Science
Education

What Students Say Versus What They Do Regarding Scientific Inquiry

IRENE Y. SALTER,[1] LESLIE J. ATKINS[1,2]
[1]*Department of Science Education and* [2]*Department of Physics, California State University, Chico, Chico, CA 95929, USA*

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ABSTRACT: We teach a course for elementary education undergraduates that gives students an opportunity to conduct open-ended scientific inquiry and pursue their own scientific questions in much the same way that practicing research scientists do. In this study, we compared what our students say declaratively about the nature of science (NOS) in surveys and interviews with what they do procedurally when engaged in authentic scientific practice. Initially, we were surprised when our students showed very little change on two different validated NOS questionnaires, adhering to seemingly memorized definitions of key NOS vocabulary such as "science" and "experiment." In contrast, on procedural measures of NOS understanding, students developed a decidedly sophisticated approach to answering scientific questions. Our data suggest that students' declarative understandings about the NOS are not a reliable measure of students' ability to engage productively in scientific practices and vice versa. We discuss why this might be and consider the implications of this disconnect on identifying the best approach to NOS instruction and on future science education research. © 2013 Wiley Periodicals, Inc. *Sci Ed* **98:**1–35, 2014

INTRODUCTION

We posed the question "What is science?" to a group of elementary education undergraduates, and they responded with a diverse set of ideas:

Correspondence to: Irene Salter; e-mail: isalter@csuchico.edu
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Briana[1]: I think that science is a way of knowing things . . . When I want to know how something works, or why something is the color that it is I would turn to science.

Susannah: I think science is basically everything . . . Science has little difference compared to religion or philosophy, those too are a science but less experimental and more thought-process based.

Maria: In science one learns why something happens by doing different experiments and research. An experiment has a certain method and steps one has to follow.

Tui: I think that science is the study of matter (including what it's made of, how it moves, what makes it work, etc.) . . . Philosophy, religion, and other like disciplines can be argued or can change due to one's beliefs or experiences, whereas science has proven theories that are known as fact.

From these varied responses, one might assume that these students would take very different approaches when engaged in scientific inquiry. Indeed, a primary rationale for engaging students in learning about the nature of science (NOS) is that such understandings allow them to successfully engage in scientific inquiry (National Research Council, 2007). For instance, you might expect that Briana would go beyond amassing data and seek answers to "how" and "why" questions, that Maria would adhere to a rigid scientific method, and that Tui would look for conclusive proof and unchanging facts about the universe.

In this paper, we explore whether this is true: Does what a student say about NOS correspond to what she does when she engages in scientific inquiry? And what does this connection, or disconnect, between *declarative NOS understandings* (an individual's ideas about science in general that can be expressed as a statement) and *procedural NOS understandings* (an individual's ability to effectively conduct scientific inquiry within a community of practice as evidenced by behavior) imply about how to organize instruction to develop students' understandings about NOS and how to measure changes over time? Before we present data describing what our undergraduate students say and do in an inquiry classroom, we first define what we mean by "NOS understanding" and then discuss why has it been so difficult to determine which pedagogical approach to NOS instruction results in the best student outcomes.

THEORETICAL BACKGROUND

Defining NOS

"Nature of science" is a loose phrase that addresses how science happens and the nature of the knowledge that scientists develop. Although philosophers of science disagree about these questions (Alters, 1997; Stanley & Brickhouse, 2001; Ziman, 2000), science educators are gradually arriving at similar conclusions regarding what students in secondary and undergraduate settings should know about NOS (American Association for the Advancement of Science, 1993; Lederman, 2008; Lederman, Abd-El-Khalick, & Bell, 2002; McComas & Olson, 2002; McGinn & Roth, 1999; National Research Council, 2012; Osborne, Simon, & Collins, 2003; Smith & Scharmann, 1999). For example, there are six recurrent NOS themes that are shared by Lederman et al. (2002), McComas and Olson (2002), and Osborne et al. (2003), each of whom took very different paths to identifying what knowledge about NOS should be taught in schools. Lederman et al. (2002) described a NOS assessment instrument widely used in science classrooms to measure students' NOS

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[1] All student names are pseudonyms.

understandings. McComas and Olson (2002) compared curriculum standards documents from around the globe. Osborne et al. (2003) conducted a Delphi study to seek consensus among science educators, scientists, historians, philosophers of science, and experts working to improve the public's understanding of science, and science teachers. Six major NOS themes were identified in all three of these documents and serve to frame the discussion of NOS throughout this paper:

- *Empiricism*: While most secondary and university students would recognize that science is grounded in empirical evidence and observation, understanding the precise role of evidence and observation in the scientific enterprise separates folk theories from expert understandings. A naive understanding would claim that experimentation leads directly, logically, and conclusively to objective truths and facts (Lederman et al., 2002). However, a sophisticated view would note that "scientific knowledge claims do not emerge simply from the data but through a process of interpretation and theory building" (Osborne et al., 2003, p. 702).
- *Process*: Practicing scientists do not follow the recipe-like scientific method that, historically, has been presented in schools. Rather, an expert understanding of the scientific process would recognize the purposeful and cyclical interplay of asking questions, generating ideas, testing hypotheses, discussing with colleagues, and refining explanations.
- *Tentativeness*: "Scientific knowledge, although reliable and durable, is never absolute or certain" (Lederman et al., 2002, p. 502). Unexpected data that conflict with an existing, well-supported theory would prompt a scientist to question the validity of the data before challenging the theory. Yet, if the data are clearly replicable, then the theory should and must be examined. A naive view may not recognize how well substantiated existing theories are or, conversely, may claim that scientific knowledge is indisputable fact.
- *Subjectivity*: Uninformed views about NOS would see little room for subjectivity in science; to many, science is based on cold, objective data in which bias should be minimized, if not eliminated. Yet the reality is that "it is possible for scientists legitimately to come to different interpretations of the same data, and therefore to disagree" (Osborne et al., 2003, p. 702).
- *Context*: Scientists are human, and, therefore, the questions they ask, the way they choose to answer them, and the explanations they generate will all be shaped by the scientist's personal history, culture, and daily environment. Outsiders may not recognize the importance of these contextual influences on a scientists' work.
- *Creativity*: "Science is an activity that involves creativity and imagination as much as many other human activities" (Osborne et al., 2003, p. 702). Those with a naive view often fail to recognize the importance of creativity in science.

Based on this review of the literature, we chose to analyze our students' NOS understandings through the lens of the six consensus themes described above. There were three other themes that were identified by some, but not all, of these studies: understanding the difference between a theory and a law; recognizing that science is done in a collaborative, social community of practice; and considering the relationship between technology and science. These themes were excluded from our analysis.

The Development and Measurement of NOS Understandings

Developing students' understandings of NOS has gained importance because, it is argued, such understandings are crucial if students are to understand and contribute to the scientific canon and become critical consumers of scientific ideas. "Students' grasp of scientific explanations of the natural world and their ability to engage successfully in scientific investigations are advanced when they understand how scientific knowledge is constructed" (National Research Council, 2007, p. 168). While there is general agreement on this point (American Association for the Advancement of Science, 1993; Lederman, 2008; McGinn & Roth, 1999; National Research Council, 2007, 2012), there is considerable debate regarding how to design instructional environments and curriculum to address this need and how to measure students' development in this area.

There are two major opposing views as to how NOS instruction should be approached in a classroom setting. The *explicit* approach engages students in structured activities followed by discussions to draw out connections to targeted NOS themes (e.g., Abd-El-Khalick & Lederman, 2000; Akerson & Hanuscin, 2007; Bell, Lederman, & Abd-El-Khalick, 1998). For instance, a common NOS classroom activity asks students to explore an "inquiry cube" (National Academy of Science, 1998, pp. 66–73) as a way to trigger discussions about constructing predictions based on observed patterns. In contrast, the *implicit* approach argues that students who engage in scientific inquiry will necessarily develop more sophisticated NOS understandings (e.g., Ford, 2008a; Holbrook & Rannikmae, 2007; Roth & Lee, 2004; Shapiro, 1996). The implicit approach is epitomized by the experience of practicing scientists who, through their immersion in the daily practice of science, are apprenticed into a sophisticated scientific epistemology.

Nonetheless, researchers have raised concerns about the efficacy of the implicit approach (Abd-El-Khalick & Lederman, 2000; Akerson & Hanuscin, 2007; Bell et al., 1998; Lederman, 2008). These scholars argue that explicit NOS instruction is both productive and pragmatic—the explicit approach has demonstrated better outcomes on pre–post survey measures, and engaging all students in authentic scientific inquiry is impractical and less relevant for general citizens who will largely become consumers, rather than producers, of scientific content (Schwartz & Lederman, 2008). One of many examples showing that the explicit approach works includes Ackerson, Abd-El-Khalick, and Lederman (2000) who studied students in a science methods class that opened with 6 hours of interactive activities specifically designed to address targeted NOS themes. Each activity was followed by class discussions about those themes. The NOS framework established in these activities permeated the rest of the methods course through structured and unstructured activities, discussions, and assignments. Whereas most students initially had inadequate views as measured by the Views of the Nature of Science questionnaire (Lederman et al., 2002) and follow-up interviews, most students developed adequate understandings by the end. In contrast, there are few gains, if any, when students engage in guided scientific inquiry activities (Bell, Matkins, & Gansneder, 2011; Khishfe & Abd-El-Khalick, 2002) or even after participating in research internships in scientific laboratories (Bell, Blair, Crawford, & Lederman, 2003). Improvement on standard NOS assessment measures such as surveys and interviews has typically only been documented when NOS themes are explicitly addressed through a guided debrief of the inquiry activities followed by written reflections (Bell et al., 2011; Khishfe & Abd-El-Khalick, 2002; Schwartz & Crawford, 2006). Based on these and other studies, many scholars conclude that "NOS understandings are cognitive instructional outcomes that should be intentionally targeted and planned for in the same manner that abstract understandings associated with high-level scientific theories, such as evolutionary theory and atomic theory, are intentionally targeted" (Khishfe & Abd-El-Khalick, 2002, p. 555).

However, the primary rationale for attending to NOS in science classes is that, by engaging in the practices that bring about scientific content knowledge, students will have a more nuanced, flexible, and accurate understanding of that content (McGinn & Roth, 1999;

National Research Council, 2012). So while it is critical that students understand how to construct scientific knowledge, this does not require that NOS understandings should be treated as a declarative construct that can be explicitly recalled and articulated by students via surveys and interviews—that is, as instructional outcomes on par with atomic theory and assessed in similar ways.

Several researchers (e.g., Ford, 2008b; Hammer & Elby, 2002; Sandoval, 2005) cite this as one reason that these NOS assessment instruments fail to show gains with implicit instructional approaches. They contend that practicing scientists do not employ explicit, declarative NOS understandings as they engage in scientific research so much as they employ a "grasp of practice" (Ford, 2008b). Loosely, a grasp of practice is "a basic understanding of the scientific endeavor and how it works" (p. 148); more precisely, it is argued that this understanding "is a form of participation, it would not be sufficient to decompose these roles into distinct components and teach them . . . Rather, this includes a holistic sociocultural awareness of how these roles interact for the aim of the discipline and how to participate in them appropriately" (Ford, 2010, p. 275). Such a grasp of scientific practice, then, is practical (Sandoval, 2005), personal (Hammer & Elby, 2002), and contextualized (Deng, Chen, Tsai, & Chai, 2011) and may not be best measured by surveys and interviews designed to assess an individual's declarative NOS understanding.

RESEARCH QUESTIONS

This paper informs this conversation by comparing students' declarative understandings about NOS with what students actually do when engaged in open-ended scientific inquiry. Much of the prior work exploring the development of students' NOS understandings failed to provide students with opportunities to fully engage in authentic scientific practices. As Sandoval (2005) points out,

> much of the practice to look at is so obviously school science and so unlike professional science that we have no real hope to expect that students would develop robust epistemologies of science, or that we could study anything other than epistemologies of school science. (p. 645)

The course assessed here, student-generated scientific inquiry, immerses undergraduate elementary education majors in doing science as scientists do, as authentically as possible in a classroom setting (Atkins & Salter, 2010; Salter & Atkins, 2012, 2013).

To us, authentic scientific inquiry means that individuals are engaged in the cognitive, epistemic, and social activities that professional scientists employ in research settings (Latour & Woolgar, 1979; Traweek, 1988). These include such scientific practices as following one's own questions, designing experiments, pursuing "coherent, mechanistic accounts of natural phenomena" (Hammer & Van Zee, 2006, p. 13), developing scientific arguments in support of explanatory models, transforming raw data into explanatory visual representations, and participating appropriately within a scientific community of practice (Chinn & Malhotra, 2002; Engle & Conant, 2002; McGinn & Roth, 1999; Osborne, 2010; Windschitl, Thompson, & Braaten, 2008). Put another way, people engaged in authentic scientific inquiry enact and embody the many NOS themes described previously. The extent to which our students' scientific practice is truly authentic has been documented previously (see Tables 2 and 3 in Salter & Atkins, 2013).

Two main research questions guided this work:

1. Does participation in an authentic scientific inquiry course improve students' declarative NOS understandings as measured by surveys and interviews?
2. What is the relationship, if any, between declarative statements regarding NOS that our students make and how these students engage in scientific inquiry?

METHODS

Study Context

The context for this study was an undergraduate science course for future teachers at a midsized state university that has been extensively described in Salter and Atkins (2013). Briefly, students were presented with complex observable phenomena (such as a cow eye, color mixing, rubber band guitars, or a pinhole camera) and challenged to develop scientific explanations and theories in the same ways that scientists might: by asking questions, constructing models, designing tests of those models, engaging in debates, writing up and presenting their findings, and critiquing one another's work. Students in the course became a collaborative scientific community which alternated between (a) work in small research teams of three to four students where students designed and conducted investigations on questions of their choosing and (b) whole-class discussions where students critiqued one another's work and debated scientific ideas. The course was cotaught by the authors.

The vast majority of the course takes an "implicit" approach, but there are occasional moments of explicitness—NOS-related activities, discussions, and writing assignments were incorporated approximately two to three times a semester. For example, we sometimes include an "umbrellaology" assignment (Somerville, 1941) that calls attention to the role of data and theory in scientific practice, asking students to define and determine what kinds of activities count as science. In the spring, our students often judge science fair projects at local elementary schools to prompt them to consider in writing and in conversation how accurately school science experiences such as science fairs capture, or fail to capture, the essence of authentic scientific inquiry as practiced in our course. These opportunities to discuss NOS-related themes followed the overall pedagogical stance of the class—while the topic of investigation and discussion (e.g., science fair) originated with the instructors, the direction of the conversation and the ultimate conclusions drawn were done by the students. In summary, although we do not target any of the NOS themes as intended student learning outcomes from the course, we do spend 3–5 hours across the 75 instructional hours in a semester problematizing NOS in an explicit manner. Thus, we cannot claim that this course takes a purely implicit approach that can directly and conclusively settle the debate concerning the most effective instructional approach to developing adequate NOS understandings. However, the data collected comparing our students' declarative and procedural NOS understandings in this primarily implicit context informs this debate in that it raises methodological concerns about how to measure changes in NOS understandings.

Data were collected from liberal studies majors enrolled in the course between August 2010 and May 2012. At our institution, 95% of liberal studies majors report that they intend to seek a multiple subjects credential to teach elementary school when they graduate. As is common with many preservice elementary educators, our students are initially wary of scientific inquiry (Jones & Carter, 2008; Tosun, 2000; Watters & Ginns, 2000), having had little, if any, prior experience with designing and conducting independent scientific investigations (Graesser & Person, 1994; Shapiro, 1996; Windschitl et al., 2008). Data sources included written surveys, structured interviews, videotapes of classroom sessions,

TABLE 1
Data Sources

Data Source	Fall 2010	Spring 2011	Fall 2011	Spring 2012
Total students enrolled	21	21	19	13
Gender (female: male)	17:4	20:1	19:0	10:3
Year in school (second: third: fourth+)	0:1:20	7:7:7	0:6:13	1:2:10
Epistemological beliefs about physical science survey ($n = 48$ with pre and post)	13	20	18	0
Views about the nature of science—Form C survey ($n = 22$ with pre and post)	0	0	15	7
Views about the nature of science—interview ($n = 4$ with pre and post)	0	0	4	0
Grasp of scientific practice analysis	0	0	19	0

copies of students' writings and drawings, fieldnotes, and instructor reflections. Not all data types were collected each semester because of our evolving questions concerning our students' epistemological sophistication. Table 1 describes the student population and the types of data collected each semester.

Epistemological Beliefs About Physical Science Survey

We initially used the Epistemological Beliefs Assessment for Physical Science (EBAPS) survey (Elby, 2001) to quantify our students' NOS understandings. The EBAPS survey is a validated instrument that probes students epistemological beliefs along five dimensions:

1. *Structure of scientific knowledge*: Is scientific knowledge a bunch of loosely connected facts and formulas or a coherent, unified whole?
2. *Nature of knowing and learning*: To learn science, should one merely absorb information from a higher authority or should one actively construct understandings?
3. *Real-life applicability*: Does scientific knowledge and thinking apply just to the classroom and laboratory or does it apply to real, everyday life?
4. *Evolving knowledge*: Where does science fall between the extremes of thinking that all knowledge set in stone versus all knowledge is mere opinion?
5. *Source of ability to learn*: Is being good at science a matter of natural ability, or is it something a person can work at?

Each item is scored on a scale of 0 (least sophisticated) to 4 (most sophisticated) resulting in an overall score and a score for each of the five dimensions. Owing to the nonlinear nature of the scoring, Wilcoxon matched-pairs signed rank tests were conducted on those students with completed pre- and postsurveys.

Classroom activities support the idea that scientific knowledge is a coherent whole, that one should actively construct understandings, and that scientific thinking applies to everyday life; thus, we expected students to show strong gains in these and other dimensions.

Views About the Nature of Science (VNOS) Questionnaire

However, the EBAPS survey results were not what we expected. Our initial conjecture was that the EBAPS survey was too closely coordinated with a traditional undergraduate physics course, asking questions about the use of a textbook or solving problems, when we use neither a textbook nor traditional problem sets in this course. Therefore, in future semesters we supplemented the EBAPS survey with the Views about the Nature of Science Form C (VNOS-C) questionnaire (Lederman et al., 2002), which consists of 10 validated, open-ended questions designed to probe students' understandings of the six NOS themes highlighted previously. The written responses of all students who completed pre- and postquestionnaires were analyzed and coded following the general methodology of Schwartz and Lederman (2008). Our initial reading of our students' responses followed a phenomenological approach (Marshall & Rossman, 2010) in that we attempted to capture the essence of our students' ideas about NOS without clouding the analysis with preliminary hypotheses about what they would likely say. This initial analysis revealed several subthemes that were refined further through additional rounds of analysis. Any student whose VNOS-C response corresponded with a given subtheme was counted. Subthemes were not mutually exclusive, and individual profiles could contain several subthemes (e.g., creativity contributes to both experiment design and data presentation). Once individual profiles were generated, pre/postcomparisons were conducted and scored by a qualitative measure of the degree of change (none, slight, or large).

The validity of the VNOS-C questionnaire was confirmed through semistructured interviews with four students following each administration of the questionnaire (Sarah, Maria, Briana, and Tui). These students were selected for the diversity of the NOS views represented by their precourse questionnaire results. In the precourse interview, students were given a copy of their VNOS-C responses and asked to read and elaborate upon their response to each item. If their verbal and written responses differed, we probed further to clarify any ambiguous responses, to ensure that we could fully understand the results of the written survey, and to faithfully represent our students' epistemological beliefs. The postcourse interview followed a similar format with the exception that we were most interested in any differences between students pre- and postcourse responses. Therefore, after students elaborated verbally upon their postcourse written responses, if those differed in any way from their precourse response they were then asked to provide further examples and describe any experiences that might have caused a change in their understandings. All interviews lasted approximately 30–45 minutes and were videotaped and transcribed.

Development of Scientific Practices

While the EBAPS and VNOS-C surveys captured *what students say* about NOS (i.e., their declarative NOS understandings) and how this changes after a semester, we also videotaped classroom sessions to capture *what students do* as they engage in scientific inquiry (i.e., their procedural NOS understandings). Given the unexpected EBAPS results, we wanted to make a first attempt at comparing students' declarative and procedural NOS understandings to explore how well these correlate. We preselected two consecutive classroom periods (a total of 3 hours) in the first week of the Fall 2011 semester and compared those with a small-group exam session (2 hours) from the 12th week of the semester.

The two early class sessions serve as an example of the early development of scientific practices in students with little background in open inquiry and can be compared to their early declarative understandings about NOS. In these sessions, students built pinhole theaters (Rathjen, Doherty, & the Exploratorium Teacher Institute, 2002), made predictions

TABLE 2
NOS Themes Reframed Into Observable Behaviors

NOS Theme	Proxy for Which Scientific Practice
Empiricism: Science is empirical and relies on inferences based on observation	Students use data in sophisticated ways—as "handmaidens to the rational activity of generating arguments in support of knowledge claims" (Driver, Newton, & Osborne, 2000, p. 297).
Process: Explanations are formed through a careful scientific process (yet there's no one way to do science)	Students adopt a flexible, purposeful scientific process that involves an interplay between generating, refining, testing, and debating ideas.
Tentativeness: Scientific knowledge is durable yet tentative	Students treat consensus knowledge claims as the best ideas we have. When presented with anomalous, unexpected data, they do not immediately do not throw out the theory but are willing to reconsider it.
Subjectivity: There is diversity and subjectivity in science	When there is disagreement, students should recognize when they should seek consensus versus when it is appropriate to agree to disagree.
Context: Ideas are influenced by their historical and sociocultural context	In their scientific work, students draw on personal experiences that are culturally, historically, and socially embedded rather than seek to exclude these as "unscientific."
Creativity: Scientists are creative	Students show creativity in all parts of their scientific enterprise (e.g., designing experiments, generating ideas and questions, communicating ideas)

about what they might see inside, and worked in groups to make sense of their observations. The group exam from late in the course was chosen to explore how students' procedural understandings compare to their declarative understandings after many weeks of immersion in doing science. We also selected these sessions because of the clear difference between the degree of instructor direction provided to students. Early class sessions required frequent instructor redirection to set classroom expectations and create an authentic inquiry environment. As the semester progresses, student voices begin to dominate the classroom. The group exam was completely student driven with no instructor involvement aside from providing a topic of study and questions for the group to answer together. The group exam asked students to predict, explore, and explain the differences between lenses of differing curvature. The method by which they choose to answer these questions, and the resources they draw upon to do so is completely determined by the students.

We examined the classroom behaviors in these class sessions according to our working consensus NOS themes. Specifically, we reframed each of the declarative NOS themes in terms of observable behaviors (things students say, do, or write) that reveal the degree to which their ability to engage in scientific practice is naive or sophisticated (see Table 2). We acknowledge that our approach to matching declarative NOS themes with observable behaviors is a rough first approximation; however, this approach allowed us to identify observable behaviors that helped us assess our students' grasp of scientific practice. When measured in this way, we were able to directly compare students' declarative versus procedural understandings for the six NOS themes. Next, we completed a first-pass transcript of the preselected class periods. Verbal utterances were captured in shorthand. Within the verbal transcript, we documented notable nonverbal behaviors captured on video such as gestures, what materials students select, and what they draw and write (Jones & LeBaron, 2002). Written artifacts from these class sessions were photographed, then cataloged and cross-referenced to what students were saying and doing at the time.

From these first-pass transcripts, we selected brief, 1–6-minute episodes of classroom behavior that provided insight into the development of scientific practice in that they offered evidence concerning students' level of sophistication regarding one or more of the target NOS themes. These selected episodes were subjected to a second-pass transcription process in which verbal utterances were expanded from the shorthand, double-checked, and all relevant nonverbal behaviors were accounted for. Finally, we examined these episodes for observable behaviors that allow us to assess our students' procedural NOS understandings.

In the transcripts below, a double dash (--) denotes a false start or tailing off at the end of an utterance. [Nonverbal behaviors are enclosed in brackets]. A slash (/) indicates overlapping utterances. Pauses of over 2.0 seconds are noted. CAPITALIZED words were spoken with greater emphasis or volume than the surrounding words. An ellipse of three dots ... indicates omitted or inaudible words. (??) denotes an unknown speaker.

The location of the camera within our classroom was the determining factor in selecting which group of students to videotape each day. The class is organized around small teams of four, and those teams change twice during the semester. It was not possible, therefore, to follow individuals, or even the same four students, for the duration of the study. However, if we consider the classroom community as a whole as captured in the selected episodes, we can make some generalizations about what our students tend to do as they learn to think, act, and interact in our class. For the group exam, we specifically asked that a group containing three of the four students selected for VNOS interviews sit near the camera to facilitate drawing the most accurate comparisons between our students' declarative versus procedural understandings about NOS.

RESULTS

EBAPS Survey

There were surprisingly few significant differences on the EBAPS survey (see Figure 1). A Wilcoxon matched-pairs signed-ranks test identified a significant change in their overall score (precourse mean score = 2.79, postcourse mean score = 2.89, $W+ = 897$, $W- = 378$, $p \leq .0124$). Notice that the degree of change, though significant, was very small, only a 10th of a point. The change in the overall EBAPS score can be almost entirely attributed to a significant improvement between students' precourse and postcourse scores in just one of the five subscales, real-life applicability ($W+ = 360$, $W– = 816$, $p \leq .0196$). There was a trend toward significance with the nature of knowing and learning subscale ($W+ = 396.50$, $W– = 779.50$, $p \leq .0501$). All other comparisons were not significant.

VNOS-C Questionnaire

Students also showed remarkable consistency in their responses to the VNOS-C questionnaire, despite their experiences engaging in authentic scientific inquiry. Few students showed major changes in their responses, and many had nearly carbon copy responses at the beginning and end of the course. Table 3 lists the subthemes that were identified and the number of students holding that view before and after the course. Detailed descriptions of these subthemes with representative student quotes were previously described in Salter and Atkins (2012). The table also presents the number of students ($n = 22$) who showed

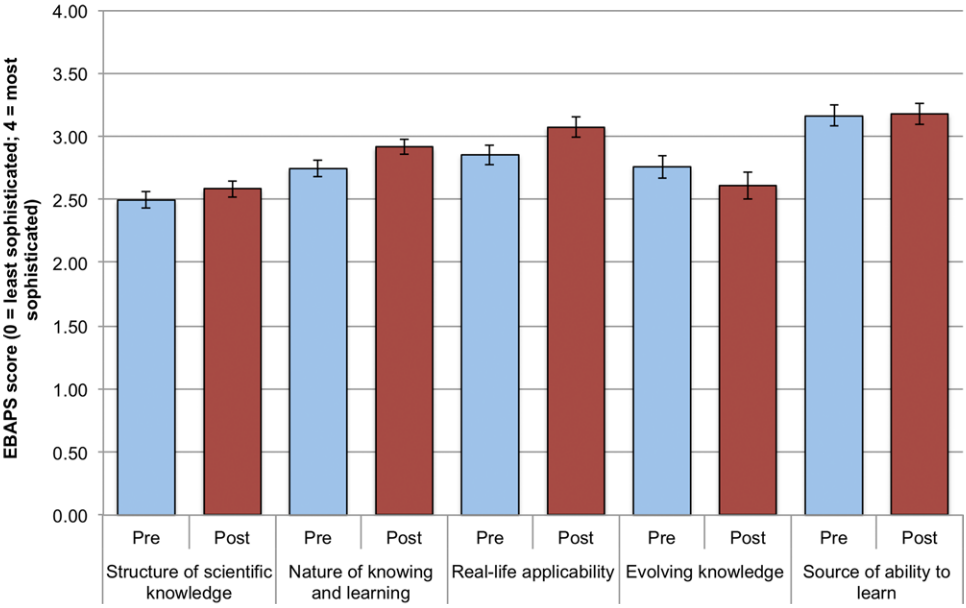


Figure 1. EBAPS data. There were few significant changes between students' pre- and postcourse scores on the 5 subscales. Error bars show standard error of the mean.

no change in their view, a slight change, or a large change. In all theme areas, the majority of students showed no change in their views.

The almost word-for-word similarity between students' responses at the beginning and end of the course was startling. For example, consider Amy:

> Precourse: An experiment is something that tests out an idea that you are trying to prove. An experiment uses different variables and controls to test out an idea or thought.
>
> Postcourse: An experiment is when you test something to prove whether or not your idea is true or false. You have various variables and controls to test an idea that you have.

Her statements are almost identical in their phrasing. Moreover, we never explicitly discussed controlled experiments and variables in the course, nor did Amy's own investigations approach experimentation as "proof." Rather, students designed experiments to purposefully refine, test, and generate explanations and models. Amy appears to be drawing from a definition of the word "experiment" that she learned previously; one that she did not enact in her own scientific practice.

There were many other examples where students apparently drew from a bank of memorized vocabulary in a manner that was disconnected from the authentic inquiry they engaged in. For example, we instructors made efforts to highlight the role of observation and experiment as providing supporting evidence for the theories raised in class; we were careful never to use the word "prove." Yet students like Jake continued to view scientific knowledge as something with "proof" even after the course:

> Precourse: Science is something that can be proven, it shows how something works or what it is, believable. Unlike other forms of happenings which can't be proven what it is, like a miracle . . . Scientific theories do change because they're just that -- theories -- till they are proven.

TABLE 3
NOS Themes and Subthemes From the VNOS-C Questionnaire[a]

NOS Theme	Subtheme	# Pre	# Post	# No Change	# Slight Change	# Large Change
Empiricism	Yes: Experiments/ observations lead directly to facts, certainty, and proven truths	12	8	15	5	2
	Yes: Experiments/ observations allow us to figure out how/why things work (and can prove to others)	4	5			
	Yes: Experiments/ observations help individuals to learn better and prove to self	10	12			
	No: Science is everything (including religion and philosophy)	2	1			
Process	Scientific method: sequential steps to follow	5	2	13	7	2
	Science fair: answer a question; variables to control; test a idea/theory to prove if right or wrong	13	15			
	Give support or evidence to a theory or idea; come up with a new idea; make discoveries	7	7			
Tentativeness	Yes: (no durability) theories change all the time	4	3	18	2	2
	Yes: (durability) theories change with new evidence	16	16			
	No: theories proven to be true	2	3			
Subjectivity	Yes: will believe whatever want to	4	3	15	6	1
	Yes: different underlying theories lead to bias/different ways to interpret same data	11	8			
	No: ultimately data will tell you (data not good enough or both ideas must be right)	14	15			
Context	Yes: affects process (funding, who can do science, what experiments to do)	5	7	13	3	5

(*Continued*)

TABLE 3
Continued

NOS Theme	Subtheme	# Pre	# Post	# No Change	# Slight Change	# Large Change
	Yes: affects interpretations (reasoning, assumptions, what conclusions open to)	2	3			
	Depends: not supposed to be but something is	4	2			
	No: Science is universal (gravity is gravity)	15	15			
Creativity	Yes: in designing experiment	18	16	14	6	2
	Yes: in coming up with new questions/ideas	10	11			
	Yes: in interpreting results/generating explanations	5	7			
	Yes: in collecting/ presenting data	3	3			

[a] One student's postcourse responses did not address the Context subtheme with enough clarity to be coded.

> Postcourse: Science is something that can be proven, while religion is somewhat is a theory which as no proof actual proof of existence, it is more of a state of mind . . . A theory is what someone thinks and has accepted but not proven til an experiment is made to prove it.

Similarly, consider Briana's persistent definition of the word "science":

> Precourse: I think that science is just a way of knowing things. It is different from religion or philosophy because they are a different way of knowing things.
>
> Postcourse: I think that science is a way of knowing things. It is different from the other disciplines because they are explaining different things.

Instances of large changes in students' responses were far less common than we had anticipated—though in hindsight, this lack of change is consistent with research advocating for explicit NOS instruction. No NOS theme positively affected more than five students in any semester, and no individual student showed large changes in more than two theme areas. In general, shifts between subthemes were specific to individuals—that is, one student might shift from thinking that science is universal to thinking that contextual factors might influence scientists' interpretations of their data, whereas another student makes the reverse shift. There were only three types of shifts that had a notable number of students making the same change. Five students of 22 shifted from thinking that creativity is used primarily for coming up with hypotheses and designing experiments to recognizing other uses of creativity as well. Four students shifted from believing that experiments lead directly to facts and proven truths to some other subtheme. Finally, five students shifted from thinking that the process of science must follow a rigid step-by-step scientific method to a more flexible process.

It is tempting to read these responses and infer that the course had little influence on students' understandings of NOS. In the following section, we examine students' behavior as they construct scientific ideas. The broader question we hope to explore is whether students' declarative understandings regarding NOS (what students say) is consistent with the procedural understandings they enact when engaged in scientific practices (what students do).

Development of Scientific Practices, Part 1: Early Class Sessions

The first class sessions opened with 40 minutes spent constructing pinhole theaters (Rathjen et al., 2002), one for each student. Briefly, a pinhole theater is a camera obscura made out of a large cardboard box that a person can wear on his or her head like an oversized helmet. A hole is cut out on the bottom of the box for the viewer's head, a screen of white paper is taped to the interior of the box in front of the viewer, and a square of tin foil is taped over a hole in the box above and behind the viewer's head. Once all the boxes were complete, students took out their science notebooks and predicted what they might see if a pin were used to poke a hole through the foil behind their head. After spending 5 minutes to think and write independently, students were arranged in a large open circle and shared their ideas while the instructors, Irene and Leslie, kept notes on the whiteboard.

Four ideas were proposed. Elena suggested you might see a bright, fuzzy spot of light, similar to the spot of light a flashlight makes on a wall. Carly thought you might see what is behind you in black and white on the screen. Maria added that you might infer something about the color of your surroundings since sitting in a green forest lends a green tint to your clothing. Finally, Ally guessed you would see the inside of your box lightly illuminated as if a dim light were turned on in a room. A straw poll found that most students agreed with Elena or Ally.

Episode 1: Shifting From Seeking the Right Answer to Sense Making. In this first episode, Irene and Leslie strove to foster a classroom culture centered on mechanistic explanatory models and personal sense making. We wanted our students to connect their initial, intuitive predictions about the pinhole theater with what they already knew about the behavior of light through previous science classes and their everyday observations. This episode highlights the way in which students gradually began to engage in this kind of conversation. To begin, Leslie asked the class,

1.1 Leslie: So ... what does each of these tell you about like-- what you like think light is?
1.2 Morgan: It allows you to see color.
1.3 Sarah: And visibility in general.
1.4 (??): Like a reflection or something?

Students' responses were thrown out haphazardly and in quick succession, as if Leslie were "fishing" for the correct definition of light. Leslie, instead of evaluating responses, simply restated their ideas:

1.5 Leslie: Okay. So it allows us to see color. It allows us to see in general. Something about a reflection?

With this invitation, Ami and Susannah, expanded on the idea of reflection, suggesting that the aluminum foil in the pinhole theater might act as a mirror such that whatever light comes into the box would reflect off of it.

Then Briana offered a theory about the behavior or light:

1.13 Briana: To kinda expand on that, I was also thinking since it's a wave, it'll-- once it goes into the tin foil it'll expand [moves two hands outward and apart] to fill the whole box instead of just going in a straight line [moves two hands forward quickly]. So like, I don't think it would just be a hole [two hands positioned to make a circle shape]. Because once it gets through that corner it's gonna expand around [repeat two hands outward and apart] and fill in everything.

In contrast to the initial descriptions of what light does and what light allows (1.2–1.4), Briana offered the beginnings of a mechanism for how light behaves—instead of moving out in a straight line, it "expands" to "fill in everything." One goal for the course is the development of models to explain phenomena, and the role that experiment can play in examining, refining, and refuting models. Although Briana's idea that light waves can expand to fill vacant space is incorrect in this context, her model offered a theoretical lens through which to view the pinhole theater and generate predictions of what we might see. Irene and Leslie tried to move the conversation in this direction:

1.16 Leslie: Is that what you guys are thinking [gestures toward Ally and Sarah who suggested they might see the inside of the box illuminated] when you are saying it allows you to see?
1.17 Sarah: Mmm-hmmm.
1.18 Leslie: Light's like something that travels, and like illuminates something to allow you to see. (2.9-second pause)
1.19 Irene: And that idea of-- like it'll fill up whatever space. Um. Does anybody-- does everybody think that's what light does. It fills up all the space that it can?
1.20 (??): Mmm-hmmm. [General positive affirmation from several students.]
1.21 Irene: It reaches all around.
1.22 Sarah: I remember it can reach anywhere. Yeah. (2.2-second pause)

Despite the encouragement, students did not respond to Briana's idea as an entry point into model building. The above exchange (1.16–1.22) was replete with pauses and vague affirmation and contained no substantive student contributions. Leslie tried again along a different path:

1.26 Leslie: I'm curious why you guys [looks towards Elena and Morgan who thought they might see a bright, fuzzy spot of light] were saying you thought it would be a bigger hole. Is it the same reason? Like the light's kinda moving out. Or-- a bigger circle.
1.27 Elena: Yeah. So you know how like-- I feel like depending on how much you let in, that light can go-- can light up an area. So if you have a small hole, [makes circle shape with one hand] it's going to let a little light in. If you have a big hole, [holds two hands outward as if holding basketball] it might let a whole bunch of light in. [Sweeps right hand around in circle.] If that makes sense. Like if we crack a door, [gestures forward toward door of room] this much, [makes small gap between two fingers] we're only going to see light like hitting that wall [gestures back toward wall behind her]. But if we open the door [moves right hand outward quickly], it would probably let light in all the room.

Following this exchange, the students in the room begin to engage in the type of sense making and model building that the instructors were encouraging. Following Elena's lead, the conversation quickly took off. Some highlights include the following:

> 1.31 Ally: Yeah I was thinking that maybe it more has to do with like where the light is coming from. Like if you are outside, and it's just-- it's bright like everywhere [circles hands around in large arc] when you open the door [moves two hands outward from wrist]. It's gonna fill up [draws arc in air with both hands] the thing more. But if you have a floodlight [moves two hands straight outward quickly] pointing straight at the door [repeats two hands straight outward quickly]. It would make more of like a beam, when you open it.
>
> 1.36 Briana: I was kinda picturing it like, just like a wave in the ocean. Being let-- if you push the water though a little narrow thing the wave is going to go past it right after it goes through [two hands close together near body then moves outward apart from each other] and it's going to keep going. So that's what I was thinking was that once it goes through the hole [two hands together in a circle shape] it's going to go right around the edges and go through [repeats hands close then outward and apart].

Ally built on Briana's original idea (1.13) by contrasting a diffuse light source with "a floodlight." Soon afterward, perhaps prompted by Ally's statements, Briana clarified her original idea as "just like a wave in the ocean" (1.36) that can travel through a narrow channel similar to the hole in the box but then spread outward again once the wave passes through.

Susannah brought Episode 1 to a close by returning to her ideas about the foil acting as a reflector:

> 1.42 Susannah: But again it's bringing back to because this specific box has a reflector that's why we're going to see more than what we would imagine we might see with just a small amount of light. Just one tiny hole doesn't really matter cause whatever that's, like, the hole is going through the foil whatever the case might be. It's gonna reflect off that foil. Cause that's what foil is. It's gonna reflect so we're gonna see more, a bigger picture than what we're expecting to see.

This first episode brings into focus students' hesitant transition from a naive NOS approach to more sophisticated engagement. Within the Empiricism NOS theme, students shifted from deferring to authority figures as the source of scientific facts in favor of more personal sense making using a theoretical framework to support new ideas. Although students shifted to a new conversational style, instructor direction was necessary to support and maintain that shift—students directed their comments to the instructors rather than one another, and nearly every other comment was from Irene or Leslie, even after the shift. Within the Context NOS theme, students brought personal experiences with dark rooms, floodlights, mirrors, and ocean waves to bear.

Immediately following Episode 1, students went outside with their boxes and made observations. Upon the first pinprick, there were exclamations of "Oh wow!" as an upside-down, reversed image of the world behind them appeared on the paper screen. Students eagerly noticed what happened as they turned and tilted their boxes. Irene enlarged the hole in two stages, causing the image to become brighter and more colorful, but blurry. Students went indoors again and spent the last 30 minutes of class working with their research group to take a first stab at making sense of what they observed and organize their thoughts on a whiteboard. For instance, the group featured in Episode 2 (Tui, Channel, Carly, and Audrey) eventually wrote the following on their whiteboard: "The light from the sun came in through the pinhole, the angle of the light changed as it entered the box. It then bounced off the white paper, was reflected off the foil again, and the image was projected." They, and many other groups as well, hung their hat on Susannah's idea that the reflection off the foil must be important to generating an image. Class was dismissed before presentations could begin.

Episode 2: Still Seeking the Right Answers From an Outside Source. The following day, as we begin Episode 2, students regrouped briefly before presenting their whiteboards. Channel brought in some new information gathered from a conversation with a friend the night before. In this episode, we observe how the group quickly deferred to the "right answer" offered by this friend and how Channel charged ahead with last-minute revisions to their whiteboard without leaving opportunities for others to interject or contribute:

2.1 Channel: I was talking to my buddy about this problem and, um, he was saying that light doesn't bend. And he was saying that when the light comes in, it comes in at all different types of angles. [Hands move back and forth from several points near shoulders toward a single point in space.] So like coming down then going in. (2.9-second pause)
2.2 Tui: Should we change anything? Cause it seems like, you know--
2.3 Channel: Yeah. Well we could still have this sentence that the light should be coming in straight lines.
2.4 Audrey: A straight line?
2.5 Channel: Like a straight line cause it doesn't go in and then change direction. It goes in [one hand moves front and back] and goes in a straight line.
2.6 Audrey: Yeah
2.7 Carly: Yeah.
2.8 Tui: Yeah. So rather than saying that the angle of the light changes as it enters, it goes straight.

Channel's friend pointed out that light should not spread to fill up the available space but rather should travel in straight lines. The group very quickly agreed with this new idea about the behavior of light and sets to work changing their whiteboard (added phrase italicized): "The light from the sun came in through the pinhole *from different directions in a straight line*. It then bounced off the white paper, was reflected off the foil again, and the image was projected." Channel was the clear director of this editing process. Although two others offered suggestions, she used her own phrasing in the end. At one point, Channel grabbed her science notebook and copied a picture from it onto the whiteboard without consulting the others in her group or even explaining what she was drawing and why.

We were surprised by how quickly students were willing to throw out their earlier consensus idea ("The angle of the light changed as it entered the box"). The two ideas (light can change directions vs. light travels in straight lines) are clearly in conflict with one another, yet students made no attempt to evaluate, resolve, or reconcile these differences in accordance with a more sophisticated approach to the Subjectivity NOS theme. Furthermore, Channel dominated all the revisions in this episode; the others in her group meekly followed her lead, as if they were bending to the "right answers" that her friend offered to the group.

The next 30 minutes consisted of groups presenting their whiteboards while other students asked questions and discussed ideas that arose. The student discourse raised many fascinating questions and concerns: If the image bounces off the white paper, reflects off the tinfoil, then ends up on the paper, why do you only see the final upside-down image, not the "direct image of the tree" from the first time it hits the white paper? What causes the very bright dot of light one could sometimes see—is it the sun? Could this pinhole theater model how the eye works? Would a mirror placed strategically inside the box flip the image right-side-up again? Why was there an image all over the box (on the sides, bottom, and top of the box) instead of just on the white paper screen? In contrast to Episode 1, the conversation rolled along with less frequent instructor involvement.

In the last 5 minutes of class, Leslie tried to point students toward identifying good opportunities for small group independent investigations, the focus of the next few class periods. For instance, she drew attention to an idea raised by Carly during the discussion of her group's whiteboard—that the tinfoil must matter because it is reflective like a mirror and you can see an image of yourself reversed in a mirror but not on a white piece of paper. Leslie suggested that substituting a black piece of paper for the tinfoil would be an easy way to test this idea. Irene offered another example of an unresolved debate that could be an easy target for further investigation: Is light acting as a wave that can spread out after passing through a hole or does light travel in straight lines?

Episode 3: A Disconnect Between What Scientists Might Offer and What Makes Sense. Just as we were wrapping up class for the day, Elena jumped in with a comment that begins Episode 3. Many of our students do not expect science class to make sense; in their experience, science offers a set of facts to memorize and procedures to follow, not explanations that make sense in the context of our everyday experience. Recent studies have shown that students may know the "right answer" to a science content question based on what they were taught a scientist would say, but really believe that a different answer is correct because the scientists' answer does not make sense (McCaskey & Elby, 2004). This episode features Elena who bravely confronted the class with her dissatisfaction and disbelief of the explanations offered so far. Her voice and expressions were animated and incredulous:

3.1 Elena: Am I the only one who's completely lost with this whole thing? Like I can't grasp any of this . . . Like none of this makes sense. Does none of this make sense? Does-- like everyone's talking about all these ideas and I literally have no idea what's happening. Like does the image go through the hole? Does it reflect through the foil? Like-- does anyone get what I'm saying?
3.2 Audrey: I get what you're saying.
3.3 [Chorus of laughter, nods, and "Yeah!" throughout the classroom.]
3.4 Ally: Like we're/ all wondering.
3.5 Ami: /Like how an image can go through a hole like that?
3.6 Elena: Like yeah. Like I'm-- I'm just completely lost.

In line 3.1, Elena acknowledged that even though many of the explanations offered by her classmates might be what a scientist would say or a reasonable right answer for an examination, they failed to make sense to her. From the response she got from her classmates (3.2–3.5), it is clear that many others also felt the same way. How could these simple explanations of light traveling in straight lines or reflecting off the foil produce the seemingly magical, movie-like images that are seen on the screen? Elena's inability to reconcile what a scientist might say with what makes sense is further highlighted by her statements from later in this episode:

3.12 Elena: What magic did you put in those boxes? Like it's so-- it's so confusing.
3.16 Elena: And it's so fast. Like when you move the image changes. There's no like processing . . . When you're moving, everything was changing.

3.17 Briana: But when you're outside, the tree doesn't disappear because I turn my head fast. It's still right there where I looked. There's this thing. It's not like it takes a second to like, "Oh [micropause]. Okay [micropause]. Now here's a building." You know?

3.18 Elena: I feel like we're not having to look through the hole like the size of a safety pin. You know like--

3.19 Briana: Okay. That's a good point.

In these 2 days of class, we emphasized the reconciliation of scientific models with everyday observations. Thus, we hoped students would "draw on personal experiences that are culturally, historically and socially embedded rather than seek to exclude these as 'unscientific'" (Table 2) as part of the Context NOS theme. For students like Elena and Ally, this reconciliation was foreign and difficult to achieve initially:

3.20 Ally: What I was going to say is that I think it's really brave of you to just like stop everybody and be like, "Hey!" . . . We were all thinking about it and we're bringing our prior experience or whatever to it and it's like-- but I don't think any of us know--

Development of Scientific Practices, Part 2: Group Exam

Twelve weeks later, we observed students as they took a group exam. Through an analysis of the group discourse, we hoped that we could determine whether our students' initial approaches in many procedural NOS themes had progressed. Have they moved beyond seeking right answers from authoritative sources (Empiricism NOS theme)? When there is disagreement, do they know when and how to seek Consensus (Subjectivity NOS theme)? Can they seamlessly bring together scientific explanations and everyday experience (Context NOS theme)?

The examination consisted of four parts. Part 1 asked students to draw a diagram predicting the difference between two biconvex lenses of differing curvature (a "bulgy" lens vs. a relatively "flat" lens) and explain their diagram in words. A template diagram was provided although students were encouraged to develop their own representations. In Part 2, students were given a bulgy lens and a flat lens with which to make observations and use that data to either support their original idea or develop a new theory. Part 3 asked them to consider the lens in the human eye and determine whether and how that lens might change shape as it attempts to focus at different distances. Finally, Part 4 had students consider why a cat might have a more bulgy cornea than humans. These questions are not ones that the class had explicitly considered during instruction, but (for the first three parts) should be able to reason through based on the models they had constructed; the final question extends those models, asking students to speculate further.

The camera focused on Carly, Tui, Maria, and Briana as they worked on their examination. These students had been working together as a research group for over 6 weeks investigating the questions: "Why do some animals like cats, snakes, and horses have differently shaped pupils?" and "Why are irises colored?" They had tangentially explored lenses by interacting with other groups who researched lenses; by participating in class discussions, readings, and assignments on lenses; and by placing lenses behind "pupils" of different shapes and "irises" of different colors to explore the interaction between the pupil, iris, and lens.

This group began their examination by reading Part 1 aloud. Carly quickly grabbed a ruler and some scratch paper and set to work on a rough draft of their diagram. Nearly an hour passed before they completed Part 1 to their satisfaction.

Episode 4: Participation in a Collaborative Scientific Community. This episode offers an example of the way this group worked together to debate and refine ideas. Episode 2 (in which Channel's group modified their whiteboard) may be contrasted with this episode to explore differences in group dynamics, the types of supporting evidence used to support arguments, the manner in which conflicts are resolved, and more.

In the first 10 minutes of the examination period, the group had constructed a rough draft diagram on scratch paper (see Figure 2a) but realized there were problems with it. Carly decided to start over and started tracing the provided template onto a blank area of the first draft scratch paper. Maria interjected,

4.1 Maria: I feel like we should do it on a different paper so we can have more room. [Hands Carly a clean sheet of notebook paper.] I feel like they're getting squished in there. [Touches first draft where the lines past the lens almost hit the edge of the paper.]
4.2 Carly: [Picks up offered paper and traces bulgy lens.] Okay. So let's try this again . . .

Maria's feedback was accepted graciously and efficiently. The others watch intently as Carly drew two originating points of light (a centered point in red pen and an off-center point in blue pen), each with three light rays hitting the left side of the lens (see Figure 2b). She then invited the others' opinion:

4.2 Carly: . . . So if we did the blue one-- [Using pencil, she draws three straight lines from where the blue rays touch the left side of the lens to a single point centered behind the lens.] Would that make sense?
4.3 Maria: No.
4.4 Tui: No.
4.5 Briana: Cause that's where the red one would end up.
4.6 Maria: Yeah.
4.7 Carly: Oh. Oh was I-- Oh you're right. [Erases pencil lines.]

In contrast to Channel's practically solo performance constructing a whiteboard at the beginning of the semester (Episode 3), this group constructed their diagram and explanation collaboratively. Although Carly held the pen, she invited the others into the process and accepted their feedback. Moreover, she invited others into a sense-making enterprise with her question, "Would that make sense?" (4.2).

Next, Maria pulled the paper toward her side of the table. Just over a week before, a group of students studying the behavior of laser beams as they enter and exit a container of water presented the class with the following "rule": "Light rays always bend in following the curve of the container" (Briana's notebook, 11/2/11). The following class period, Irene provided an analogy describing that light rays bend when they encounter a curved lens similar to the way a sculling boat with four rowers would naturally turn when the boat encounters a muddy current at an angle. Maria applied this strategy (considering the direction and degree of refraction at each interface) to the examination by drawing faint tangent lines where each light ray hits the top of lens to better visualize the angle at which each light ray enters the lens. Maria invited her group members' feedback as she drew:

4.8 Maria: . . . So this one. [Pencil touches where middle light ray hits lens.] Wouldn't it curve it this way though? [Twists fingers clockwise above paper.] A little bit like-- [Draws continuation of middle light ray through lens at a very slight bend.] (4.8-second pause)

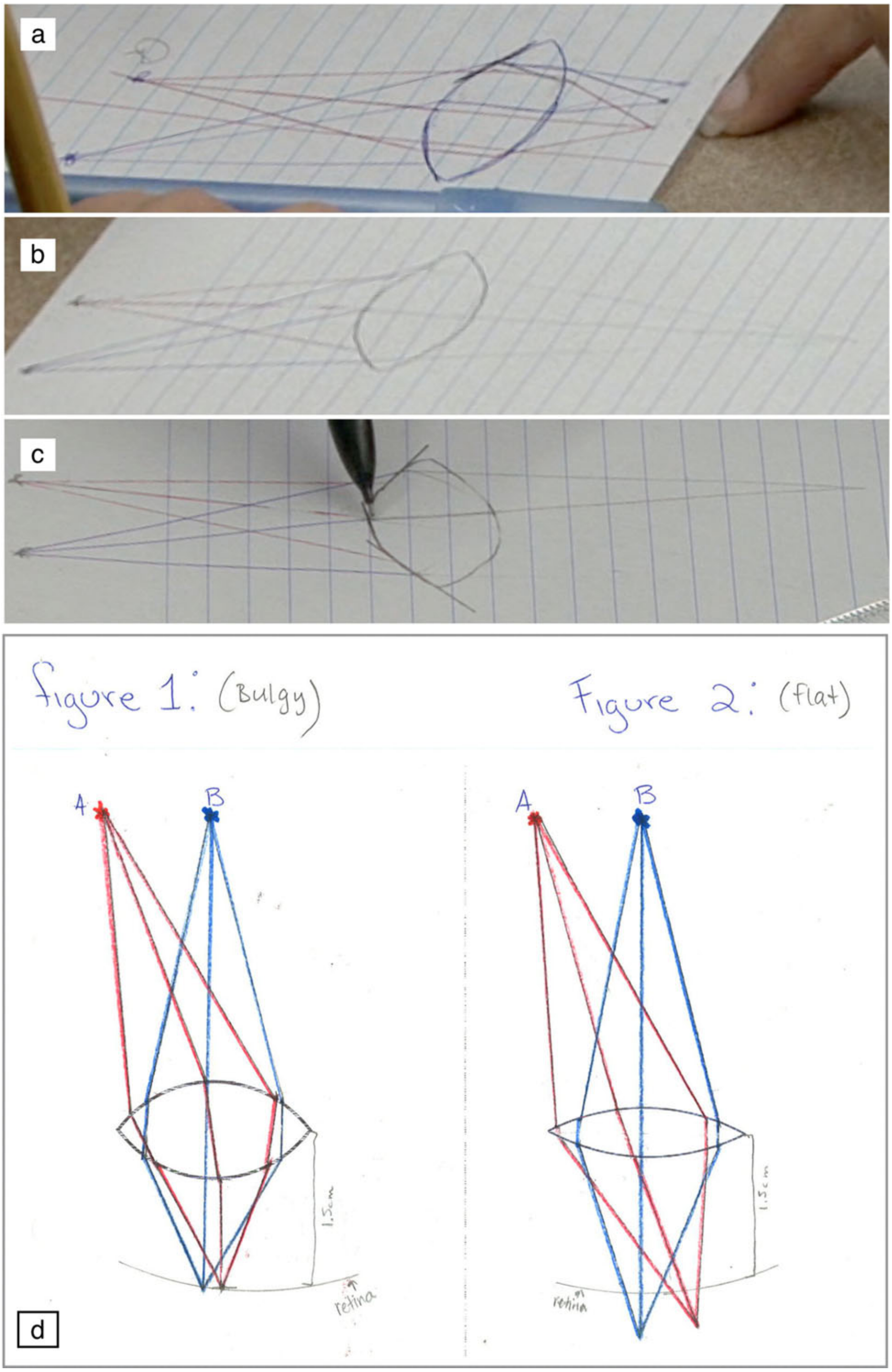


Figure 2. Group exam lens diagrams. (a) First sketch. Maria's finger points out that "they're getting squished in there" (line 4.1). (b) Carly's attempt. She asks "would that make sense?" (line 4.2). (c) Maria's attempt. The group debates whether the middle blue ray should bend more where it enters the lens (indicated by Maria's pencil). (d) Final diagram. Note that the curved line representing the retina and the distance labeled 1.5 cm were not introduced until Episode 5.

4.9 Briana: Yeah.

4.10 Maria: And this one [points to upper light ray where it hits lens] would be the same right? So inward? [Draws continuation of upper light ray through lens at a sharper bend.] And this one [points to bottom light ray where it hits lens] is perpendicular kind of so it--

4.11 Briana: So looking at this one [points to upper light ray where it passes through lens] the way that they described the whole boat thing-- Yeah it would turn this way. And this one [points to middle light ray where it passes through lens] would turn this way too.

4.12 Tui: Mmm-hmmm.

Maria's idea proved useful to others in her group. With her group's approval, Maria used her ruler to draw firm lines extending her tentative guesses (see Figure 2c). However, as the lines were drawn, Briana raised a new concern:

4.16 Briana: It's gotta bend more than that. I feel like if they were looking at that they'd say that's a straight line all the way from here [points to starburst] to there. [Points to where lines come together past lens.]

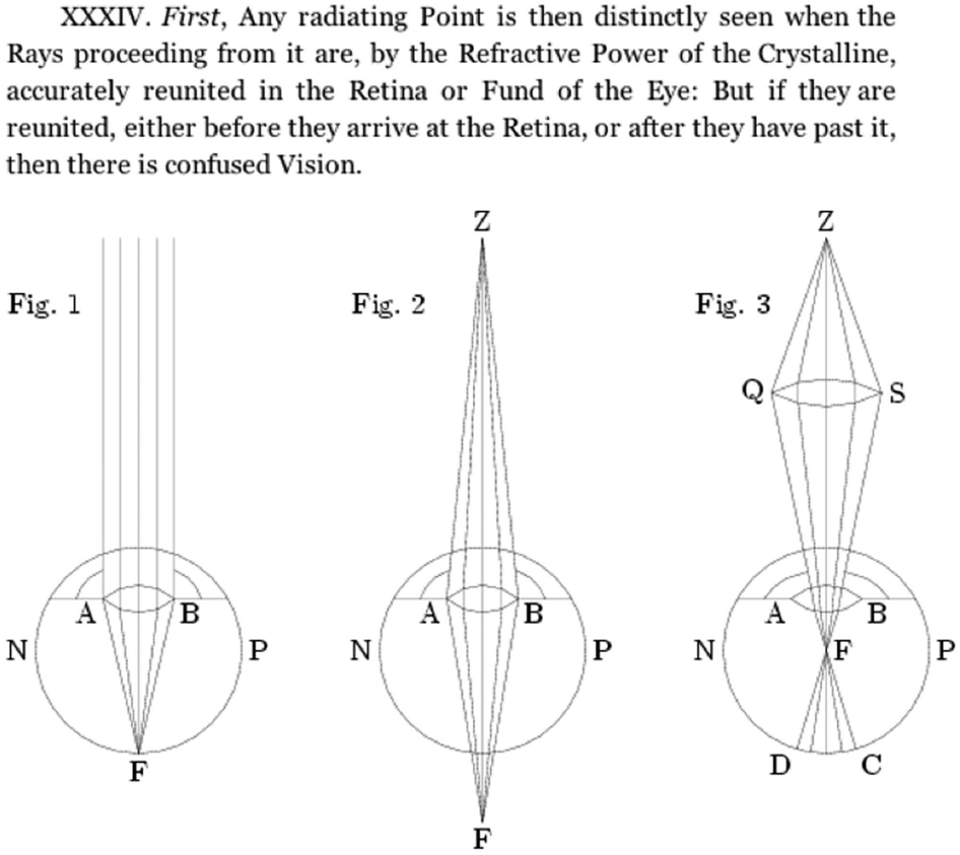
Tui supported Briana's assertion and suggested that the image point should shift downward. Maria responded by modifying her diagram and then handed the paper back to Carly.

This episode is representative of the entire hour this group spends diagramming. The entire effort is highly collaborative. They often switched artists, and there were frequently two or three fingers or pencils touching the paper simultaneously. With respect to the Subjectivity NOS theme, students recognized the importance of different opinions and actively sought out their teammates feedback as they worked (4.2, 4.8, 4.10). This collaborative effort stands in stark contrast to the way Channel's group deferred to Channel and her friend when they worked on their whiteboard in the first week of class. In terms of the Empiricism and Process NOS themes, there was a clear interplay between generating, refining, and debating ideas that was grounded in theories generated from data. Their final diagram was representative of their combined efforts (see Figure 2d). As they wrapped up Part 1 of the examination, their written explanation concluded, "The main difference between Figure 1 and Figure 2 is the distance between A and B on the retina. On Figure 1, A and B are closer together on the Retina than they are in Figure 2" (Group exam, p. 1).

Episode 5: Multiple Strands of Data Lead to a Scientific Breakthrough. As the group moved into Parts 2 and 3 of the examination, they made some observations with a bulgy and a flat lens and considered which would be better for focusing on nearby objects and which would be better for focusing on far away objects. Tui was the first to suggest that a bulgy lens might be best for nearby objects because a bulgy lens would bend light rays more; after some discussion, the others agree. This episode explores how several lines of evidence come together to support Tui's idea as well as another creative breakthrough.

Forty minutes before this episode begins, Briana retrieved a handout from class (Figure 3) with a passage by George Berkeley. At that time, she pointed out that Berkeley's Figure 1 could not feature a bulgy lens because the light rays would bend in too much. Episode 5 begins as she revisited this idea:

5.1 Briana: In the very beginning though, we were talking about this one [points to their Part 1 flat lens diagram] being far away based on this diagram [picks up Berkeley



XXXIV. *First*, Any radiating Point is then distinctly seen when the Rays proceeding from it are, by the Refractive Power of the Crystalline, accurately reunited in the Retina or Fund of the Eye: But if they are reunited, either before they arrive at the Retina, or after they have past it, then there is confused Vision.

Figure 3. Diagram from George Berkeley's *An Essay Towards a New Theory of Vision* (1709, p. 34). Provided as an in-class reading to spark a conversation about blurriness.

> handout] because if it was flatter like that [points to flat lens diagram] and they're so far away that they are almost coming in parallel lines [points to Figure 1 of Berkeley] . . .

Carly then relates the Berkeley diagram back to Tui's idea that a bulgy lens would bend light rays more, and conversely, that a flat lens would bend light rays less. The exchanges that followed drew further connections between the Berkeley diagrams and Tui's ideas. Finally, Carly became confident enough to pencil in some labels on their lens diagram: "Near" under the bulgy lens and "far" under the flat lens.

Next, Maria added further evidence to the pile by drawing attention to the actual observations they made with physical lenses. Previously, they observed that when a flat lens was held at a constant 15 centimeters above the paper, a point source light had to be "very far away to get a fry-an-ant spot (≈60 cm from paper)" (Group Exam p. 4), but the light could be much closer to the bulgy lens to achieve the same concentrated image point. Maria pointed out,

> 5.8 Maria: You know how with the flat lens we were all the way up here, [holds hand far above head] so then all the rays are coming in parallel already [brings hands down towards table gesturing towards single spot above table].

5.9 Briana: Yeah.
5.10 Maria: They will come to that one spot together. The angles just-- Yeah.
5.11 Briana: Because like if it was far away and the lens was bulgy, it would bend it too much.
5.12 Maria: Mmm-hmmm. And they would be--
5.13 Briana: Out of focus. Like it would bend it too much and they'd be meeting back here [points to a spot below the image points] past the retina or something and it wouldn't actually--

Maria's move is an example of how students are using data in sophisticated ways as part of the Empiricism NOS theme—she did not use the data to state the obvious (e.g., Maria could have said, "The flat lens only worked when the light was far away so it must be for viewing far away things.") but rather, she used the data to generate arguments in support of coherent, mechanistic explanations (e.g., Maria relates the far away light source to the parallel light rays in Berkeley's diagram as well as Tui's ideas about bulgy lenses bending light more than flat ones.)

In line 5.13, Briana introduced the idea that a bulgy lens might bend light too much so that it would not meet *on* the retina, but instead might meet *past* the retina. Although her language did not match where she pointed on the paper (Briana should have said meet *before* the retina), Tui immediately picked up on the importance of this idea:

5.14 Tui: Well what's nice about our drawing is that our retinas are in different places [puts left finger on bulgy lens image point and pencil in right hand on flat lens image point].
5.15 Briana: No.
5.16 Maria: But that's okay because this is the curve for that one [lightly draws line connecting image points on bulgy lens diagram] and that is the curve for the other one [lightly draws line connecting image points on flat lens diagram].
5.18 Tui: Yeah but that's not-- our retinas stay the same size from where our lens is so--
5.19 Carly: Yeah.
5.20 Tui: So that one [points to bulgy lens diagram] would be blurry.
5.21 Maria: It's just-- (7.8-second pause) It's not like they're the same eyes. Wait, I don't know.
5.22 Tui: I think they are. I think it's talking about how our lens changes.

At first, Maria and Briana do not understand what Tui is trying to say (5.14). Tui has realized that the distance between the lens and retina in an eyeball would stay the same, no matter what shape the lens takes on. Thus, if you interpret their two diagrams in Figure 2d as the same eye accommodating to a single object, then only one lens shape, the bulgy lens, would work. Briana's comment (5.15) and Maria's comment (5.21) reveal that they do not yet grasp Tui's idea. Tui continues to try and explain:

5.26 Tui: . . . So that this [uses thumb and forefinger of both hands to measure distance from originating points of light and lens for both bulgy and flat lens] is the same distance. This [uses thumb and forefinger to measure distance from lens to the image points] is a clear image. So I think that's--
5.27 Carly: Cause these all [points to Figures 1 and 2 in Berkeley] go to the same part too.
5.28 Briana: Ohhh!
5.29 Tui: It's like this [indicates Figures 2 and 3 in Berkeley] where they meet up isn't/ at the right spot.

5.30 Briana: /If these [points to line of originating points of light on diagram] are at the same distance, it's not going to be clear on one of these [touches bulgy then flat lens diagram] /because it would have to be--
5.31 Tui: /Yes, that's what I mean.
5.32 Briana: --far away for it to be clear.
5.33 Tui: That's why I think it is important that we didn't do our retina in the same place.

As the others "get it," the conversation went into overdrive in the same way that Gallas (1995) reported an "uproar and a temporary dissolution of order in the group" (p. 42) when a new theory emerges among the children in her elementary classroom. Briana and Tui interrupted each other and completed each other's thoughts (5.29–5.32) as they fed off the energy the new theory brought to the discussion. After a few more utterances both Carly and Maria came on board. Tui reached for a protractor and added a curved retina to both parts of the group's lens diagram such that the retina was always equidistant from the center of the lens (see Figure 2d). In the written portion of the examination, they state,

> Our observations makes sense with our diagram from part one. If both the lenses are the same distance from the objects (A + B) being observed, Figure 1's rays will be in focus on the retina while Figure 2's rays would be blurry (focused past the retina). The bulgy lens (Figure 1) bends the light at bigger angles [than the flat lens (Figure 2)] causing the light rays from 1 point to come back together in less distance." (Group Exam p. 4)

Episode 5 reveals some of the strategies our students use to "shop for ideas" (Hammer & Van Zee, 2006, pp. 21–23), resolve conflict, and make scientific breakthroughs. They continually refer to Berkeley as a consensus idea that can be applied to other situations. This is supplemented by their own observations and ideas about the relationship between lens curvature and the behavior of light rays. The ability to draw upon such diverse strands of supporting evidence highlight the many ways in which students are creative (Creativity NOS theme) and can use data in sophisticated ways (Empiricism NOS theme). Finally, although their ideas are not fully fleshed out, this episode suggests a sophisticated grasp of the Process NOS theme in that they know to shop for ideas from many diverse sources without instructor support.

Episode 6: Connecting the New Breakthrough to Prior Knowledge. A final episode in the last 10 minutes of the period provides an opportunity for us to observe a powerful moment of personal sense making that allowed this group to weave together their investigations about pupil shape to the new theories developed during this examination. To begin Episode 6, Briana read from Part 4 of the examination:

6.1 Briana: And the next question is, "Does the bulgy cornea interact in any way with the cat's slit pupil?"
6.2 Carly: No. Right?
6.3 Tui: Ummm, I think it would focus/ in on--
6.4 Briana: /A little bit.
6.5 Tui: --the center of it. Like how we were talking-- like how like their slits sits on their lens differently.
6.6 Briana: Yeah.

Their first impression was that there would be a minor effect—that as the slit pupil sits on the lens, the lens corrects any blurriness by bringing all the light rays from a single originating point back together again on the retina. In prior experiments with a pinhole theater fitted with differently shaped "pupils" and a lens, Briana observes, "We basically saw the same thing with every single shape" (Briana's science notebook, 10/14/11). A few days later, the group tried highly elongated slits in their pinhole theater and a lens placed before the "pupil." They observed that the image on the screen was elongated in the same direction as the slit and concluded that "pupils don't warp vision, they just limit the range… For animals, there is (usually) a preferred range of view depending on (1) how they get their food + (2) if they are hunted or not." (Tui's science notebook, 10/31/11). For instance, they concluded that crepuscular ambushers like cats or snakes would benefit from vertically slit pupils since they could open their pupils wider in the semidarkness to let in more light, but even with narrowed pupils, they would be able to stalk their prey from above or below at close range, only sacrificing a little peripheral vision in return.

However, as they think more deeply about this examination question, Tui and Briana discovered a connection between their prior investigations and what they learned about lenses through working on the group exam:

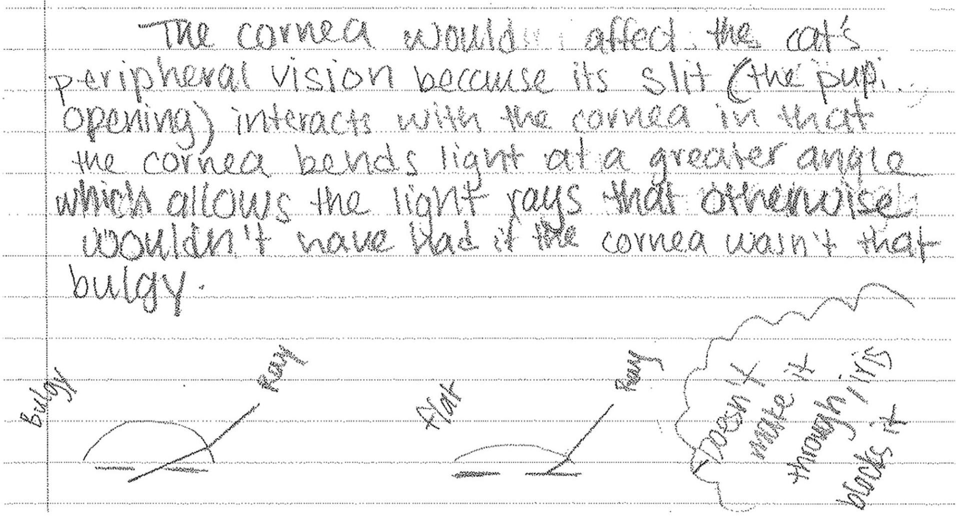
6.9 Tui: Oh, but maybe the cornea WOULD interact with the peripheral vision. Because it's going to allow more in and bend in and get in the slit.
6.10 Briana: Oh, THAT'S interesting to think about. Because we weren't even considering/ that before.
6.11 Tui: /We weren't thinking about--
6.12 Briana: We weren't even considering the cornea.
6.13 Tui: So they're still not going to have the peripheral vision. [Opens arms to the sides.]
6.14 Briana: So it might not be like us but, if you just think of peripheral as the edge of their vision--
6.15 Tui: So when we were doing it, we needed to have the lens outside *and* inside to be able to tell.
6.16 Briana: A bulgy lens and a flat one.
6.17 Tui: Mmmmmm! [Laughs with Briana.] Eureka! I learned something new on the last day.

The conversational order dissolved once again as a new theory emerged. Briana and Tui realized that the bulgy cat cornea could bend light rays coming from the periphery into the interior of the eye, ones that otherwise would not make it into the vertically slit pupil. However, in the uproar, Briana and Tui have run ahead of the others in their group. Buried among the continued conversation between Briana and Tui, Maria and Carly played a supporting role:

6.18 Maria: So what is it?
6.26 Carly: Will you repeat it for me?

Though easy to ignore Maria and Carly's role in the dialog, such conversational moves—extending and revoicing conversational turns—position ideas as having value to the conversation and can function to maintain and resolve a conversation (Barron, 2003; Hogan, Nastasi, & Pressley, 2000; Sawtelle, Sikorski, Turpen, & Redish, 2012). Tui explained the idea further, while Briana developed a diagram. Between their efforts to carefully articulate their ideas, Carly and Maria came to agree with the claims:

6.28 Briana: [To Maria who was still writing] Hold on, wait a minute let's just talk this out really quick.



The cornea would affect the cat's peripheral vision because its slit (the pupil opening) interacts with the cornea in that the cornea bends light at a greater angle which allows the light rays that otherwise wouldn't have had if the cornea wasn't that bulgy.

Figure 4. Group's response to Part 4 of the examination. Maria wrote the text, and Briana drew the diagram.

6.29 Maria: Okay.
6.30 Tui: So the bulgy cornea will let the light bend in a little more. So it would get in. Like it would help the peripheral vision because we were thinking like light from here [holds flat hand out 45 degrees from face] wouldn't get in [brings wrist in toward eye]. But if like here [holds flat hand out 60 degrees from face] it's coming [brings wrist in towards eye] and then bending in [changes angle of hand to nearly perpendicular to face], then that can fit too [darts hand in and out from eye].
6.31 Briana: [Drawing on scratch paper] So it like if it's--
6.32 Tui: With the bigger bulge it comes into the slit--
6.33 Carly: OH! . . . That makes sense.

We can compare Episode 3 in which Elena feels "completely lost" (3.1) with Episode 6 where Tui has her "Eureka!" moment (6.17). Whereas at the start of class, Tui and Briana might have accepted feeling "lost" as part of being in science class, they now not only seek scientific theories for themselves but fully integrate disparate experiences including everyday knowledge, their extensive research on differently shaped pupils, and their new understandings developed during the examination.

Furthermore, we can compare Channel's one-sided idea development and whiteboard construction (Episode 2) with the far more community-minded approach of this group in Episode 6. Maria and Carly, though playing less of an active role in developing the ideas, are engaged and asking for clarification; Tui and Briana systematically explained their ideas, and through this explanation refined their claims. The final product was a combination of a written explanation by Maria and a set of diagrams by Briana (see Figure 4).

Relationship Between Declarative and Procedural Understandings About NOS

We can now return to the question that began this paper: "Does what a student say about NOS reflect what they actually do when they engage in authentic scientific inquiry?" For example, if we consider Episodes 4–6 as a whole, we can see that Carly and Maria primarily adopt the role of artist or scribe, whereas creative, breakthrough scientific ideas are mostly generated by Tui and Briana. Is this because Carly and Maria have different underlying assumptions about the purpose of science? For example, in her precourse VNOS-C questionnaire, Maria said that "an experiment has a certain method and steps one has to follow." Even at the end of the course, she maintains a science fair approach: "Part of an experiment is having a question ... Other parts of an experiment is the data, observations ... Finally there's a reflection (what is this information telling me & why do I think this.)" Might she reject the flexible approach to data collection and analysis taken by her group members? Or perhaps this difference in their participation suggests that Carly and Maria have a weaker understanding of NOS and weaker overall grasp of scientific practice?

In Table 4, one can see from the VNOS-C coding of Maria, Tui, and Briana's postcourse response (and degree of change) that differences between what they *say* about NOS cannot explain the difference in the style of their participation. With only one exception, Maria always shares her NOS stance with either Tui or Briana. Carly failed to complete the postcourse reflection, thus her data are not shown.

Furthermore, our development of scientific practice analysis suggests that Carly and Maria understand the goal of science and know how to engage in scientific practices just as well as Tui and Briana. For instance, Carly and Maria do not attempt to push the others in their group to look to an authority figure for answers; they do not insist upon following a rigid, stepwise scientific method; nor do they discount everyday evidence as "unscientific." In fact, it is Maria who brings in the strategy of drawing tangent lines in Episode 4 and integrates the group's direct observations with bulgy versus flat lenses with their emerging theories in Episode 5.

Their unique participation styles are most likely related to different individual strengths. For instance, Maria is generally a quiet, organized, and meticulous student. She seems to simply be playing to her strengths by adopting the role of the observant note-taker and the maker of connections between existing lines of evidence.

So is there any relationship at all between what students say and what they do when it comes to NOS? If you attempt to match an individual students' declarative statements about NOS and what they do in authentic inquiry settings, generally there is little relationship (Table 4). A perfect example of this is in the realm of the Creativity NOS theme. For instance, in Tui's postcourse interview she says: "I think that scientists have to use creativity, um otherwise they would just study the same things. Like-- we definitely had to use creativity in this class to figure out how to find things out." When pressed for examples of times in the course that she used creativity and imagination, she provided three examples, all of which were related to the experimental design phase. Her interview corresponds well with the written response on the VNOS-C questionnaire: "I think that scientists have to be creative during their experiments or else they would never find any new results! I think that most of the creativity is needed during the planning and design stages." However, consider the two creative insights Tui had in Episodes 7 and 8. First she imagined that perhaps the two figures they had drawn represented the same eye looking at the same object but with different shaped lenses. Later, she realized a cat's bulgy cornea could interact with a slit pupil to allow greater peripheral vision. Yet somehow these bursts of creativity as applied to coming up with new ideas and interpreting results did not meet with her definition of what should "count" as creativity. Although she was clearly creative, she failed to consider these instances on the questionnaire and interview.

Another example of a disconnect between what students say and do may be found with Briana and the Process NOS theme. Consider this excerpt from Briana's postcourse interview:

TABLE 4
Comparison of What Students Say Versus What They Do

	What They Say			
NOS Theme	Maria	Tui	Briana	What They Do
Empiricism	Yes: Experiments help individuals to learn better (slight change from experiments/observations lead to facts)	Yes: Experiments help individuals to learn better (no change)	Yes: Experiments/observations allow us to figure out how/why things work (no change)	Students use multiple data sources to support their own insights and new theories (Episodes 4–6)
Process	Science fair (slight change from the scientific method approach)	Science fair (no change)	Science fair (slight change from the scientific method approach)	Students adopt a very flexible experimental approach to generating and testing ideas that is clearly not science fair like (throughout course)
Tentativeness	No: Theories proven to be true (no change)	Yes: (Durability) theories change with new evidence (no change)	Yes: (Durability) theories change with new evidence (no change)	No evidence in these episodes
Subjectivity	No: Ultimately data will tell you (no change)	No: Ultimately data will tell you (slight change from perhaps some bias but ultimately data will tell you)	No: Ultimately data will tell you (no change)	Students talk out their differences, presenting more and more supporting lines of evidence until the whole group is convinced (Episode 5 and 6)
Context	Both: affects process but ultimately science is universal (no change)	Both: affects interpretations but ultimately science is universal (no change)	Both: affects process but ultimately science is universal (slight change from just universal)	Students actively seek out deep, personal understanding that aligns with everyday experiences (Episode 6)
Creativity	Yes: in designing experiment and in collecting/presenting data (no change)	Yes: in designing experiment and interpreting results/generating explanations (slight change from just interpreting results)	Yes: in interpreting results/generating explanations (large change from designing experiment and in collecting/presenting data)	Students are creative in many ways: coming up with ideas (Episodes 5 and 6), collecting data (Episode 5), generating explanations (Episode 5 and 6), and communicating ideas (Episodes 4–6)

The degree and direction of changes in these three students' VNOS-C responses are in parenthesis.

Int.1 Briana: I'd say an experiment is like when you think of something or you think you've figured out how something works, you have to go and test your hypothesis to see if it's right. So your experiment would be figuring out what you think it is and trying to prove if you are right or not. And then if you are, well I guess your your experiment was successful, but if not, then figuring out the variables and different stuff like that to see if you can try again.
Int.2 Leslie: Are there particular steps that someone has to go through to have a valid experiment?
Int.3 Briana: Um, I'm trying to think back to what we did in class. We always had-- see like with the box theater we had predictions first of what we thought would happen and then, um, why we thought that would happen. Then we would do the observation or the experiment and see if our thoughts were right or not. And then, from there change it or tweak it until you get what you want.
Int.4 Leslie: And you think that's pretty standard for all of science? That that's when you're doing experiments that it's having a prediction of what I'm going to see and testing it out?
Int.5 Briana: Yeah. You need to have an idea of what you are trying to find and what you think you will find and then you have to go and test to see if you find that.

Clearly, she *says* that science follows a relatively straightforward scientific method with a hypothesis followed by a test to determine whether your prediction was correct. However, that is not representative of what actually happened procedurally. For instance, all of Briana's data collection about slit pupils preceded any theory generation. The only "hypothesis" that Briana went into her pinhole theater experiments with were of the "what--if" variety: "We want to know how the shape of the pupil affects how things see," (Briana's science notebook, 10/7/11) and "Today we are going to take the index cards with different shapes cut in them and use them with the box to see how the images change, or don't" (Briana's science notebook, 10/14/11). They could not possibly "see if our thoughts were right or not" (Int.3) because they had not established concrete predictions going into their experiments. It was only after collecting data that they generated any theories about how differently oriented pupils might benefit animals with different lifestyles. Similarly, it was only after thinking about lenses for 2 hours that Briana realized there might be a relationship between a cat's bulgy cornea and its slit pupil.

A final example is provided by Carly and the Epistemology theme. The grasp of scientific practice analysis in Episode 2 shows how Carly and the others in her group readily changed their original idea to the one espoused by Channel's friend (defer to authority) in contrast to the sense making based on multiple types of data that occurred in Episodes 5 and 6. If what students say and what they do were correlated, one might assume that the EBAPS subscale related to the nature of knowing and learning (to learn science, should one merely absorb information from a higher authority or should one actively construct understanding?) would reflect a substantial shift in that subscore. In fact, there was very little change in Carly's score: from 2.69 to 3.06. The two areas in which Carly's score did change pre--post was in real-life applicability (does scientific knowledge and thinking apply just to the classroom and laboratory or does it apply to real, everyday life?; from 2.75 to 1.75; interestingly the decrease indicates that she believes science to be *less* applicable to real life than before) and evolving knowledge (where does science fall between the extremes of thinking that all knowledge set in stone versus all knowledge is mere opinion?; from 1.33 to 3.00).

CONCLUSIONS

In this study, there were few changes on the declarative measures of NOS understanding (EBAPS, VNOS-C, and interviews). This corroborates a similar finding with students in our course (Salter & Atkins, 2013) documenting a nonsignificant shift toward more expert NOS views after the course using a different validated survey measure, the Views about Sciences Survey (Halloun, 2001; Halloun & Hestenes, 1996). Here, although there was a significant increase in NOS understanding according to the EBAPS survey, the change was very small, from a precourse average of 2.79 to a postcourse average of 2.89. Even with the open-ended VNOS-C questionnaire, students on the whole show little overall change in their declarative NOS understandings. Taken together, this evidence strongly suggests that the answer to our first research question (does participation in an authentic scientific inquiry course improve students' declarative NOS understandings as measured by surveys and interviews?) is: not much.

In contrast, our students' procedural NOS understandings showed greater improvement. Whereas students initially struggled to engage productively in this open-inquiry setting (Episodes 1–3), 12 weeks later (Episodes 4–6) students were proficient at the many, intertwined aspects of authentic inquiry: generating ideas, designing experiments, using many types of evidence to support those ideas, and participating in a scientific community. For example, within the Empiricism theme, they initially sought "right" answers from their instructors (Episode 1) and accepted feeling "lost" as a natural part of science (Episode 3); by the end of the course, students expertly used observations and reasoning to support their ideas and theories (Episodes 5 and 6). Similarly, within the Subjectivity theme, in Episode 2, students casually dismissed one idea (light can change directions) in favor of another idea (light travels in straight lines) with little attempt to resolve or reconcile the differences; in Episodes 5 and 6, students sought consensus by presenting more and more lines of evidence until everyone was convinced. Clearly, what students did in the classroom changed considerably; however, our methodology is not developed enough to cleanly attribute the changes in students' scientific practices to the immersion experience in authentic scientific inquiry. We were unable to follow the same students over the course of the semester and closely monitor individual gains. Moreover, while the immersion experience in open-inquiry may have caused students to develop a more sophisticated grasp of scientific practice, it remains possible (or even probable) that the differences can be attributed to greater self-efficacy, fewer support structures (they do not ask us the right answer because they know we will not give them direct answers), different expectations about the course itself rather than about NOS, or greater familiarity with one another and with the content. The idea of familiarity may be particularly important. For example, the first time you enter a new friend's kitchen to help cook a meal, an outside observer might interpret your deference to your friend and your inability to find tools and ingredients as evidence that you are a poor chef. Increasing familiarity with your friend's kitchen and practice working together as a team would make you appear to be a better chef in the same way that familiarity with our classroom expectations and practice working with a research team would make our students appear to be better scientists. However, we would argue that much of becoming a better scientist with a more sophisticated approach to scientific practices is *exactly* this kind of familiarity with the culture, expectations, support structures, and community within which science takes place. Skill in scientific practice is inherently highly contextual, both with respect to the content of a particular area of research and with the social practices characteristic of that field—a highly skilled geologist would be all thumbs in a molecular biology setting. While additional research and methodological refinements are clearly necessary, we suspect that our students' procedural understandings did improve as the result of our course in that the course provided an authentic scientific context in which they could familiarize themselves with the know-how and social dynamics necessary to be successful in that particular scientific context.

Most interestingly, their competency with scientific practices appears unrelated to their declarative NOS understandings. In answer to our second research question (What is the relationship, if any, between declarative statements regarding NOS that our students make and how these students engage in scientific inquiry?), what they say seems to be mired in memorized definitions of key vocabulary words (e.g., “science,” “experiment,” and “creativity”) even though what they *do* goes well beyond these strict confines. For instance, Briana claims that experiments must follow a certain pattern—one that is consistent with a stepwise scientific method—and even attempts to fit her experiences in the course into that framework, though the authentic scientific work she does bears little resemblance to the pattern she describes.

These observations about our students would predict that even professional scientists who are deeply immersed in highly contextualized authentic, scientific inquiry may score poorly or inconsistently on declarative instruments like the VNOS questionnaire—which they do (Schwartz & Lederman, 2008; Wong & Hodson, 2010). Although scientists are fully and intimately versed in the doing of science, they do not need to reflect declaratively on their scientific practice; as a result, their declarative NOS understandings are often inconsistent with other scientists and with the claims of experts in the history, philosophy, and sociology of science. Thus, both scientists and students who can successfully engage in scientific practices may not necessarily be able to articulate the knowledge that they bring to bear. As Hammer and Elby (2002) state,

> Questioning students in these ways [declaratively] about their epistemologies may be, to borrow an old joke, like interviewing golfers about their swings, off the course and away from their clubs: “Do you inhale or exhale when you swing the club?” It is not something they talk about ordinarily, and they may not know the answer. (p. 4)

It may very well be the case that, to improve scores on tests of declarative NOS understandings, explicit instruction is necessary. However, if NOS understandings are primarily important for the supporting role it plays in constructing scientific ideas, then surveys assessing declarative NOS understandings may be less appropriate than measures that describe the degree to which students employ a sophisticated grasp of scientific practice.

We concur with others like Hammer, Ford, and Elby (Elby & Hammer, 2001; Ford, 2008b; Hammer & Elby, 2002) who claim that those immersed in the doing of science require a contextualized, nuanced, and sophisticated scientific epistemology, one that declarative NOS assessment instruments are poorly equipped to measure. The procedure we used to follow the development of our students’ scientific practice via observable behaviors matched to the six consensus NOS themes could serve as a step toward developing more standard approaches to measuring the development of procedural NOS understandings. This may be particularly relevant as American schools begin to shift from older state science standards that often target declarative knowledge about NOS (National Research Council, 1996) to the Next Generation Science Standards that focus on actively engaging students in scientific practice (Achieve Inc., 2013; National Research Council, 2012).

These findings leave us with several unanswered questions and avenues for further research. First, if solid procedural NOS understandings do not necessarily bring about better declarative understandings, then what benefits does an ability to engage in scientific practices afford? As advocated throughout the science education literature (e.g., Ford 2008b;

McGinn & Roth, 1999; National Research Council, 2012; Osborne, 2010), we believe that fluency with scientific practices enables students to react like a scientist when they encounter scientific information in the media, in sociopolitical contexts, and in everyday life. There is some preliminary evidence that procedural NOS understandings may lead to an ability to critically consume scientific information (Allchin, 2011; Ford & Kniff, 2006); however, further studies are essential to determine whether procedural understandings alone are sufficient or whether declarative understandings are necessary (Khishfe, 2012). Another major question concerns who, if anyone, might truly need a clear declarative understanding about NOS. While expert science researchers do not necessarily need sophisticated declarative NOS understandings, we have not yet explored whether that is true for science educators who develop curriculum and instruction in science. Absent declarative understandings, educators may fall back on folk theories of NOS—if not in the practice of science, then in the teaching of science. Akerson, Morrison, and McDuffie (2006) showed that explicit NOS instruction in a science methods class leading to more sophisticated NOS understandings was not sufficient to impart lasting changes in teachers' classroom practices. Longitudinal studies of education majors like ours are necessary to determine whether their ability to engage in sophisticated scientific practices in our classroom carries over into their own future classrooms and whether improved declarative NOS understandings are necessary as well.

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REFERENCES

Abd-El-Khalick, F., & Lederman, N. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. International Journal of Science Education, 22(7), 665–701.

Achieve, Inc. (2013). Next generation science standards. Washington, DC: Achieve, Inc., on behalf of the twenty-six states and partners that collaborated on the NGSS.

Akerson, V., Abd-El-Khalick, F., & Lederman, N. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conceptions of nature of science. Journal of Research in Science Teaching, 37(4), 295–317.

Akerson, V., & Hanuscin, D. (2007). Teaching nature of science through inquiry: Results of a 3-year professional development program. Journal of Research in Science Teaching, 44(5), 653–680.

Akerson, V., Morrison, J., & McDuffie, A. (2006). One course is not enough: Preservice elementary teachers' retention of improved views of nature of science. Journal of Research in Science Teaching, 43(2), 194–213.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. Science Education, 95(3), 518–542.

Alters, B. (1997). Whose nature of science? Journal of Research in Science Teaching, 34(1), 39–55.

American Association for the Advancement of Science. (1993). Benchmarks for science literacy. New York: Oxford University Press.

Atkins, L. J., and Salter, I. Y. (2010). Student-generated scientific inquiry. Presented at the American Association of Physics Teachers Annual Conference, Portland, OR, July 2010.

Barron, B. (2003). When smart groups fail. Journal of the Learning Sciences, 12(3), 307–359.

Bell, R., Blair, L., Crawford, B., & Lederman, N. (2003). Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. Journal of Research in Science Teaching, 40(5), 487–509.

Bell, R., Lederman, N., & Abd-El-Khalick, F. (1998). Implicit versus explicit nature of science instruction: An explicit response to Palmquist and Finley. Journal of Research in Science Teaching, 35(9), 1057–1061.

Bell, R., Matkins, J., & Gansneder, B. (2011). Impacts of contextual and explicit instruction on preservice elementary teachers' understandings of the nature of science. Journal of Research in Science Teaching, 48(4), 413–436.

Berkeley, G. (1709). An essay toward a new theory of vision (2nd ed.). Dublin, Ireland: Aaron Rhames, for Jeremy Pepyat, Bookseller in Skinner-Row.

Chinn, C., & Malhotra, B. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. Science Education, 86(2), 175 – 218.

Deng, F., Chen, D. T., Tsai, C. C., & Chai, C. S. (2011). Students' views of the nature of science: A critical review of research. Science Education, 95(6), 961 – 999.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. Science Education, 84, 287 – 312.

Elby, A. (2001). Helping physics students learn how to learn. American Journal of Physics, 69(S54), S54 – S64.

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. Science Education, 85(5), 554 – 567.

Engle, R., & Conant, F. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. Cognition and Instruction, 20(4), 399 – 483.

Ford, M. J. (2008a). Disciplinary authority and accountability in scientific practice and learning. Science Education, 92, 404 – 423.

Ford, M. J. (2008b). "Grasp of Practice" as a reasoning resource for inquiry and nature of science understanding. Science & Education, 17, 147 – 177.

Ford, M. J. (2010). Critique in academic disciplines and active learning of academic content. Cambridge Journal of Education. 40(3), 265-280.

Ford, M. J., & Kniff, K. J. (2006). Groundwork for progress supporting scientific literacy: An expert-novice study. Presented at the Annual Meeting of the National Association for Research in Science Teaching, San Francisco, CA, April 2006.

Gallas, K. (1995). Talking their way into science: Hearing children's questions and theories, responding with curricula. New York: Teachers College Press.

Graesser, A., & Person, N. (1994). Question asking during tutoring. American Educational Research Journal, 31(1), 104 – 137.

Halloun, I. (2001). Student views about science: A comparative survey. Beirut, Lebanon: Educational Research Center.

Halloun, I., & Hestenes, D. (1996). Views about sciences story. Presented at the National Association for Research in Science Teaching, St. Louis, MO, April 1996.

Hammer, D., & Elby, A. (2002). On the form of a personal epistemology. In B. Hofer & P. Pintrich (Eds.), Personal epistemology: The psychology of beliefs about knowledge and knowing (pp. 169 – 190). Mahwah, NJ: Erlbaum.

Hammer, D., & Van Zee, E. (2006). Seeing the science in children's thinking: Case studies of student inquiry in physical science. Portsmouth, NH: Heinemann.

Hogan, K., Nastasi, B. K., & Pressley, M. (2000) Discourse patterns and collaborative scientific reasoning in peer and teacher-guided discussions. Cognition and Instruction, 17(4), 379 – 432.

Holbrook, J., & Rannikmae, M. (2007). The nature of science education for enhancing scientific literacy. International Journal of Science Education, 29(11), 1347 – 1362.

Jones, M., & Carter, G. (2008). Science teacher attitudes and beliefs. In S. Abell & N. Lederman (Eds.), Handbook of research on science education (pp. 1067 – 1104). New York: Routledge.

Jones, S. E., & LeBaron, C. D. (2002). Research on the relationship between verbal and nonverbal communication: Emerging integrations. Journal of Communication, 52(3), 499 – 521.

Khishfe, R. (2012). Nature of science and decision-making. International Journal of Science Education, 34(1), 67 – 100.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. Journal of Research in Science Teaching, 39(7), 551 – 578.

Latour, B., & Woolgar, S. (1979). Laboratory life: The construction of scientific facts. Princeton, NJ: Princeton University Press.

Lederman, N. (2008). Nature of science: Past, present, and future. In S. Abell & N. Lederman (Eds.), Handbook of research on science education (pp. 831 – 879). New York: Routledge.

Lederman, N., Abd-El-Khalick, F., & Bell, R. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. Journal of Research in Science Teaching, 39(6), 497 – 521.

Marshall, C., & Rossman, G. B. (2010). Designing qualitative research (5th ed.). Thousand Oaks, CA: Sage.

McCaskey, T. L., & Elby, A. (2004). Probing students' epistemologies using split tasks. Presented at the Physics Education Research Conference, Sacramento, CA, August 2004.

McComas, W. F., & Olson, J. K. (2002). The nature of science in international science education standards documents. In W. F. McComas (Ed.), The nature of science in science education: Rationales and strategies (pp. 41–52). Dordrecht, The Netherlands: Kluwer (Springer).

McGinn, M. K., & Roth, W. M. (1999). Preparing students for competent scientific practice: Implications of recent research in science and technology studies. Educational Researcher, 28(3), 14–24.

National Academy of Science. (1998). Teaching about evolution and the nature of science. Washington, DC: National Academies Press.

National Research Council. (1996). National Science Education Standards. Washington, DC: National Academies Press.

National Research Council. (2007). Taking science to school : Learning and teaching science in grades K-8. (R. Duschl, H. Schweingruber, & A. Shouse, Eds.). Washington, DC: National Academies Press.

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

Osborne, J. (2010). Arguing to learn in science: The role of collaborative, critical discourse. Science, 328(5977), 463–466.

Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. International Journal of Science Education, 25(9), 1049–1079.

Rathjen, D., Doherty, P., & the Exploratorium Teacher Institute. (2002). Square wheels: And other easy-to-build, hands-on science activities (An Exploratorium science snackbook series). San Francisco, CA: The Exploratorium.

Roth, W., & Lee, S. (2004). Science education as/for participation in the community. Science Education, 88, 263–291.

Salter, I. Y., & Atkins, L. J. (2012). Surveys fail to measure grasp of scientific practice. Presented at the Physics Education Research Conference, Philadelphia, PA, August 2012.

Salter, I. Y., & Atkins, L. J. (2013) Student generated scientific inquiry: Course development, outcomes and implications. Journal of Science Teacher Education, 24(1), 157–177.

Sandoval, W. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. Science Education, 89(4), 634–656.

Sawtelle, V., Sikorski, T. R., Turpen, C., & Redish, E. F. (2012). Examining the positioning of ideas in the disciplines. Presented at the Physics Education Research Conference, Philadelphia, PA, August 2012.

Schwartz, R., & Crawford, B. (2006). Authentic scientific inquiry as context for teaching nature of science. In L. Flick & N. Lederman (Eds.), Scientific inquiry and the nature of science (pp. 331–355). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Schwartz, R., & Lederman, N. (2008). What scientists say: Scientists' views of nature of science and relation to science context. International Journal of Science Education, 30(6), 727–771.

Shapiro, B. (1996). A case study of change in elementary student teacher thinking during an independent investigation in science: Learning about the "face of science that does not yet know". Science Education, 80(5), 535–560.

Smith, M., & Scharmann, L. (1999). Defining versus describing the nature of science: A pragmatic analysis for classroom teachers and science educators. Science Education, 85(4), 493–509.

Somerville, J. (1941). Umbrellaology, or, methodology in social science. Philosophy of Science. 8, 557-566.

Stanley, W. B., & Brickhouse, N. W. (2001). Teaching sciences: The multicultural question revisited. Science Education, 85(1), 35–49.

Tosun, T. (2000). The impact of prior science course experience and achievement on the science teaching self-efficacy of preservice elementary teachers. Journal of Elementary Science Education, 12(2), 21–31.

Traweek, S. (1988). Beamtimes and lifetimes: The world of high energy physicists. Cambridge, MA: Harvard University Press.

Watters, J., & Ginns, I. (2000). Developing motivation to teach elementary science: Effect of collaborative and authentic learning practices in preservice education. Journal of Science Teacher Education, 11(4), 301–322.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. Science Education, 92, 941–967.

Wong, S., & Hodson, D. (2010). More from the horse's mouth: What scientists say about science as a social practice. International Journal of Science Education, 32(11), 1431–1463.

Ziman, J. (2000). Real science: What it is and what it means. Cambridge, England: Cambridge University Press.