts on cancerous cells. Additionally, I was a biology peer mentor for the first semester of my sophomore year, which introduced me to the Engineering and Science Education department. I then joined this project [BioEd URE] and participated in another form of undergraduate research. In some ways, I am a typical microbiology major: I am on the pre-med track and interested in the public health side of microbiology. However, my interest in sociology makes me different from others in my major because these subjects don't always cross paths past the introductory sociology requirement. Also, I worked with students as an Orientation Ambassador and a biology peer mentor, so I am interested in learning more about the education aspect of biology and learning more about how students like myself learn about biology.

Participant Curricula during the BioEd URE

In addition to the general participant description M.W. provided, we further contextualize her experience by describing some of the course work she completed concurrently with the BioEd URE. M.W. participated in the BioED URE for one semester and was not able to continue the project because of curricular and time constraints. During the BioEd URE semester, M.W. was enrolled in 11 credits of science courses, a 3-credit psychology course, a 3-credit science writing course, and the 2-credit BioEd URE, for a total of 19 credits.

The science writing course likely affected M.W.'s writing skills, so we present some details about this course, beginning with the course description.

> [This Science Writing Course] introduces students to the study and practice of professional scientific communication through the analysis of and writing of the major genres in the discipline. It focuses on the principles, strategies, and styles of

TABLE 2. Description of researcher roles on project

	Description	Researchers
Coders	Analyzed papers and reflections. Wrote and revised the paper and reflection analysis memos. Constructed themes.	D.L. and D.D.-R.
Critical peer review	Read the paper and/or reflection analysis memos. Critiqued the analysis and conclusions.	C.F. and C.K.
Autoethnographic review	Critiqued analysis and conclusions and provided thick autoethnographic descriptions of classroom and BioEd URE experiences	M.W.

scientific argumentation and audience adaptation in written media. It is designed for students in the sciences.

As part of the course, M.W. completed a literature review paper. We present the rubric for the literature review assignment in Appendix C in the Supplemental Material. In particular, criteria 4 and 7, emphasizing synthesis of research articles and constructing your own conclusions could have been influential in M.W.'s writing for the literature review assignment.

Research Design

The contextual nature of epistemic cognition (Hammer *et al.*, 2005; Watkins and Elby, 2013; Chinn *et al.*, 2014) compelled us to study M.W.'s science epistemology in context. Given our focus on context, we chose to construct a case study that "investigates a contemporary phenomenon (the 'case') in depth and within its real world context, especially when the boundaries between phenomenon and context may not be clearly evident" (Yin, 2018, p. 15). Aligning our study with a case study approach also provided a means to ensure procedural validity through the general methodology provided by this approach. A case study approach is a flexible methodology that can accommodate a variety of data sources (Baxter and Jack, 2008), which allows us to leverage research papers and written reflections generated by M.W. to produce a thick description of her case. These descriptions allow researchers to answer "how" and "why" questions about phenomena over which they have little or no control (Yin, 2018), such as how or why student epistemologies developed in response to an intervention. In fact, case study methodology has been used by researchers to study science identity (Tan and Barton, 2008a,b) and science epistemology (Watkins and Elby, 2013).

Despite the benefits of case studies, some researchers express concerns around the scope, rigor, and generalizability of the results. Case studies generate a vast pool of data, which may tempt researchers to answer questions that are too broad. To address this constraint, it is important that case studies are bound by time, place, or context (Stake, 2006; Creswell, 2012; Yin, 2018) and that the researchers define the unit of analysis to focus on salient parts of the data (Baxter and Jack, 2008). This case study is bound by time and context. The analysis is bounded by time in the sense that the analysis focused on the time M.W. spent as a researcher in the BioEd URE. To provide more context about the development of her thinking about scientific knowledge, we also analyzed assignments she completed 1 year before the BioEd URE (research papers she had previously written), and one semester after the BioEd URE (a reflection she wrote about the BioEd URE after the experience had concluded). The unit of analysis is M.W. herself. Finally, case studies "are generalizable to theoretical propositions and not to populations or universes" (Yin, 2018, p. 20). In other words, our case study results can be used to expand epistemic theory, but not to extrapolate the behavior of students outside our case. To consider the case in light of other students, Stake (2000) suggests that researchers "describe the cases in sufficient descriptive narrative so that readers can vicariously experience these happenings and draw conclusions (which may differ from those of the researchers)" (p. 439). To ensure the transferability of our case study to other contexts, we provide descriptions that faithfully represent M.W.'s lived experience. To ensure the authentic representation of M.W.'s lived experience, we combined our case study approach with elements of an autoethnography.

Autoethnography is a research approach that combines elements from autobiography and ethnography, allowing researchers to explore a cultural phenomenon through their own personal experiences (Ellis *et al.*, 2011; Hughes *et al.*, 2012). Autobiography describes events that led to significant change in the author's life, and ethnography explains how engagement with a culture made these moments of change possible (Ellis *et al.*, 2011). Within autoethnography, it is important that the personal experiences, thoughts, and actions are documented and made visible for analysis. Additionally, it is important that the researcher moves from experience-near (their own experiences) to experience-far (larger cultural relevance) throughout data collection and analysis. There are multiple approaches that can be used to support this process. For this work, we used M.W.'s responses to the URE reflection prompts and our research team discussions. These data were analyzed by experts within the theoretical space. The reflection prompts and research team discussions supported M.W.'s documentation of her own personal experiences, thoughts, and actions, making them visible for analysis and providing her with the space to consider her own context. D.L. and D.D.-R. developed the reflection prompts and participated in the research team discussions, providing a means to support the process of going from experience-near to experience-far. Specifically, they were able to ask additional questions of M.W., allowing further exploration of specific experiences, and they were also able to guide her developing understanding of epistemic theories, allowing M.W. to participate in the process of analyzing her own experience and reflect specifically on her developing epistemic cognition. Much of the initial data analysis was conducted by D.D.-R. and D.L. because of their expertise and understanding of epistemic cognition; however, M.W. was actively engaged in data analysis through extensive member-checking, reviewing, and providing feedback on D.D.-R. and D.L.'s analysis. This process ensured that the outcomes of this work provide an authentic representation of M.W.'s experience and go beyond M.W.'s own experience to make larger statements on the general cultural phenomenon of developing students' epistemic cognition. It is through the combination of our case study analysis perspective and M.W.'s autoethnographic lens that we seek to explore how M.W.'s engagement in this biology education URE affected her science epistemology.

Qualitative Data Selection

This study grew from discussions with M.W. during her experience with the BioEd URE. Consequently, the data we analyzed were not so much collected, but selected from assignments that M.W. completed during her time as a researcher in the BioEd URE. The data for this study consisted of three papers M.W. wrote for course work and reflections she wrote during the BioEd URE (Figure 1). M.W. wrote the first two papers for an introductory biology class during her first year (academic year 2016–2017): one in the Fall semester and the other in the Spring semester. Both papers were literature reviews on a scientific issue related to biology, referencing peer-reviewed journal articles. The instructions for the assignments were identical, except that students were asked to include an ethics section in the paper in the Spring semester. The rubric for the biology literature

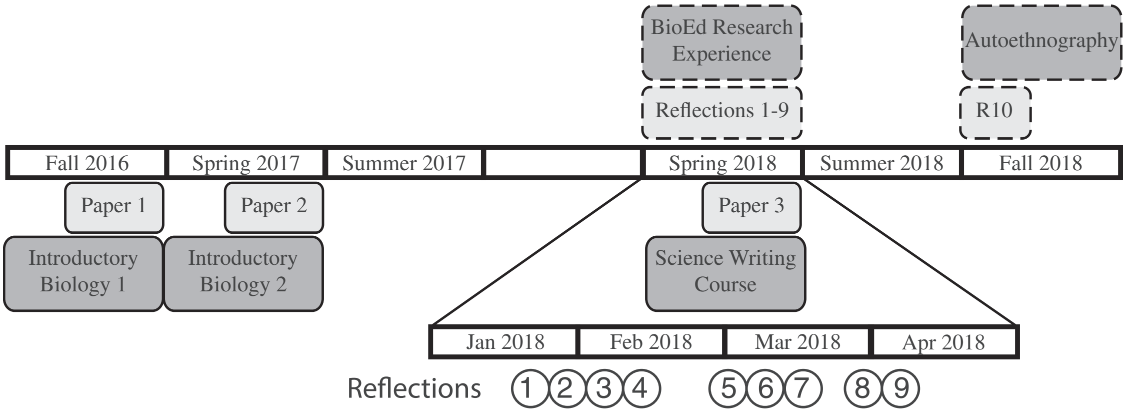

FIGURE 1. Timeline showing the sequence of M.W.'s courses, the three course research papers, her BioEd URE, the autoethnographic study, and the 10 written reflections. M.W. wrote her first two research papers in an introductory biology class in Fall and Spring semesters of 2016-17. She wrote her third paper in a science writing course in Spring 2018 while she was concurrently participating in the BioEd URE. The autoethnographic study, looking back on her experiences in her science courses and during the BioEd URE, occurred during the Fall.

review papers can be found in Appendix B in the Supplemental Material. We selected M.W.'s two introductory biology papers because they were part of the data set for the BioEd URE. As we describe in the *Results*, M.W. had begun a self-analysis of her science epistemology of her own accord, starting with these two papers. It was this self-analysis that inspired the development of the present case study. M.W. wrote the third paper for a science writing course in her sophomore year. This assignment was also a literature review on a scientific subject, and M.W. chose to write the paper on a subject related to biology. We included this paper in the case study, because it provided an opportunity to explore M.W.'s epistemology in a similar context: through her scientific writing in a literature review.

M.W. wrote a total of 10 reflections, nine written during the URE and the 10th during the Fall semester of her junior year (Figure 1 and Table 4). The nine reflection prompts during the URE were all derived from discussions we had with M.W. during research meetings. The 10th reflection asked M.W. to reflect on her epistemic growth by asking her whether or not she believed she could write a paper of the same quality as her third literature review paper as a first-year student, and if there was anything she would change about the papers she wrote for her introductory biology class. The topic of each of the reflections is stated in Appendix A in the Supplemental Material. No guidance was given on format or length, but M.W. generally kept reflections to one typed page, single-spaced.

Qualitative Data Analysis

In the present case study, we analyzed M.W.'s three research papers and the 10 reflections she wrote in connection to the BioEd URE (Figure 2). M.W.'s research papers were analyzed for empirical evidence of changes in her science epistemology. Her reflections were analyzed to determine what aspects of her education, which included the BioEd URE, were influential in the development of her science epistemology. Analyses of M.W.'s research papers and reflections were summarized in two analysis memos: one for her research papers and one for her reflections (Figure 2). All data were consensus coded by D.L. and D.D.-R. by first coding the data separately, then meeting to discuss code definitions and meanings. They reconciled disagreements through discussion, applying codes that aligned best with the data.

Analysis of the three research papers focused on the claims M.W. presented, the data she used to support the claims, and

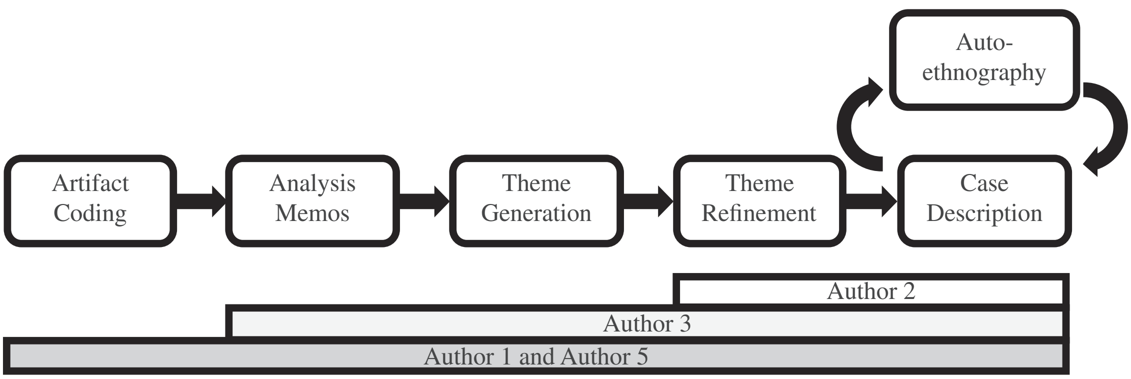

FIGURE 2. Summary of analysis. M.W. (Author 2) helped to refine the themes and case descriptions by leveraging her autoethnographic descriptions. C.K. (Author 4) provided a perspective on the analysis that was further removed from the data. D.L. (Author 1) and D.D.-R. (Author 5) were involved throughout the analysis process.

the warrants that explained the connections between her claims and her data, as described by the Toulmin argument pattern (TAP; Toulmin, 2003). We view argument as an epistemic practice, a means by which knowledge is justified (Kuhn, 1991; Kelly, 2008). As such, the kinds of data and warrants M.W. employed to support her claims give valuable insight into the ways she thought about knowledge in science. Analysis of M.W.'s research papers began with a read-through to get a feel for the data, followed by coding of the reference section. The coding pair identified arguments using TAP, noting connections between argument structures and/or identifying an overarching argument, if present. These identified arguments were coded, taking into account the kinds of sources M.W. used as data, the ways in which she described the data from the sources, and how she used the data to support her hypothesis. For example, where M.W. restated the conclusions from a particular source, we coded these excerpts as "reporting." In contrast, where M.W. used data from multiple sources to construct an assertion not found in those sources, we labeled these excerpts as "synthesis." Once coding was complete, an analysis memo was written to integrate meaning-making from the paper analysis. More details about the analysis memos are provided at the end of this section.

Analysis of M.W.'s reflections focused on her epistemic thinking. Like the research paper, analysis of these data began with a read-through to familiarize ourselves with the data. We then analyzed the data by identifying excerpts related to the epistemic thinking framework (Barzilai and Zohar, 2014). Leveraging the epistemic thinking framework in our coding helped us to identify excerpts that demonstrated M.W.'s EMK about science, and the EMS she used to develop this knowledge. D.L. and D.D.-R. initially planned to code the reflections similarly to the paper analysis, but the first attempts at coding made it evident that deconstruction of the data into constituent parts left many of the details of M.W.'s epistemic development undescribed. To address this challenge to theoretical validity, D.L. and D.D.-R. shifted their approach to one informed by narrative analysis, which allowed them to consider the reflections as a coherent whole (Polkinghorne, 1995). The identified excerpts were grouped in chronological order, and a narrative was written in the form of an analysis memo, using the excerpts from M.W.'s reflections as a framework.

The analysis of the research papers was also summarized in separate analysis memos that were coconstructed by the coders. Both analysis memos included a descriptive representation of the data followed by a summary of salient interpretations emerging from the analysis (Lee *et al.*, 2019). The analysis memos were written by either D.L. or D.D.-R. Once the analysis memos were drafted, D.L. and D.D.-R. reviewed and revised them until consensus was reached. To enhance theoretical validity, a third researcher, C.K., who did not code the data, critiqued the data and analysis memos written by the coding team by looking for data that contrasted with conclusions drawn by D.L. and D.D.-R. C.K., D.L., and D.D.-R. discussed any disagreements until they reached consensus; then the analysis memos were finalized.

Theme and Narrative Construction

Once the two the analysis memos were finalized, D.L. and D.D.-R. read through them to integrate the paper analysis with the reflection analysis. They then individually generated a list of themes and met to discuss each theme to decide if the themes were salient or should be combined. Once they reached consensus, D.L. and D.D.-R. wrote descriptions of each tentative theme. The themes served as the principal components that facilitated the retelling of how M.W.'s science epistemology developed during her time spent participating in the BioEd URE. At this point, C.K. critiqued the theme descriptions and the narrative, attempting once again to disconfirm each theme. C.K., D.L., and D.D.-R. discussed any disagreements on the theme descriptions and narrative until they reached consensus, then revised the narrative as necessary. Once finished, the theme descriptions and narrative were presented to M.W., who refined the narrative through her autoethnographic lens. M.W. wrote responses to each theme, highlighting points of agreement and disagreement, drawing from her own experience to provide evidence for her claims. The research team (including M.W.) then met to resolve any disagreements and revise the narrative (Figure 2).

RESULTS

Through our analysis of M.W.'s papers and reflections, we tell the story of M.W.'s developing science epistemology, which resulted in her development of agency toward constructing scientific knowledge. The diversity of artifacts that we collected allowed us to assess M.W.'s epistemic practices. The research papers we collected illustrate M.W.'s use of epistemic practices in the context of her classroom experiences (Table 3). It is clear from her research papers that M.W. shifted from listing facts from instructors and peer-reviewed sources to building reasoned arguments of her own making between papers she wrote before and during the research experience.

From the analysis of her research papers, it is not clear why M.W. shifted her approach from reporting information to knowledge construction. However, M.W. reveals the reasons for the changes in her biology epistemology through her written reflections. Furthermore, her self-analysis of the data we collected filled many of the gaps left from our analysis. For this reason, we focus our efforts in this paper on the reflections M.W. wrote during the BioEd URE. In the following sections, we tell the story of M.W.'s development of science epistemology through the reflections she wrote during the BioEd URE. We support this narrative with selections from M.W.'s responses to our analysis, presented in *italicized text*. Through the chronological analysis of M.W.'s reflections, we found that her epistemic development occurred through three distinct steps. First, M.W. realized that *her thoughts about knowledge differed between contexts*. The realization that her epistemology was situated and differed between contexts allowed her to reflect on her *perceptions about her role as someone who could challenge published claims* in the context of the BioEd URE. M.W.'s reflections about her ability to challenge published claims influenced her *development of agency toward scientific knowledge production*. We describe each component of the narrative in greater detail in the following sections.

M.W.'s Thoughts about Knowledge Differ between Contexts

Previous work has found that individuals' thoughts about knowledge is contextual (Louca *et al.*, 2004; Chinn *et al.*, 2014), so we begin our description of M.W.'s epistemic practices with a discussion about the contexts in which she places her

TABLE 3. Research paper analysis summary

Paper	Paper context	Primary epistemic practice	Representative quote
1	Introductory Biology class, Fall of freshman year	Reporting information; no conclusions are made; facts are presented without further explanation.	"Palbociclib is a CDK4/CDK6 inhibitor that as of February 2015, has been approved by the Food and Drug Administration (FDA) toward treating breast cancer. This inhibitor works by targeting and stopping the production of CDK4/6 in cells. This inhibitor dephosphorylates the protein pRb along with arresting the G1 phase of the cell cycle."
2	Introductory Biology class, Spring of freshman year	Simple arguments, M.W. attributes her conclusions to her sources.	"Genetically diverse crops differ in that the population is able to resist extreme changes in environmental conditions because some are more resistant than others to changes in environmental factors. The decrease in biodiversity of livestock feed crops is dangerous because it increases the likelihood that the crops will undergo massive crop failure, leading to unprecedented changes in the global food supply (Di Falco, 2004)."
3	Science Writing class, Spring of sophomore year	Complex arguments, M.W. synthesizes information from multiple sources to construct her own conclusions.	"The current method of treatment includes three therapies that target the bacteria themselves: proton pump inhibitors, amoxicillin, and clarithromycin (Molina-Infante and Gisbert, 2014). However, the efficiency of these antibiotics is on the decline, with studies showing a decrease from 81.3% to 77.5% antibiotic effectiveness (Chung *et al.*, 2011). Some of the main factors found to contribute to this decrease are antibiotic resistance, drug compliance, and degradation of the antibiotics by the acidic nature of the stomach (Chung *et al.*, 2011). Therefore, the future for treating H. pylori infections lies in finding more effective antibiotics as well as alternative treatments besides antibiotics."

epistemology. Through her first two reflections, M.W. describes three contexts in which she interacted with knowledge from her own perspective: during an undergraduate science class, while thinking about sociocultural issues, and while citing scientific papers. Upon reflecting on these contexts, M.W. explains how she views and interacts with knowledge within these contexts. At the beginning of the BioEd URE, M.W. makes a clear delineation between her thinking in science class and with sociocultural issues such as making decisions about universal healthcare. Her first written reflection reveals diverging ideas about how she determines what is correct in classroom and sociocultural contexts.

> My aim or goal in [STEM] class is to get a good grade so that I can get into a top graduate school program. I determine what is right in class by what my professor says. If he teaches a topic a certain way, I assume that he is right because he is the one that will end up grading my papers.
>
> […] My aim when evaluating our healthcare system is to learn the truth so that I can make an educated decision on whether I support or do not support universal health care. I want to make an educated decision, rather than just going along with what my friends or family believes.—Reflection 1

These excerpts reveal M.W.'s classroom aim of "getting a good grade" in a STEM class context, and her sociocultural aim to "learn the truth" in the context of making decisions about healthcare policy. She describes a difference in decision making between the two contexts: she defers to the instructor in STEM class but makes her own educated decision when talking about healthcare policy.

In her second reflection, M.W. analyzes her own research papers (Table 3) and reflects on her thinking. We did not ask M.W. to analyze her own research papers as part of the reflection; she decided to do this on her own. The following excerpt is a part of this self-analysis.

> I fell into the routine of almost paraphrasing what the articles said, rather than interpreting them myself. I think that I do this because I trust the publications, and since I didn't do the trials or research on my own, I don't feel like I am in a position to challenge their claims.—Reflection 2

Through her self-analysis, M.W. finds that she does not feel like she is "in a position to challenge" claims made by researchers, because she "didn't do the trials or research on my own." Her perception that she cannot challenge the claims made in publications occurs within a third context, where M.W. feels she is only able to question claims if she was involved in data collection or analysis.

M.W.'s Perception of Her Own Place in Challenging Research Claims Changed during the BioEd URE

During the BioEd URE, we provided M.W. with activities explicitly designed to increase her willingness to challenge scientific claims. We contend that these activities influenced M.W.'s willingness to challenge claims made by scientists. For example, 1 week after we assigned Reflection 2, we discussed the issue of

TABLE 4. BioEd URE reflection questions

Reflection date	Reflection question	Justification
January 23	Reflect on the epistemic aims, ideals, and reliable processes in the context of your classes and in the context of a real-world problem.	This reflection was assigned to help M.W. familiarize herself with the components of the AIR model for epistemic cognition (Chinn *et al.*, 2014).
January 30	What are you struggling to understand in this research project? How does one know what information to trust or not trust?	In her initial reads through the data, M.W. found it difficult to interpret students' papers. This reflection was assigned to help her think about what counts as trustworthy information.
February 11	Find an article using Web of Science/ERIC or another database. Summarize and critique the paper.	This reflection was assigned to help M.W. find peer-reviewed articles using a literature database. Summarizing and critiquing the paper was an exercise to help M.W. develop confidence in critiquing published literature. We let M.W. choose her own paper so that she could choose a topic that was most interesting to her. It was important for M.W. to critique literature so that she could find strong articles that were pertinent to the BioEd URE.
February 14	Reflect on how you came up with "fake chemistry" to find a correct answer on your chemistry exam.	M.W. had just taken an exam and felt that she had made up "fake chemistry" to answer a question. This reflection was assigned to help M.W. understand how she selected bits of prior knowledge to construct her answer. We felt that reflecting on this kind of knowledge construction would help her understand how other students might construct knowledge in our data.
March 3	Examine the clarity/correctness framework by Cheatham and Tormala. Can you connect what students are saying to what they know by using this framework?	This reflection was assigned to help us determine whether the clarity/correctness framework was suitable for the BioEd URE data analysis
March 7	In your mind, what is the difference between your experience in a laboratory research experience vs. this education research experience?	This reflection was assigned to help M.W. think about the similarities and differences in epistemologies between different contexts.
March 11	You mentioned that you wrote a literature review for your science writing class. Reflect on how you wrote that literature review and compare it to how you've written other literature reviews.	M.W. told us of a literature review she wrote in a science writing course. This reflection was assigned to help M.W. think through how the epistemology she used when writing the literature review was similar to and/or different from the epistemology she used when writing Papers 1 and 2. We reasoned that thinking through differences in how she applied her own epistemology would help M.W. to analyze the BioEd URE data.
March 29	Block off what you believe to be the student arguments in the paper. Once blocked off, reflect on what parts of the student's paper are important to our analysis.	This reflection was assigned to help M.W. analyze the BioEd URE data.
April 4	You mentioned that one of your friends changed her paper topic because she was afraid that she would not agree with her TA. Think about how you and others choose your paper topics, and whether or not it affects how you look for evidence.	This reflection was assigned to help M.W. think about student motivations and how these motivations might affect their epistemologies.
October 7	(After the research project) Reflect on the two papers you wrote in your introductory biology class and the paper you wrote in your science writing class. Could you have written the paper you wrote in your science writing class as a freshman? What would you change about these papers now?	This reflection was assigned to indirectly ask M.W. how her epistemology may have changed between writing Papers 1, 2, and 3.

underdetermination, the idea that multiple interpretations can be drawn from the same body of evidence. We used this discussion to stress to M.W. the importance of considering multiple interpretations and forming her own conclusions, even if they differed from ours. Following this discussion, we asked M.W. to find a published journal article and summarize it in a written reflection so that she could practice interpreting data and forming her own conclusions. M.W. read the article she chose with a critical eye.

My issue with this article was that the abstract presented the findings in a confusing way so that after I finished reading the article, I felt like the authors had lied to me. The abstract states, "results indicate that the presentation of controversial topics, particularly evolution, in the context of public health could be used to encourage public acceptance of scientific viewpoints." However, the discussion/conclusion talks about how the study showed no support of the student's acceptance of global warming being influenced by evidence-based explanations. The study did show a

> significant change in the student's opinions on evolution, but not on global warming. Therefore, the wording of the abstract is misleading because it implies that their theory can be applied to many topics or on a larger scale; this is not necessarily true.—Reflection 3

This excerpt demonstrates M.W.'s ability to critique the claims of researchers and her willingness to do so in the context of the BioEd URE. It was interesting to find M.W. critiquing the claims made by authors of her selected article because of the statements she made in Reflection 2: "I trust the publications, and since I didn't do the trials or research on my own, I don't feel like I am in a position to challenge their claims." The short time between Reflection 2 and Reflection 3 (12 days) suggests that M.W. already possessed the skills to critique scientific literature but did not feel that it was proper for her to form her own conclusions in specific contexts. In the following extract, M.W. explains why she was able to challenge the conclusions made in the published article. The excerpt is M.W.'s self-analysis of her own work, so it is presented in italics.

> *In the context of the reflection, I was able to challenge the paper because it was my own reflection, there was not a right or wrong answer, and it was solely my opinion. Just like determining my stance on healthcare, it was a place for me to determine my own opinion. In STEM class, there is no room to decide what I think is right or wrong, the subject requires me to learn the processes and present it on the test.*

M.W. explains in this self-analysis that the difference in context between the reflection and STEM class facilitated her willingness to challenge claims made in a published journal article. However, there is also evidence that her willingness to challenge scientific claims made in published literature transferred to the paper she wrote in her science writing course (Paper 3). In the following excerpt, M.W. critiques the claims made in a paper describing antibiotic treatment regimen.

> One newly developed antibiotic treatment developed in 2000 is called sequential therapy. This therapy treatment includes a proton pump inhibitor (PPI) and amoxicillin for 5 days, as well as a PPI, clarithromycin, and tinidazole triple therapy for an additional 5 days. This treatment method was found to have a higher eradication rate than the standard triple therapy described previously. This higher rate was contributed to the decreasing *H. pylori* density in the stomach and corresponding increase in the effectiveness of the antibiotics clarithromycin and metronidazole.[16] However, these studies fail to investigate whether the improvement in the eradication rate is due to the sequential therapy or the increased amount of antibiotic use.—Paper 3

As in her first and second research papers, M.W. cites scientific journal articles to support her claims. However, unlike in her first two papers, M.W. qualifies data presented by the cited study, pointing out her own interpretation that the studies failed to determine whether the eradication rate was due to sequential therapy or a higher dosage of antibiotic. Her critique suggests that M.W. embodied an additional role in Paper 3 that we had not seen in our analysis of Papers 1 or 2: the role of not just a reporter of scientific information but also that of a science critic.

M.W.'s science epistemology continues to evolve during the BioEd URE, and she discusses these changes throughout Reflections 5–9. However, she most clearly articulates how the BioEd URE influenced her epistemology in her final reflection. Because the final reflection was written a semester after the experience, M.W. has had time to reflect upon her experience during the BioEd URE.

> I also think that this research project has expanded my outlook on the science field because I see how there are many variables that play into science and it's not always straightforward and black and white. Science is more than just numbers and data; you have to interpret that data and draw patterns from the articles that you read.—Reflection 10

The final sentence in this excerpt reflects the changes we see between the papers M.W. wrote before the research experience and the paper she wrote during the URE. M.W. states that science knowledge is not only data reporting, but also includes interpretation and the drawing of her own conclusions. Later in the reflection, M.W. discusses her past self and compares what she thought about science as a freshman to how she now thinks about science.

> I think as a freshman, I assumed that you were not "allowed" or that it wasn't science if I took a stance in one direction over the other. I definitely held back my opinion in the paper because I thought that it wouldn't be right to put what I believed in the paper because it would seem too biased. Now I know that it's okay to put your stance in a paper, as long as you can back it up with evidence while still acknowledging the limitations of your ideas. I learned that science is a lot trickier than I originally thought because you do want to present truthful information, but you can still put what you believe based on drawing real conclusions from your own research.—Reflection 10

While a first-year student, she felt that she was not supposed to take a stance in science, but she now believes that she can present beliefs as long as they are supported by evidence. We interpret "opinion" "belief" and "stance" in this excerpt as M.W.'s own conclusions drawn from the data she presents.

M.W. Develops Agency toward Scientific Knowledge Construction during the BioED URE

M.W.'s realization that science requires interpretation of data, coupled with her comments about not having room to decide what is right or wrong in her STEM class and holding back her opinion in her papers, shows that she did not feel that it was proper for her to construct knowledge in the context of a classroom. However, her critique of the research paper in Reflection 3 and the shift in her writing style in Paper 3 led us to believe M.W. developed agency toward knowledge construction during the BioED URE. We define agency as an individual's perceived capacity to act and make choices independently within a specific structure (Archer, 2002). In our case, the structure refers to constructing knowledge in the discipline of biology. However, because agency is a concept that focuses on an individual's perceived capacity to act with intentionality (Archer, 2002), it is not possible for us, as researchers outside M.W.'s mind, to draw concrete conclusions about her agency. Therefore, we explained the concept of agency to M.W. and asked her to respond to our interpretation. M.W. explains how participation in the URE affected her agency toward forming her own conclusions in her response to our analysis.

> *This URE taught me what agency is and how agency is valuable in the scientific world. That's why my reflections show how I started to see how science is not just the statement and summarization of data, but the interpretation of results. This URE taught me that my ideas and my opinions matter, as long as I back up my interpretation with data, I have the ability to make my own conclusions. Although I still feel like being an undergraduate student comes with hesitation from others to accept the conclusions I make, I am confident in my ability to make those conclusions on my own. If I had not been assigned to read and reflect on the research article that I found to be misleading or be encouraged to critique articles that I read, I do not believe that I would have developed agency in my scientific writing.*

Through M.W.'s response, we conclude that one of her reasons for interpreting and drawing conclusions from published data is because she feels that she has the capacity to do so. She feels that she has the agency to make independent conclusions from published data. Upon review of our analysis, M.W. wrote the following response, summarizing her views about her feelings of agency in her classes and the BioEd URE.

> *Having agency matters to me in determining my stance on health care because it's a topic that is going to stick with me for the rest of my life. My understanding of STEM really only matters to the extent that I understand it enough for the test in my class. Therefore, whether or not I had agency in the context of the STEM classroom did not seem important to my learning at the time I wrote the reflection because I was just trying to earn a good grade in the course. When I read the article that I was assigned to write a reflection on, I honestly remember being annoyed with the author. The abstract was misleading; I read through the paper and felt that the abstract made a way too broad, overarching claim that I did not feel was completely supported in their research.*

In her response, M.W. revisits her first reflection, commenting on how the different STEM classroom and healthcare contexts influenced her scientific agency. Forming her own conclusions was not an important goal in the STEM class, as the assessments only considered the instructor's information as knowledge. As such, whether or not M.W. felt the agency to construct her own conclusions was moot, because her goal was non-epistemic: "to earn a good grade in the course." She contrasts the STEM course structure with the paper critique during the BioEd URE, where she felt there was a space for her to construct her own opinion. Critiquing the paper resulted in an emotional response wherein she felt frustrated with the conclusions drawn by the authors. This emotion is important, as it can serve as motivation, in M.W.'s case, to challenge the claims of others. This experience seems to have transferred to M.W.'s writing in Paper 3, where she challenges the conclusions of one of her sources.

DISCUSSION

In this paper, we analyze one student's biology literature reviews from three classes and written reflections to determine how she thinks about the nature of biology knowledge and its construction before and during participation in a BioEd URE. This analysis is supplemented by the student researcher, M.W., who describes her experience through an autoethnographic lens. Analysis of M.W.'s reflections and classroom papers suggests that she came to realize that she could critique knowledge produced by science experts, which led to the development of her agency toward scientific knowledge production.

Reflexivity Helped M.W. Refine Her Thoughts about Biology Knowledge Construction and Develop Scientific Agency

M.W.'s written reflections give us insight into her reflexivity, defined as the internal conversation that helps an individual to evaluate and re-evaluate their actions and decisions (Archer, 2012). For example, in Reflection 4, M.W. felt that she was making things up, describing her problem-solving process as "fake chemistry," but while re-examining her actions, realized that she solved the chemistry problem by applying prior knowledge to a new context. Through the BioEd URE and other experiences, M.W. gained an awareness about her own ability to apply concepts to challenge questions. M.W.'s examination of her own actions resulted in a change in her thinking about how she constructs solutions to problems, a hallmark of reflexivity (Archer, 2010; Weinstock *et al.*, 2017).

Participating in research experiences has been shown to enhance scientific agency and project ownership (Hester *et al.*, 2018), but less is known about how that agency develops during the experience. By making her reflexive practice explicit, M.W. helped to fill this gap by providing insight into how her scientific agency developed over the course of the BioEd URE. It is evident from M.W.'s third reflection that asking her to critique a scientific journal article was an important part of her scientific agency development. However, for her to develop scientific agency, M.W. had to first recognize how she thought about scientific knowledge and that she thought about scientific knowledge differently between contexts. In using reflexivity to examine these contexts, M.W. found that she felt little agency toward constructing knowledge in her STEM course, because in that context, the instructor decides what counts as knowledge. However, in the context of the BioEd URE, M.W. felt that her own ideas could count as knowledge, so long as she could support her ideas with evidence. We hypothesize that the structure of the training for the BioEd URE contributed to the development of M.W.'s agency toward scientific knowledge construction. Other researchers have also found differences between students' views of knowledge within their courses and research experiences (Faber *et al.*, 2016; Faber and Benson, 2017).

Possible Influences the BioEd URE Structure Had on M.W.'s Feelings of Agency toward Scientific Knowledge Construction

While M.W.'s reflections were an important part of the development of her agency, it is important to remember that the reflections were embedded within the structure we provided in the BioEd URE that was designed to help M.W. explore ways of knowing in science while embodying the role of a knowledge builder. We cannot definitively say what aspects of the BioEd URE or other educational experiences were integral for M.W.'s development of science agency. However, the development of

M.W.'s feelings of agency toward scientific knowledge production could be explained through the interaction between structure and agency. Structure refers the roles that are made available to agents and the systems that maintain these roles (Case, 2013), which influence the kinds of intentional actions that individuals can take (Akram, 2013). The venue we provided for M.W. to share her conclusions for critique provided a role for M.W. that included agency as a fellow knowledge builder (Longino, 2002). However, her conceptualization of her STEM course only provided M.W. with the role of an information gatherer. As a result, whether or not M.W. felt a sense of scientific agency was not important, because the perceived structure of the STEM class did not provide a space for M.W.'s intentional knowledge-building actions. These two examples illustrate the important role that structure plays in the development of scientific agency (Case, 2013; Schenkel *et al.*, 2019).

Our results suggest that the structure that we provided during the BioEd URE played a role in the development of M.W.'s scientific agency, along with her other educational experiences. We designed our BioEd URE to ensure that the structure provided a space where M.W. could develop a feeling of scientific agency. As discussed in the overview of the URE, the design of the experience incorporated the four norms of scientific knowledge production outlined by Longino (2002). Ensuring that M.W. felt *tempered intellectual equality* in the *venues that we provided for critique* presented M.W. with a space where she could act intentionally to construct knowledge. Furthermore, our explicit discussions about discipline-specific epistemology helped to outline the *public standards of quality* in the context of biology and education research, which gave M.W. the tools to evaluate her own claims.

An important part of the structure was the assignment that required M.W. to critique a published journal article. This assignment helped M.W. realize that she is allowed to critique published knowledge and that she is not required to blindly trust published information. This realization strengthened her role in science knowledge production and led to her feeling more like an agent in the production of scientific knowledge. In her response to our analysis, M.W. explicitly stated: *"If I had not been assigned to read and reflect on the research article that I found to be misleading or be encouraged to critique articles that I read, I do not believe that I would have developed agency in my scientific writing."*

Another important aspect of the BioEd URE structure was the assignment of written reflections, which facilitated her reflexivity. The reflection prompts grew out of discussions in analysis meetings during the BioEd URE. For example, Reflection 3 came from a discussion about M.W.'s perception that she was not in a position to challenge the claims made by researchers. In that discussion, D.L. and D.D.-R. established the importance of M.W.'s independent analysis in the context of the BioEd URE. In doing so, D.L. and D.D.-R. established a norm for the knowledge (epistemic) culture (Knorr-Cetina, 1999) of the BioEd URE. M.W. internalizes this norm in her responses to our analysis, noting that, in this URE, "my ideas and my opinions matter, as long as I back up my interpretation with data." In Reflection 10, M.W. incorporates this epistemic norm into her EMK about science knowledge, saying: "Science is more than just numbers and data, you have to interpret that data and draw patterns from the articles that you read." This refined idea about scientific knowledge construction helped to form M.W.'s agency toward scientific knowledge construction, because it established her role as an active agent in the interpretation of scientific data and the construction of scientific knowledge.

This paper expands on research that explores the connection between epistemic thinking and researcher identity formation in undergraduate engineering students. Much like M.W.'s experience, the work in engineering found that participants formed their ideas about knowledge generation through reflexivity. Participants compared their newly formed ideas to their own research actions and social interactions, influencing their researcher identities (Faber *et al.*, 2019). While our paper does not explicitly ask questions about identity, the emergence of agency in our thematic analysis makes this discussion relevant, because identity is deeply interwoven with agency. An individual's sense of self (identity) has been shown to dictate the intentional actions taken (agency) in a given context (Archer, 2002). Epistemic discussions during the URE helped M.W. form her EMK about knowledge production in the context of the BioEd URE. Specifically, M.W. constructed knowledge of herself as a knowledge producer, providing a space in which she could intentionally enact the actions of a knowledge generator. These discussions support and extend previous research showing that explicit instruction on science epistemology enhances students' understanding of the NoS (McDonald, 2010; Bell *et al.*, 2011).

Study Limitations

The primary limitations associated with this study are related to the study sample, data collection, and subject as researcher. It is important to note that the study we present in this paper was developed in response to interesting insights from one student participating in a BioEd URE, and thus was not planned from the beginning as a case study with autoethnographic approaches. Because this paper describes an individual student's experience in a URE, the results should not be generalized beyond the study context. Additionally, M.W. is a high-achieving honors student and cannot be counted as representative of an "average student." However, the combination of case study and autoethnographic approaches facilitated the construction of an in-depth description that provides an example of how a student developed her science epistemology and scientific agency. It is also important to note that the BioEd URE was intentionally designed around epistemology. As such, results from this study cannot be generalized to biology research experiences that do not include discussions around how knowledge is generated, assessed, and justified. However, there is evidence that discussion of science epistemology in the BioEd URE influenced how M.W. approached knowledge construction in her biology course work. Therefore, we believe that biology instructors and research mentors can use the general structure of our BioEd URE as an example of how epistemic discussions can be integrated into an URE.

The data we analyzed in this study were generated by M.W. for multiple classes and were not designed specifically to answer our research questions. The conclusions we draw from these data, specifically the development of her science epistemology and her feelings of scientific agency, therefore cannot be causally connected to M.W.'s participation in the BioEd URE. In particular, M.W.'s previous research experience as well as her participation in her psychology courses and the science writing course may have significantly influenced her epistemic development. Consequently, we do not claim that the BioEd URE caused M.W. to develop science epistemology or scientific agency; instead, we attribute these developments to her whole experience as an undergraduate student. Additionally, M.W.'s involvement in the URE lasted only one semester because of curricular and time constraints. If her experience had spanned several semesters, it may have influenced her overall experience and the results of this study.

Including M.W. as a researcher who used self-analysis to bring additional insights into our work helped to address both theoretical and ethical validity; however, it also brought challenges to communicative validity and process reliability. By introducing M.W. to the theoretical concepts of epistemology and agency, we introduced the possibility that her analysis would consist of what she felt we wanted to hear as researchers. With respect to our interpretation of her epistemic development, this limitation is of less concern, as she would need to be aware of and understand her own epistemology in order to tell us what we wanted to hear. Likewise with scientific agency, we cannot be certain that her increased feelings of agency are directly associated with her new understandings of science epistemology. We (D.D.-R. and D.L.) did observe M.W. exercising her scientific agency through the BioEd URE, which allows us to begin to triangulate her responses that are associated with her experience in the BioEd URE. These limitations are not unique to this work and are shared across all studies that use self-reported data to some capacity.

With that said, before asking M.W. to be a participant researcher and as part of the BioEd URE, we discussed the quality framework described in this paper and stressed the importance of presenting authentic experience as opposed to what we wanted to hear. There is also evidence in M.W.'s research papers that suggest she developed feelings of scientific agency between writing her second and third research papers. Finally, as qualitative researchers, we are at the mercy of what our study participants are willing to share. While we stress the importance of data authenticity to our participants and triangulate our interpretations among different forms of data, in the end, we must trust what our participants share on some level. M.W. has given us no reason to doubt the authenticity of her accounts.

Implications

The reflections that M.W. wrote during the BioEd URE made explicit her thinking about scientific knowledge and may have also helped her to reify her thoughts about scientific knowledge construction. For many students, their own ways of knowing are tacit (Hofer, 2004), and reflective writing could be one way for students to make explicit and evaluate these ways of knowing. Scientific writing has been found to help students develop reasoning skills in both K–12 (Tytler and Prain, 2010) and higher education learning environments (Quitadamo and Kurtz, 2007). During the BioEd URE, M.W. engaged in both scientific and reflective writing, which helped to activate her reflexivity, leading to development of her ideas about knowledge production. M.W.'s learning process mirrors the experiential learning cycle, in which learners *reflectively observe* (RO) *concrete experiences* (CE), helping them to construct *abstract conceptualizations* (AC) that can later be tested through *active experimentation* (AE) as other concrete experiences (Kolb *et al.*, 2001). M.W.'s written reflections (RO) helped her to process her experiences (CE) during the URE. She also wrote about her initial thoughts about knowledge production (AC), which she could test during discussions with D.L. and D.D.-R. (AE). Our description of M.W.'s learning process has implications for teaching practice. While written reflection has been shown to enhance learning, our results suggest that once students have finished reflecting, educators should ensure that students are provided the opportunity to apply and test their abstract conceptualizations in new contexts. In this way, students will have opportunities to complete their learning cycles (Kolb *et al.*, 2001).

An additional implication for teaching practice comes from M.W.'s responses to our analysis. D.L. and D.D.-R. interpreted a pattern of composing paragraphs primarily with paraphrased information (often with some inaccuracies) and concluding with a citation as indicating a lack of EMK of scientific knowledge construction and a lack of interpretation or synthesis of information. Based on M.W.'s input, it became clear that a lack of synthesis might actually be a lack of agency or the perception that student scientific agency is not valued in the classroom. Moreover, mistakes or misconceptions in scientific writing might actually indicate an attempt at synthesis. The challenge is for instructors to show students that constructing conclusions is valued as much as producing accurate descriptions of phenomena. Of course, biology educators do not want students conjuring false conclusions. As such, educators should provide venues for students to present their work for critique, so that students may discuss the accepted standards of science and acquire the cognitive tools necessary to produce accurate descriptions.

CONCLUSIONS

UREs provide opportunities for undergraduates to engage in the process of constructing scientific knowledge. Through this case study, we found that one student's 1) thoughts about science epistemology differed between contexts, 2) perceptions of her role as a critic of published knowledge changed over the course of the study, and 3) feelings of agency toward knowledge construction developed during her time in the BioEd URE. While we cannot draw causal relationships between these claims and the BioEd URE, our analysis of reflections that M.W. wrote during the BioEd URE illustrate part of the reflexive process that facilitated M.W.'s epistemic development. Our work also reveals the importance of context, specifically the structure of the learning environment in the development of one student's science epistemology and scientific agency.

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