STUDENTS LEARNING FROM THE SKULL EVOLUTION LAB: PERCEPTION OF GOALS, DRAWING CONCLUSIONS, AND THE RELATION BETWEEN EVIDENCE AND BIOLOGICAL KNOWLEDGE

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Dedicated to my Parents

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ABSTRACT

Biology education in both high school and college calls for integrating scientific knowledge and reasoning into authentic laboratory in recent years. Students are expected to learn science by participating in the process of inquiry, argumentation, and explanation.

The purpose of this study is to investigate how the 9th and 12th grade students interpret their learning experiences during laboratory activities and evaluate students' use of biological knowledge and understanding about the nature of science.

The results suggest most students were able to understand the main purpose of the laboratory activities. Most students were able to use change across traits to support the conclusion of evolutionary change. However, only a small number of students realized the limitation of the evidence.

Overall, this study provides support that the conceptual analysis of disciplinary evidence scaffolded activity helps both 9th graders and 12th graders with their authentic laboratory experience during laboratory activities.

INTRODUCTION

In modern education, authentic laboratory experiences in high school science are considered an important aspect of developing students' scientific literacy and of preparing students for postsecondary education and/or careers in science. A growing body of literature in the learning sciences has emphasized the need to rethink how students come to learn and participate in the epistemic practices of scientific knowledge-building and evaluation, such as inquiry, modeling, explanation, and argumentation (Chinn & Malhotra, 2002; Sandoval & Reiser, 2004). In a comprehensive review of high school laboratory experiences, Singer et al. (2006) noted the limitations of standard laboratory experiences in providing students with opportunities for authentic practice. For traditional lab experiences, results are predetermined and predictable, and the experience significantly differs from true scientific investigations. The study identified several goals for more authentic high school laboratory experiences: developing an understanding of scientific concepts, developing scientific reasoning abilities and operation skills, understanding the nature of science (NOS), and growing students' interest in science. Recent reform proposals have called for a transformation of laboratory classes in both high school and college to integrate student engagement with the core concepts of science through epistemic practices of inquiry, modeling, explanation, and argumentation (National Research Council, 2012; Brewer & Smith, 2011; Smith, 2015).

The current study examines students' reflections and feedback on their learning from laboratory tasks that are designed to support the understanding and use of biological evidence through dialogic and written scaffolds provided by the instructor during laboratory activities. This study is a secondary analysis of interview data collected as part of the Exploring Biological Evidence (EBE) project (Samarapungavan et al., 2017), which examines the effect of instructional scaffolding on students' understanding and use of evidence in biology laboratory tasks. The EBE project is guided by the conceptual analysis of disciplinary evidence (CADE) framework (Samarapungavan, 2018; Samarapungavan et al., 2018, 2019). The CADE framework is a theoretical synthesis of literature on students' understanding and use of scientific evidence from the history and philosophy of science (and biology), cognitive research on epistemic reasoning, and science-education research on the epistemic dimensions of scientific practice. The CADE framework emphasizes the need to explicitly scaffold evidentiary considerations (e.g., relevance, scope, and quality of evidence) for students as they engage in scientific practices, such as inquiry, explanation, and argumentation. The current study is driven by the following research questions:

1. How do students self-report the purposes of laboratory inquiry?
2. What do students' self-reports indicate about their understanding of the specific evidence for human evolution that they collected as part of their human evolution laboratory?
3. What do students' self-reports indicate about their broader understanding of the role of scientific evidence in relation to biological knowledge?

The theoretical framework that motivates this study and the research questions is described in the following section.

Theoretical Framework

As previously noted, calls for the reform of science education and learning have been emerging. Responding to these calls for reform, educators have begun to design and implement laboratories that support student engagement in the authentic practices of science. For example, researchers have reported that when secondary and postsecondary students have the opportunity to actively participate in the exploration process and construct knowledge through discussion, they demonstrate a better understanding of the biological content (Derting & Ebert-May, 2010; Sun et al., 2017). Other researchers have explored students' acquisition of skills related to authentic laboratory work, such as experimental, reasoning, and communication skills (Hossain et al., 2018; Tsybulsky & Muchnik-Rozanov, 2019). Furthermore, compared to students who engage in cookbook-style laboratories with a single predetermined outcome, those who work on laboratory tasks that are structured to foster collaboration with peers and embody more open-ended, real-world inquiry practices are better able to explain how scientific knowledge is produced and to justify their own conclusions from investigations (Hossain et al., 2018; Tsybulsky & Muchnik-Rozanov, 2019).

However, the cited studies examined only broad outcomes; they did not explore the learning trajectories of students in specific classroom activities and how their unique experiences in a task context may be associated with success or failure on the task. Research has suggested that simply engaging in the process of conducting laboratory investigations is insufficient for students to construct meaningful knowledge (Sandoval & Reiser, 2004). Therefore, science educators are now devoting their attention to research on how students acquire, evaluate, and use knowledge.

Kitchener (2002) coined the term "epistemic cognition." Epistemic cognition is defined as understanding the processes by which knowledge is constructed, evaluated, and revised. Epistemic cognition has its roots in epistemology, the branch of philosophy concerned with the origins, nature, and justification of knowledge (Hofer & Pintrich, 1997). In psychology and education, the concept of epistemic cognition grew out of two domain-general approaches to the study of cognition: (1) metacognition and (2) scientific reasoning. In a theoretical review of epistemic cognition, Chinn et al. (2011) noted that evidentiary reasoning is central to epistemic cognition but also highly complex. For example, as individuals engage in epistemic cognition on a given task, they employ not only their personal history of experience and knowledge but also their epistemic aims and values, their beliefs about the sources of justification for knowledge, and their understanding of reliable and unreliable processes for generating and validating knowledge. Elby et al. (2016) identified two reasons to study epistemic cognition in scientific practice: (1) understanding the nature of scientific knowledge is one of the ultimate goals of science education and (2) epistemic cognition is essential for students to be able to engage in science (i.e., to participate in the practices of science).

Sandoval (2016) summarized several themes related to epistemic cognition in relation to science learning: (1) the relationship between epistemic cognition and academic outcomes in education (including academic achievement and other constructs, such as self-regulation), (2) how epistemic cognition is shaped in task-specific and domain-specific contexts, and (3) epistemic change in response to intervention. In this study, I focus primarily on understanding how one aspect of students' epistemic cognition, namely their ability to understand and reason with the biological evidence for evolution, is influenced by their participation in laboratory tasks that are specifically constructed to support the integration of core biological content and epistemic reasoning.

The CADE Framework

Samarapungavan (2018) noted the connection between the CADE framework and curriculum reform documents, namely the Next Generation Science Standards (NGSS Lead States, 2013) and Vision and Change in Undergraduate Biology Education (Brewer & Smith, 2011). The CADE framework introduces more fine-grained standards for specific scientific practices and unpacks the evidence constructs from the knowledge perspective and reasoning perspective, which can be used to analyze scientific practice.

As mentioned above, the CADE framework was developed to analyze how students use evidence in scientific practice. It describes three relationships: the "theory to evidence relationship," the "evidence to data relationship," and the "evidence to theory relationship." These three relationships are relevant to different stages of scientific practices. The scientific practices relevant to the theory-to-evidence relationship are formulating testable hypothesis and creating arguments or explanations. The evidence-to-data relationship involves scientific practice of designing, executing, and analyzing data models. The evidence-to-theory relationship is associated with scientific practices if there is sufficiency of evidence to support the theory.

The second and third research questions emphasize the evidence constructs closely connected with the CADE framework. The second research question— "What do students' self-reports indicate about their understanding of the specific evidence for human evolution that they collected as part of their human evolution laboratory?"—is relevant to the evidence-to-data relationship. More specific to the Skull Evolution Lab, students were expected to identify relevant evidence and make arguments. The third research question— "What do students' self-reports indicate about their broader understanding of the role of scientific evidence in relation to biological knowledge?"—is relevant to the evidence-to-theory relationship, that is, to how students understand the relationship between evidence and theory in general.

Scientific Reasoning

In the context of scientific discovery, classic psychological approaches have historically studied the logical, domain-general rules of reasoning in terms of rules of inference (Johnson-Laird, 2006), such as *modus ponens* (conditional statements of the form "if *p* then *q*") and *modus tollens* (conditional statements in which, assuming that "if *p* then *q*" is true, the absence of the consequent *not-q* negates the antecedent, i.e., *not-p* is inferred), as well as general patterns of casual reasoning, such as the control-of-variables strategy in scientific inquiry (Klahr, 2000).

Since the 1980s, a substantial body of research has shown that disciplinary knowledge is critical to scientific reasoning and epistemic cognition (Samarapungavan, 2008; Wu et al., 2016; Zimmerman, 2000). For example, studies have reported that when scientific reasoning is treated as an independent (domain-general) ability, high reasoning ability alone is not a significant predictor of academic-achievement variables (Jensen et al., 2017; Wu et al., 2016).

In response to the evolution of more contextual learning sciences approaches since the 1990s, scholars have begun to place more emphasis on the interplay of conceptual knowledge and reasoning in scientific practice. For example, contemporary research has examined how students use their formal and informal knowledge of the world in contexts of causal and mechanistic reasoning, as well as in contexts of justification (Russ et al., 2008; Sandoval et al., 2016).

The Role of Content Knowledge in Reasoning

The recognition of the interplay of discipline-specific and domain-general knowledge and skills in psychology and education parallels developments in the history and philosophy of science (Chapman & Wylie, 2016). Discipline-specific and domain-general knowledge play different but complementary roles across varied domains and different tasks. Furthermore, it is important to consider the interplay between these types of knowledge in research on reasoning and in the design of more effective models for teaching and learning (Samarapungavan, 2018). Discipline-specific knowledge facilitates students' understanding of the premises of a specific model or mechanism and helps them imagine counterexamples or alternative mechanisms.

Additionally, methodological norms and criteria for constructing and evaluating knowledge can vary by discipline. Students who are capable of casual/mechanistic reasoning in some domains may lack the specific knowledge needed to reason well in other disciplines. For example, scholars have discussed strategies of historical contextualization (using archival material and artifacts to understand historical narratives, persons, and events in their unique and specific temporal, spatial, and social contexts) to illustrate the importance of discipline-specific knowledge in historical reasoning processes (Desimone, 2009; Van Boxtel & Van Drie, 2012, 2018). In contrast with researchers in scientific disciplines, expert historians widely use contextualization as a strategy for evaluating how historical evidence is leveraged for knowledge claims. The discipline of biology also has unique features. For example, understanding biological phenomena requires students to represent and think across levels of interacting systems (Mayr, 2004; Sober, 2002; Wilensky & Reisman, 2006). Many biological phenomena, such as dynamic population equilibrium in species, are emergent properties of what Chi et al. (1994) described as constraint-based interactions across systems rather than properties of linear causal processes.

The Move from Reasoning to Practice

One hallmark of the learning sciences has been the move from a focus on reasoning to a focus on scientific practices, such as inquiry, explanation, and argumentation. The focus on practices involves a more integrated perspective on how students learn to do science—for example, how they learn to conduct investigations of phenomena, to explain the mechanisms that underlie or cause phenomena, and to present or evaluate arguments for competing models or mechanisms. Engaging in the practices of science requires the integration of core conceptual knowledge, methodological skills, and epistemic reasoning (NGSS Lead States, 2013). The NGSS emphasize PK–12 performance standards for students relating cross-cutting scientific reasoning skills with disciplinary knowledge and practices for each scientific discipline.

An important line of work in science education has focused on helping teachers and students develop their understanding of the NOS, that is, of how scientific knowledge is constructed, evaluated, and revised over time. Abd-El-Khalick et al. (2017) found that typical science textbooks provide limited and shallow support for students' comprehension of the NOS. Engaging students in the practices of science is a promising way to enhance students' understanding of the NOS (Bell et al., 2012). At the high school and college levels, researchers have designed various types of activities to help students develop their understanding of the NOS (Tsybulsky, 2018; Tsybulsky et al., 2018). Four aspects of the NOS are assessed in these studies: (1) knowledge is tentative and can change over time, (2) scientists need to communicate with each other, (3) scientists use multiple methods, and (4) knowledge generated by scientists can be influenced by society and technology. These aspects are aligned with the NGSS. However, most recent studies of the NOS have used surveys to examine students' focused development of their understanding of the NOS. Few studies have examined how students develop an understanding of the NOS as they engage in specific scientific practices and how they apply this understanding in specific scenarios.

Furthermore, researchers have borrowed from constructivist meaningful learning traditions in education (Mintzes et al., 1997) to encourage students to engage in sensemaking as they participate in scientific practices in the science classroom (Manz, 2012). Yates and Marek (2014) noted that it is hard to understand the sources of students' misconceptions by looking only at "results" because more than one factor can contribute to students' nonnormative ideas. Engaging students in sensemaking through dialogue and archiving of their progress (e.g., through annotated artifacts or models) can help teachers and researchers capture intermediate products of the learning process and understand the learning trajectories of students. Sensemaking encompasses a number of scientific practices, including explanation, justification, and argumentation performed in the context of meaningful learning.

Several studies have provided support for explanation-driven activities and those that require students to assess the quality of arguments (Chinn & Brewer, 2001; Sandoval & Millwood, 2005; Songer & Gotwals, 2012). Students can clarify the connection between evidence and conclusions by engaging in the process of explanation and argumentation. The justification of knowledge is also a core construct in epistemic cognition. Chin et al. (2011) defined justification as the process of explaining one's beliefs. According to the NGSS, high-quality justification is an expected competency in science and engineering practices. Student justifications can help instructors see how their students are building knowledge and can help them adapt instruction to support more effective knowledge-building. Integrating sensemaking with scientific practices in the classroom can help students articulate epistemic value. Epistemic value refers to how students evaluate the importance of knowledge. When laboratory activity involves different types of knowledge, epistemic value can guide students in identifying the types of knowledge they focused on during a laboratory activity (Chin et al., 2011). The construct of epistemic value plays an important role in explaining the connection between students' everyday or informal experiences of science and their formal science learning in the classroom context.

Rationale for Current Study

An important implication of the described research is that in order to foster authentic learning and epistemic reasoning in science, effective instruction needs to help students build connections between disciplinary core content and epistemic reasoning as they engage in authentic scientific practices.

The current study contributes to the understanding of high school students' biology learning by analyzing their self-reported reflections on their experience with a laboratory task in which they explored data on human evolution by comparing life-size models of a set of seven hominid skull replicas. The task was derived and modified by the high school teachers in consultation with EBE researchers. The modifications comprised dialogic and written scaffolds designed to help students connect disciplinary knowledge of evolutionary biology with their reasoning about the evidence they were generating from skull measurements. The task required students to construct a phylogenetic tree for hominid evolution based on laboratory data collected by comparing a variety of skull features (such as the slope of the skull) across a set of hominid skull replicas and based on data regarding the age of the hominid skull fossils obtained from a database.

Previous studies have explored the important role of prior knowledge in the process of self-explanation in science learning (Margulieux & Catrambone, 2019; Neubrand & Harms, 2017). These studies have demonstrated that students with low prior knowledge need additional guidance in their search for relevant information. Few studies have focused on students' prior experience in science-relevant activities or on how this experience influences their evidentiary reasoning and learning from laboratory inquiry. One of the purposes of the current study was to analyze the influence of prior experience on what students learned from laboratory inquiry. More specifically, the primary goal of this study was to investigate how students interpreted their own learning experiences after engaging in scaffolded inquiry tasks that support evidentiary reasoning. A second goal was to determine whether students' experiences with EBE tasks were related to an enhanced understanding of the NOS. Another goal in this research was to examine whether students connected their biological content knowledge—that is, their knowledge of hominid evolution—

with the epistemic practices through which this knowledge was derived. As I explain in the methodology section, these goals were implemented by developing a framework for analyzing students' postimplementation interviews based on relevant NGSS for knowledge of the NOS and core disciplinary content knowledge of human evolution.

The key research questions were (1) How do students self-report the purposes of laboratory inquiry? (2) What do students' self-reports indicate about their understanding of the specific evidence for human evolution that they collected as part of their human evolution laboratory? and (3) What do students' self-reports indicate about their broader understanding of the role of scientific evidence in relation to biological knowledge?

METHODOLOGY

This study was an interpretive qualitative study. The data were collected as part of the EBE project (Samarapungavan et al., 2017). The goal of the project was to learn how students understand and apply evidence in a biology laboratory. In this study, the main source of data was the interviews conducted with students after they completed an intervention task designed to determine their understanding and use of the evidence of human evolution.

Both top-down and bottom-up strategies of analysis (Chi, 1997) were used in the study. Top-down strategies were used when codes were drawn from the existing literature and the theoretical framework (Hogan & Maglienti, 2001; NGSS, 2013; Samarapungavan, 2018a, Samarapungavan et al., 2018b; Samarapungavan et al., 2019). Prior research has revealed that top-down codes often need to be adapted to capture the richness of new data. Bottom-up codes were developed inductively by analyzing the meaning segments (idea units) contained in students' responses. By comparing and coordinating the initial top-down and inductive bottom-up coding, a final coding scheme was developed for the new dataset.

Task Context

Before being interviewed, the students completed a previously created evidentiary reasoning lab on human evolution. In this lab, they measured and compared various dimensions of a set of hominid skulls and obtained data on the estimated age of the skulls. The morphological and age data were used by students to construct an evolutionary tree showing the common ancestry and divergence of the hominid species they had investigated. Throughout their investigations, students recorded the measurements, organized the data for comparison, and answered sets of questions from an accompanying laboratory guide. The questions were designed to help scaffold students' attention to and understanding of the evidence they had gathered for the purpose of constructing their phylogenetic trees. The NGSS (2014, MS-LS4) have established the following core disciplinary content related to evolution for high school students: Students should (1) understand that fossils can serve as evidence for "the existence, diversity, extinction, and change of many life forms throughout the history of life on Earth" and (2) be able to infer the history of evolution by assessing the similarities and differences among fossils. Moreover, understanding the role of adaptation and natural selection in human evolution an important NGSS standard. The NGSS core disciplinary content served as a guide for the learning objectives in the hominid evolution investigation and for the coding of the quality of students' understanding of disciplinary evidence.

Participants and Interview Procedures

The participants were twenty high school students from three classrooms (sixteen 9th graders from two high schools and four 12th graders from one high school). Students were interviewed at the end of the semester. Each interview was conducted in a quiet space in the schools. All interviews were audiotaped and transcribed.

Interview Structure and Content

The interviews consisted of eight questions that examined three broad aspects of students' learning (see Table 1): (1) the students' prior extracurricular and in-class experiences with science- and biology-related activities (e.g., *Do you participate in any science-related projects or experiences outside of your regular classwork?*), (2) what the students learned during the evolution laboratory activity (e.g., *What did the data from your laboratory tell you about human evolution?*), and (3) the students' epistemic understanding of the nature and role of scientific evidence in biology (e.g., *Overall, what have you learned from these laboratory activities about the nature of scientific evidence in biology?*).

Table 1. Interview questions by theme

Theme	Interview Questions
1. Extracurricular participation and experiences with science.	Q1. Do you participate in any science-related projects or experiences outside of your regular classwork? (If yes, follow up) Can you tell me a little bit about these activities?
2. Reflections on skull-evolution lab.	Q2. Today, we are going to talk about the skull-evolution lab that you completed during your class. What was the purpose of the lab?
3. Reflection on the relationship between evidence and conclusions.	Q3. As you did this laboratory, what did you learn about the kinds of evidence that biologists use to study evolution and species ancestry? (If needed, follow up)
	Q4 What did the data from your laboratory tell you about human evolution?
	Q5. Do you believe that data from fossil records can provide evidence for ancestral relationships among species?
4. Broad understanding of the role of scientific evidence in relation to biological knowledge.	Q6. How did working on these tasks affect your understanding of the role of scientific evidence in relation to biological knowledge?

Coding Scheme and Analysis

Theme 1: Extracurricular Participation and Experiences with Science

The information about students' prior participation in science-related extracurricular activities was collected from Question 1. Codes and corresponding response examples are presented in Table 2.

Table 2. Coding scheme by question for Theme 1 with response examples

Interview Questions	Codes	Response Examples
Q1. Do you consider yourself good at science? (Follow up) Why do you think you are good/not good at science? Q2. Do you participate in any science-related projects or experiences outside of your regular classwork? (If yes, follow up) Can you tell me a little bit about these activities?	1. Students have no prior science-related extracurricular experience.	*"Not really."*
	2. Experience with biology content.	*"We did a project . . . testing what types of water grow bacteria faster."*
	3. Experience with specific scientific practices and skills (e.g., designing/conducting experiments, data analysis).	*". . . we run the experiment . . .. Testing what types of water grow bacteria faster. Tap water, filtered water, and bottled water, we just test and see which is worse."*

Theme 2: Learning about Evolution from the EBE Hominid Comparison Lab

Information about students' perceptions of the goals of their EBE laboratory task (the hominid evolution skull lab) was collected from responses to Question 2. The coding scheme and corresponding response examples are presented in Table 3.

Table 3. Coding scheme by question for Theme 2 with response examples

	Theme 2	
Questions	Codes	Response Examples
Q3. Today, we are going to talk about the skull evolution lab that you completed during your class. What was the purpose of the lab?	1. Organize skulls by age/ Compare skulls to understand how they evolved over time.	*"And we had to …, we had to see ... … put them in order from like, oldest to most."*
	2. Compare skulls to understand how they evolved and describe the evidence of specific types of changes.	*"We use . . . the prognathism. The U and V, the teeth, carbon dating, and we draw a family tree, the ancestor of humans and relative humans. We use a lot of different tools . . . help us figure out what common trait [has been] passed on . . ."*

Theme 3: Reflection on Evolution Concepts: Connections Between Evidence and Conclusions

Questions 3–5 probed students' understanding of how different types of evidence support scientific conclusions. The coding scheme is described in Table 4.

Table 4. Coding Scheme by question for Theme 3 with response examples

	Theme 3	
Q4. What did you learn about the kinds of evidence that biologists use to study evolution and species ancestry? Q5. What did the data … tell you about human evolution? Q6. Do you believe that data from fossil records can provide evidence for ancestral relationships among species?	1. Only describe data collected from the lab.	*"When we measured like the distance between the eyes for the skulls and the length of the canine teeth . . ."*
	2. Only state a conclusion; do not explain how data provide evidence for the conclusion.	*"Not a straight line, there are other species [that] branch off, go distinct."*
	3. Connect data on changes in one trait to a conclusion about evolutionary change.	*"I feel like skulls get bigger because human skull[s] [get] bigger when they are older, like brain sizes."*
	4. Draw on varied data about how changes across multiple traits support conclusions about evolution over time.	*"As the skulls came to more recent, different, data . . . forehead is way bigger. The canine gets smaller."* *"It showed that possibly, the diet changed. The size of the canines was not as large as times goes on. .... Size of brain is increasing ...means they are increasing intelligent. They can get an idea how they changed from beginning to where we are now."*

Theme 4: Broad Understanding of the Role of Scientific Evidence in Relation to Biological Knowledge.

The data for this theme came from responses to Question 6, and the coding categories and corresponding response examples are provided in Table 5.

Table 5. Coding scheme by question for Theme 4 with response examples

Questions	Codes	Response Examples
Q7. How did working on these tasks affect your understanding of the role of scientific evidence in relation to biological knowledge?	1. Assert that biological knowledge is based on evidence: no elaboration.	*"Evolution is real, there is evidence for that. Biology changes. . .. We can't prove anything; we wouldn't know everything. We have evidence. Based on evidence, we have conclusions and facts."*
	2. Illustrate how evidence is used to support conclusions with examples from lab activity.	*"Working in the lab . . . [has helped me to] get in [the] mind of biologists. It helped me to look at and identify different features; like I had my hypothesis, what the order would be, and just working . . . [on the] lab help[ed] me identify what the order actually was by looking at key differences."*
	3. Discuss uncertainty and limits of evidence and how institutional/communal processes of verification and feedback contribute to the growth of knowledge.	*"A lot of times, they have to take different [pieces of evidence] because in our lab, we only have the head; we weren't able to look at the entire body. Scientists should work [with] what they have and what they are given. [There is] a lot of guesswork and checking because they can't really go to a book like we could and ask where they [species] come from. So, scientists are discovering it. A lot of guesswork and checking going through entire scientific community... and they get feedback. Sometimes it is good feedback and sometimes it is not. As a scientific community, it is good to have both.*"

The interviews of five students (two 12th graders and three 9th graders) were coded by an additional independent coder. The interrater agreement was 93%. Disagreements were resolved by discussion.

RESULTS

The results are presented in relation to the three research questions that guided this study: (1) How do students self-report the purposes of laboratory inquiry? (2) What do students' self-reports indicate about their understanding of the specific evidence for human evolution that they collected as part of their human evolution laboratory? and (3) What do students' self-reports indicate about their broader understanding of the role of scientific evidence in relation to biological knowledge?

RQ1: Students' Self-Reports Concerning the Purpose of Laboratory Inquiry

Table 6. Results for theme 2: frequency and percentage of responses by grade

Codes	9th Grade Fr. (%)	12th Grade Fr. (%)	Total Fr. (%)
1. Organize skulls by age / Compare skulls to understand how they evolved over time.	4 (25%)	1 (25%)	5 (25%)
2. Compare skulls to understand how they evolved and describe evidence of specific types of changes.	12 (75%)	3 (75%)	15 (75%)
Total	16 (100%)	4 (100%)	20 (100%)

Note. Fr. = frequency

The first research question concerned students' understanding of the purposes of laboratory inquiry. This question was addressed by our analysis of students' responses to Question 2 for Theme 2 (see Table 6). From the analysis, it was observed that most of the students (75% of those interviewed) regarded the learning of the history of evolution and the learning of the evidence for evolution as the two main goals of the skull evolution laboratory investigation. There was no difference in performance by grade level. Most 9th and 12th graders understood that the comprehension of the history of evolution and the comprehension of the evidence for evolution were the main goals of the lab.

RQ2: Students' Reasoning About the Conclusions Made Based on Laboratory Data

Table 7. Results for theme 3 reflections on the skull evolution laboratory

Codes	9th Grade Fr. (%)	12th Grade Fr. (%)	Total Fr. (%)
1. Describe one piece of data from the laboratory but do not explain how it provides evidence of evolution.	3 (18.8%)	-	3 (15%)
2. Describe a conclusion about evolution such as the branching of new species from a common ancestor but do not explain how the laboratory data provide evidence for the conclusion.	4 (25%)	-	4 (20%)
3. Connect data on changes in one trait to a conclusion about evolutionary change.	3 (18.8%)	1 (25%)	4 (20%)
4. Draw on varied data about how changes across multiple traits support conclusions about evolution over time.	6 (37.5%)	3 (75%)	9 (45%)
Total	16 (100%)	4 (100%)	20 (100%)

Note. Fr. = frequency

The second research question was based on the analysis related to Questions 3–5 (see Table 1). The overall quality of the 9th graders' responses was lower than that of the 12th graders. The majority of 12th graders performed better at connecting multiple streams of data to evolutionary change. Most of the 9th graders' responses did not connect evidence to specific evolutionary changes or explain conclusions using evidence from the laboratory activity.

RQ3: A Broad Understanding of the Relationship Between Evidence and Knowledge

Table 8. Relationship between evidence and knowledge by grade

Codes	9th Grade Fr. (%)	12th Grade Fr. (%)	Total Fr. (%)
0. No answer.	1 (6.25%)	-	1 (5%)
1. Assert that biological knowledge is based on evidence: no elaboration.	9 (56.25%)	2 (50%)	11 (55%)
2. Illustrate how evidence is used to support conclusions with examples from the laboratory activity.	4 (25%)	1 (25%)	5 (25%)
3. Discuss uncertainty and limits of evidence and institutional/communal processes of verification and feedback contributing to the growth of knowledge.	2 (12.5%)	1 (25%)	3 (15%)
Total	16 (100%)	4 (100%)	20 (100%)

Note. Fr. = frequency

The third research question was based on the analysis related to Question 6. Table 8 shows that more than half of the students did not articulate that biological knowledge is based on evidence. Only 15% of students discussed in detail how evidence can contribute to the growth of knowledge. There was no performance difference between 9th and 12th graders.

Relationship Between Prior Extracurricular Experience and Understanding the Role of Evidence in Scientific Knowledge-Building

Table 9. Responses for Purpose of Laboratory by Extracurricular Experience

	Theme 1: Extracurricular Experience		
Theme 2: Purpose of Laboratory	1. No science-related experience	2. Science-related experience	Total
	Fr. (%)	Fr. (%)	Fr. (%)
1. Organize skulls by age/ Compare skulls to understand how they evolved over time.	2 (10%)	3 (15%)	5 (25%)
2. Compare skulls to understand how they evolved and describe evidence of specific types of changes.	4 (20%)	11 (55%)	15 (75%)
Total	6 (30%)	14 (70%)	20 (100%)

Note. Fr = frequency

Table 10. Responses for Reflection on Evolution Concepts by Extracurricular Experience

	Theme 1: Extracurricular Experience		
Theme 3: Reflection on Evolution Concepts	1. No science-related experience	2. Science-related experience	Total
	Fr. (%)	Fr. (%)	Fr. (%)
1. Describe one piece of data from the laboratory but do not explain how it provides evidence of evolution.	2 (10%)	2 (10%)	4 (20%)
2. Describe a conclusion about evolution such as the branching of new species from a common ancestor.	2 (10%)	2 (10%)	4 (20%)
3. Connect data on changes in one trait to a conclusion about evolutionary change.	-	3 (15%)	3 (15%)
4. Draw on varied data about how changes across multiple traits support conclusions about evolution over time.	2 (10%)	7 (35%)	9 (45%)
Total	6 (30%)	14 (70%)	20 (100%)

Note. Fr = frequency

Table 11. Responses for Theme 4 (Role of Scientific Evidence) by Theme 1 (Extracurricular Experience)

	Theme 1: Extracurricular Experience		
Theme 4: Broad Understanding of the Role of Scientific Evidence in Relation to Biological Knowledge	1. No science-related experience	2. Science-related experience	Total
	Fr. (%)	Fr. (%)	Fr. (%)
No answer	1 (5%)	-	1 (5%)
1. Assert that biological knowledge is based on evidence: no elaboration.	5 (25%)	6 (30%)	11 (55%)
2. Illustrate how evidence is used to support conclusions with examples from the laboratory activity.	-	5 (25%)	5 (25%)
3. Discuss uncertainty and limits of evidence and institutional/communal processes of verification and feedback.	-	3 (15%)	3 (15%)
Total	6 (30%)	14 (70%)	20 (100%)

Note. Fr. = frequency

Table 8 demonstrates that prior experience related to scientific practices and skills helped students identify the multiple learning goals of the laboratory. Table 9 suggests that students with science-related extracurricular experience were better able to use multiple lines of evidence to support their claims. Table 10 suggests that students' extracurricular experience with science did not give them an in-depth understanding of the general role of scientific evidence in relation to biological knowledge.

By grade level, only one 12^{th} grader had no science-related experience. Most 9^{th} graders and the only 12^{th} grader who did not have science-related extracurricular experience could identify the multiple learning goals of the laboratory. Most 9^{th} graders without science-related extracurricular experience performed worse on supporting their claim using multiple lines of evidence. However, this was not the trend among 12^{th} graders.

DISCUSSION

The purpose of the study was to evaluate students' reflections on the nature and role of evidence for hominid evolution from a biological laboratory task in which they investigated hominid evolution through a comparison of the morphological features of hominid skulls. Students' more general understanding of the relationship between scientific evidence and biological knowledge was also investigated. One of this study's contributions is its exploration, from a learner's perspective, of students' thinking on the topic of evolution based on a set of laboratory tasks. Students' retrospective reflections on their laboratory activity provided insight into their epistemic learning. The results suggest that the CADE scaffolded laboratory activities helped direct students' attention to important epistemic dimensions of the relationship between biological knowledge and evidence, both in the specific context of their evolutionary tree investigations and more generally.

"Using multiple lines of evidence to defend arguments" is an important epistemic dimension of evidence-to-data relationships in the CADE framework (Samarapungavan, 2018). This epistemic consideration also aligns with the NGSS expectations and literature. *The NGSS Science and Engineering Practice* (2014, MS-LS4) expects students to be able to "engage in an argument from evidence." Answers that contained neither arguments nor evidence were considered low-level answers. In total, 45% of the students could use multiple lines of evidence to support their arguments, which met the NGSS. Hogan and Maglienti (2001) argued that one of the essential differences between scientists and science students is that scientists use a variety of lines of evidence to judge the quality of argument, whereas students tend to use single, isolated pieces of evidence. The findings from the current study suggest that the CADE scaffolded skull-comparison laboratory investigation helped students draw upon multiple lines of evidence to support their conclusions about hominid evolution. Our results are consistent with the work of Sandoval and Millwood (2005), who found that the scaffolded learning context helps students coordinate evidence with claims.

In total, among 9th graders, students with experience with science-related extracurricular activities performed much better on using multiple lines of evidence to support their arguments than 9th graders without experience with science-related extracurricular activities. Sandoval (2003) analyzed two reasons for students' failure to cite data to support claims: Students have difficulty interpreting data, and they do not realize the importance of evidence when making explanations. Experience with science-related extracurricular activities may have helped students make better arguments based on evidence. Participation in science-related extracurricular activities helped students practice data presentation (e.g., one student reported his experience in a science fair, which involved collecting data from a laboratory investigation and presenting data at the end of project). Biology content knowledge helped students better engage in evidence-based arguments during the laboratory because such students had a deeper understanding of the relationship between evidence and claims.

However, our study does not provide sufficient evidence to draw strong conclusions about the role of prior extracurricular experience. First, the interview questions only asked whether students had prior experience with science-related extracurricular activities. The questions did not probe the frequency, length, or quality of students' participation in prior extracurricular activities. The more time students devote to such activities, the more likely they are to have a deeper understanding of the relationship between evidence and knowledge in general.

Considering the limitations of evidence is also an epistemic dimension of evidentiary reasoning described in the evidence-to-theory relationship of the CADE framework. It is also referenced in the NOS standards on NGSS. The NGSS (2014, Appendix H) list two categories related to a broad relationship between evidence and scientific knowledge. One category states that "scientific knowledge is based on empirical evidence," and the other category states that "scientific knowledge is open to revision in light of new knowledge." The interview data suggests that as a result of engaging in the human evolution laboratory, students understood that biological knowledge originated from scientific evidence, but only a small number of students gave specific examples from the laboratory to elaborate on this idea. Only 15% of the students recognized the uncertainty and limits of evidence and that knowledge can grow as new evidence emerges. Borgerding et al. (2017) reported that more than half of the students in an evolution class did not realize that knowledge is tentative. This understanding is one of the expectations of the NGSS, but it remains a common challenge in the teaching of evolutionary biology in all grades. There is room for student growth.

Quigley et al. (2011) suggested that using explicit reflective instruction in science-related after-school programs can help students improve their understanding of the NOS, especially their understanding of the tentative NOS. It suggests that participation in science-related activity is by itself not enough for students to gain a more in-depth understanding of the tentative nature of evidence. Appropriate instruction is necessary to help students consider the tentativeness of evidence and understand the role of evidence in creating knowledge.

The CADE framework emphasizes connecting evidence to reasoning about biological mechanisms, such as processes of natural selection. The NGSS for high school biology specify core disciplinary content for evolution and the evidence related to this content (2014, HS-LS4-2). Based on the interviews, most students in the current study construed the goal of their laboratory tasks quite narrowly as one of assessing the similarities and differences between skulls for the purpose of constructing phylogenetic trees that show the ancestry and evolutionary branching of hominid species over time. Although most students successfully combined evidence from skull comparisons with information about the age of the fossil specimens to justify their tree, few students explicitly discussed the evolutionary mechanisms that may have given rise to these similarities and differences.

One possible reason students failed to discuss evolutionary mechanism is the design of the laboratory; most questions focused on assessing the similarities and differences between the skulls, but few questions encouraged the students to think more deeply about the mechanisms of evolution. For example, in the laboratory guide for one class, out of ten questions, only one asked, "Why do you think the teeth, such as the canine teeth in modern apes, are so different from the canines of modern humans?" Moreover, in the laboratory guide for the class, out of ten questions, only one asked about the mechanisms of evolution. Thus, the task itself did not stress the mechanisms of evolution, and it appears that there was a missed opportunity to more explicitly connect data derived from the laboratory activity to evidence for the mechanisms of evolution.

Limitations and Conclusions

One of the limitations of this study is the small number of students in the sample, especially 12^{th} graders. There were only twenty students in the study. All the selected high schools were located in Indiana. More studies are needed to generalize the conclusion to high school students in other areas and different grade levels.

Another limitation of the study is that all the students volunteered to participate in the study because they were interested in science. Further research is needed to generalize the results to high school students without an explicit interest in science.

The small sample of 12^{th} graders also limited the ability to explore the role of extracurricular science experience. There were only four 12^{th} graders in the sample, and only one of them reported no prior extracurricular experience with science. Further, age is a possible confounding factor for the small sample, because the 12^{th} graders were likely to have had more opportunities for participation in extracurricular science activities through after-school clubs, such as ecology clubs or Lego Robotics groups. Future research with larger samples at each grade level would facilitate the exploration of prior extracurricular experience in greater depth.

As mentioned in the methods section, the participants came from different public schools. School demographic and achievement data published by the state suggest that the overall student populations in these schools differ on important dimensions, with some schools having greater numbers of students on free or reduced lunch programs (an indicator of poverty). Student population also differ on academic measures such as college readiness (as indicated by coursework taken). With regard to the 12^{th} graders, one of the classes included students with a very wide range of academic abilities and achievement ranging from students taking the class for dual (college and high school) credit to special education students who simply needed a course to graduate, in contrast the other 12^{th} grade classes comprised of mostly academically advanced, college-bound students. The current study was not designed to examine how student demographic variables and their academic achievement levels influenced their perceptions of their own learning from the project tasks. Future research that examines how students with different demographic profiles experience learning from the project's evidentiary reasoning tasks is necessary.

Despite these limitations, the current study provides support for the idea that using CADE scaffolds to help students connect biological evidence to core disciplinary knowledge enhances their evidentiary reasoning in the context of laboratory tasks. Specifically, students reported drawing on multiple lines of evidence to support their conclusions, which is an important aspect of sophisticated evidentiary reasoning.

REFERENCES

Abd-El-Khalick, F., Myers, J. Y., Summers, R., Brunner, J., Waight, N., Wahbeh, N., Zeineddin, A. A., & Belarmino, J. (2016). A longitudinal analysis of the extent and manner of representations of nature of science in U.S. High school biology and physics textbooks. *Journal of Research in Science Teaching*, *54*(1), 82–120. https://doi.org/10.1002/tea.21339

Brewer, C. A., & Smith, D. (Eds.). (2011). *Vision and change in undergraduate biology education: A call to action*. American Association for the Advancement of Science.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2012). Beyond understanding: Process skills as a context for nature of science instruction. In M. Khine (Ed.), *Advances in nature of science research* (pp. 225–245). Springer. https://doi.org/10.1007/978-94-007-2457-0_11

Borgerding, L. A., Deniz, H., & Anderson, E. S. (2017). Evolution acceptance and epistemological beliefs of college biology students. *Journal of Research in Science Teaching*, *54*(4), 493–519. https://doi.org/10.1002/tea.21374

Chapman, R., & Wylie, A. (2016). *Evidential reasoning in archaeology*. Bloomsbury.

Chi, M. T. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *Journal of the Learning Sciences*, *6*(3), 271–315. https://doi.org/10.1207/s15327809jls0603_1

Chi, M. T., Slotta, J. D., & De Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction*, *4*(1), 27–43. https://doi.org/10.1016/0959-4752(94)90017-5

Chinn, C. A., & Brewer, W. F. (2001). Models of data: A theory of how people evaluate data. *Cognition and Instruction*, *19*(3), 323–393. https://doi.org/10.1207/S1532690XCI1903_3

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*(2), 175–218. https://doi.org/10.1002/sce.10001

Chinn, C. A., Buckland, L. A., & Samarapungavan, A. (2011). Expanding the dimensions of epistemic cognition: Arguments from philosophy and psychology. *Educational Psychologist*, *46*(3), 141–167. https://doi.org/10.1080/00461520.2011.587722

Derting, T. L., & Ebert-May, D. (2010). Learner-centered inquiry in undergraduate biology: Positive relationships with long-term student achievement. *CBE—Life Sciences Education*, *9*(4), 462–472. https://doi.org/10.1187/cbe.10-02-0011

Desimone, L. M. (2009). Improving impact studies of teachers' professional development: Toward better conceptualizations and measures. *Educational Researcher, 38*(3), 181–199. https://doi.org/10.3102/0013189x08331140

Elby, A., Macrander, C., & Hammer, D. (2016). Epistemic cognition in science. In J. A. Greene & W. A. Sandoval (Eds.), *Handbook of epistemic cognition* (pp. 125–139). Routledge.

Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research, 67*(1), 88–140. https://doi.org/10.3102/00346543067001088

Hogan, K., & Maglienti, M. (2001). Comparing the epistemological underpinnings of students' and scientists' reasoning about conclusions. *Journal of Research in Science Teaching, 38*(6), 663–687. https://doi.org/10.1002/tea.1025

Hossain, Z., Bumbacher, E., Brauneis, A., Diaz, M., Saltarelli, A., Blikstein, P., & Riedel-Kruse, I. H. (2017). Design guidelines and empirical case study for scaling authentic inquiry-based science learning via open online courses and interactive biology cloud labs. *International Journal of Artificial Intelligence in Education*, *28*(4), 478–507. https://doi.org/10.1007/s40593-017-0150-3

Jensen, J. L., Neeley, S., Hatch, J. B., & Piorczynski, T. (2017). Learning scientific reasoning skills may be key to retention in science, technology, engineering, and mathematics. *Journal of College Student Retention: Research, Theory & Practice*, *19*(2), 126–144. https://doi.org/10.1177/1521025115611616

Johnson-Laird, P. (2006). *How we reason*. Oxford University Press.

Kitchener, R. F. (2002). Folk epistemology: An introduction. *New Ideas in Psychology*, *20*(2–3), 89–105. https://doi.org/10.1016/s0732-118x(02)00003-x

Klahr, D. (2002). *Exploring science: The cognition and development of discovery processes*. MIT Press.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education, 96*(6), 1071–1105. https://doi.org/10.1002/sce.21030

Margulieux, L., & Catrambone, R. (2019). Finding the best types of guidance for constructing self-explanations of subgoals in programming. *The Journal of the Learning Sciences*, *28*(1), 108–151. https://doi.org/10.1080/10508406.2018.1491852

Mayr, E. (2004). *What makes biology unique? (Considerations on the autonomy of a scientific discipline)*. Cambridge University Press.

Mintzes, J. J., Wandersee, J. H., & Novak, J. D. (1997). *Meaningful learning in science: The human constructivist perspective*. In G. D. Phye (Ed.), *Handbook of academic learning: Construction of knowledge* (pp. 405–447). Academic Press. https://doi.org/10.1016/B978-012554255-5/50014-4

National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas.* National Academies Press.

Neubrand, C., & Harms, U. (2016). Tackling the difficulties in learning evolution: Effects of adaptive self-explanation prompts. *Journal of Biological Education*, *51*(4), 336–348. https://doi.org/10.1080/00219266.2016.1233129

NGSS Lead States. (2013). *Next generation science standards: For states, by state*s. The National Academies Press.

Quigley, C., Pongsanon, K., & Akerson, V. L. (2011). If we teach them, they can learn: Young students' views of nature of science during an informal science education program. *Journal of Science Teacher Education*, *22*(2), 129–149. https://doi.org/10.1007/s10972-010-9201-4

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education*, *92*(3), 499–525. https://doi.org/10.1002/sce.20264

Samarapungavan, A. (2008). Reasoning. In L. H. Anderman & E. Anderman (Eds.), *Psychology of classroom learning: An encyclopedia* (pp. 729–735). Gale.

Samarapungavan, A. (2018). *Constructing scientific evidence: The role of disciplinary knowledge in reasoning with and about evidence in scientific practice.* In F. Fischer, C. A. Chinn, K. Engelmann, & J. Osbome (Eds.), *Scientific reasoning and argumentation* (pp. 56–76). Routledge.

Samarapungavan, A., Clase, K., Misra, C., Pelaez, N., Gardner, S., Karakis, N., Li, S., & Wills, J. (2019). *Using CADE to deconstruct students' evidentiary reasoning in secondary biology laboratory tasks* [Poster session]. The 13th Conference of the European Science Education Research Association (ESERA), Bologna, Italy.

Samarapungavan, A., Clase, K., Pelaez, N., Gardner, S., & Rogat, A. (2017). *Exploring biological evidence: Helping students understand the richness and complexity of evidentiary constructs in biology* [Award]. National Science Foundation. https://nsf.gov/awardsearch/showAward?AWD_ID=1661124&HistoricalAwards=false

Samarapungavan, A., Clase, K., Pelaez, N., Gardner, S., Misra, C., Duncan, R. G., Chinn, C., Barzilai, S., Berland, L. K., McNeill, K. L., Manz, E., Wylie, A., & Sandoval, W. A. (2018). Unpacking dimensions of evidentiary knowledge and reasoning in the teaching and learning of science. In J. Kay & R. Luckin (Eds.), *ICLS 2018 Proceedings, Rethinking learning in the digital age: Making the learning sciences count* (Vol. 2, pp. 1251–1258). International Society of the Learning Sciences. https://repository.isls.org/bitstream/1/601/1/273.pdf

Sandoval, W. A. (2003). Conceptual and epistemic aspects of students' scientific explanations. *The Journal of the Learning Sciences*, *12*(1), 5–51. https://doi.org/10.1207/S15327809JLS1201_2

Sandoval, W. A. (2016). *Disciplinary insights into the study of epistemic cognition*. In J. A. Greene, W. A. Sandoval, & I. Bråten (Eds.), *Handbook of epistemic cognition* (pp. 184–193). Routledge.

Sandoval, W. A., & Millwood, K. A. (2005). The quality of students' use of evidence in written scientific explanations. *Cognition and Instruction*, *23*(1), 23–55. https://doi.org/10.1207/s1532690xci2301_2

Sandoval, W. A., & Reiser, B. J. (2004). Explanation-driven inquiry: Integrating conceptual and epistemic scaffolds for scientific inquiry. *Science Education*, *88*(3), 345–372. https://doi.org/10.1002/sce.10130

Sandoval, W. A., Greene, J. A., & Bråten, I. (2016). Understanding and promoting thinking about knowledge: Origins, issues, and future directions of research on epistemic cognition. *Review of Research in Education*, *40*(1), 457–496. https://doi.org/10.3102/0091732x16669319

Singer, S. R., Hilton, M. L., Schweingruber, H. A. (2006). *America's lab report: Investigations in high school science*. National Academies Press. https://doi.org/10.17226/11311

Smith, D. (2015). *Vision and change in undergraduate biology education: Chronicling change, inspiring the future*. American Association for the Advancement of Science.

Sober, E. (2002). Philosophy of biology. In N. Bunnin & E. Tsui-James (Eds.), *The Blackwell companion to philosophy* (2nd ed., pp. 317–344). Blackwell. https://doi.org/10.1002/9780470996362.ch12

Songer, N. B., & Gotwals, A. W. (2012). Guiding explanation construction by children at the entry points of learning progressions. *Journal of Research in Science Teaching*, *49*(2), 141–165. https://doi.org/10.1002/tea.20454

Sun, D., Looi, C., & Xie, W. (2016). Learning with collaborative inquiry: A science learning environment for secondary students. *Technology, Pedagogy and Education*, *26*(3), 241–263. https://doi.org/10.1080/1475939X.2016.1205509

Tsybulsky, D. (2018). Comparing the impact of two science-as-inquiry methods on the NOS understanding of high-school biology students. *Science & Education*, *27*(7–8), 661–683. https://doi.org/10.1007/s11191-018-0001-0

Tsybulsky, D., & Muchnik-Rozanov, Y. (2019). The development of student-teachers' professional identity while team-teaching science classes using a project-based learning approach: A multi-level analysis. *Teaching and Teacher Education*, *79*, 48–59. https://doi.org/10.1016/j.tate.2018.12.006

Tsybulsky, D., Dodick, J., & Camhi, J. (2018). High-school students in university research labs? Implementing an outreach model based on the “science as inquiry” approach. *Journal of Biological Education*, *52*(4), 415–428. https://doi.org/10.1080/00219266.2017.1403360

Van Boxtel, C., & Van Drie, J. (2012). “That's in the Time of the Romans!” Knowledge and strategies students use to contextualize historical images and documents. *Cognition and Instruction*, *30*(2), 113–145. https://doi.org/10.1080/07370008.2012.661813

Van Boxtel, C., & Van Drie, J. (2018). Historical reasoning: The interplay of domain-specific and domain-general aspects. In F. Fischer, C. A. Chinn, K. Engelmann, & J. Osbome (Eds.), *Scientific reasoning and argumentation* (pp. 142–161). Routledge. https://doi.org/10.4324/9780203731826

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories—An embodied modeling approach. *Cognition and Instruction*, *24*(2), 171–209. https://doi.org/10.1207/s1532690xci2402_1

Wu, H. L., Weng, H. L., & She, H. C. (2016). Effects of scaffolds and scientific reasoning ability on web-based scientific inquiry. *International Journal of Contemporary Educational Research*, *3*(1), 12–24.

Yates, T. B., & Marek, E. A. (2014). Teachers teaching misconceptions: A study of factors contributing to high school biology students’ acquisition of biological evolution-related misconceptions. *Evolution: Education and Outreach*, *7*(1), 1–18. https://doi.org/10.1186/s12052-014-0007-2

Zimmerman, B. J. (2000). Self-efficacy: An essential motive to learn. *Contemporary Educational Psychology*, *25*(1), 82–91. https://doi.org/10.1006/ceps.1999.1016