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High School Students' Ideas about Theories and Theory Change after a Biological Inquiry Unit

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Abstract: Students' epistemological beliefs about scientific knowledge and practice are one important influence on their approach to learning. This article explores the effects that students' inquiry during a 4-week technology-supported unit on evolution and natural selection had on their beliefs about the nature of science. Before and after the study, 8 students were interviewed using the Nature of Science interview developed by Carey and colleagues. Overall, students held a view of science as a search for right answers about the world. Yet, the inconsistency of individuals' responses undermines the assumption that students have stable, coherent epistemological frameworks. Students' expressed ideas did not change over the course of the intervention, suggesting important differences between students' talk during inquiry and their abilities to talk epistemologically about science. Combined with previous work, our findings emphasize the crucial role of an explicit epistemic discourse in developing students' epistemological understanding. © 2003 Wiley Periodicals, Inc. J Res Sci Teach 40: 369–392, 2003

Students beliefs about the nature of scientific knowledge and the ways in which that knowledge is produced and evaluated affect how they attempt to learn science (Hammer, 1994; Hogan, 1999; Roth & Roychoudhury, 1994; Songer & Linn, 1991). One of the primary goals in current national standards for science education is that students' engagement in inquiry should help them develop a sophisticated understanding of the nature of science (e.g., National Research Council, 1996). This poses a dilemma: If students' beliefs about science are going to drive, at least in part, the ways in which they conduct their own inquiry, how can such inquiry change students' beliefs about what science is about? There is a large body of research to suggest that students' beliefs about science and their views of themselves as science learners may be inconsistent with goals for scientific inquiry and inquiry-based science learning [for reviews, see Driver, Leach, Millar, & Scott (1996) and Lederman (1992)]. This raises two serious questions regarding inquiry-based science learning approaches: Can inquiry experiences in fact change students' beliefs about

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the nature of science? If the answer to this question is yes or maybe, how can we structure inquiry experiences so that they are likely to develop students' understanding of the nature of science?

This article presents an effort to answer the first question empirically by examining whether and how high school students' beliefs about the nature of science changed over the course of a 4-week inquiry-based unit on natural selection and evolution. The broader project from which our data are taken is an effort to understand how we might answer that second question using an approach we call explanation-driven inquiry, in which students' inquiry is explicitly framed and supported as an effort to develop causal, evidence-based explanations using theoretical frameworks of the discipline (Reiser, Tabak, Sandoval, Smith, Steinmuller, & Leone, 2001; Sandoval & Reiser, under review). Here, we want to know whether students' efforts to coordinate rich, complex sets of data with causal explanations for events of natural selection would change their understanding of the nature of science, especially their ideas about what theories are, how they change, and the relationship between theories and experimentation. Would students' personal investigation into real scientific problems change their expressed views about formal science?

Science as Epistemic Practice

We view science as a socially situated practice in which scientists' values for what count as good questions, appropriate methods, and good answers are constructed and negotiated within particular scientific disciplines and communities. Such practices are inherently epistemic, based on ideas about what kind of knowledge is valued. This view is supported by current philosophical views of science (e.g., Kuhn, 1970) and by sociological studies of professional science (e.g., Latour, 1987; Latour & Woolgar, 1986). In line with this view of scientific practice, we ground our approach in sociocultural views of learning (Lave & Wenger, 1991; Vygotsky, 1978) and especially the model of cognitive apprenticeship (Collins, Brown, & Newman, 1989). On this view, to learn science is to be apprenticed into the reasoning and discursive practices of particular scientific communities. Such an apprenticeship is inherently epistemic, necessarily including the development of standards for evaluating both knowledge claims and the methods for generating them.

There is a difference, though, between epistemic practice and epistemological practice. Epistemic practices are those concerned with the generation and evaluation of knowledge (Sandoval, Bell, Coleman, Enyedy, & Suthers, 2000). Epistemological practices would be those concerned specifically with epistemology, or theories of knowledge. For example, students could engage in theory building or theory discovery without necessarily questioning their ideas of what theories are and what they are for. On the other hand, students' engagement in desired epistemic practices, such as considering the fit of theories to evidence, evaluating alternative hypotheses or explanations, and so on (cf. Gitomer & Duschl, 1995), may rely on epistemological conceptions of the nature and purpose of science. That is, students need to understand why it is worth considering alternatives, or why theories need to fit data, and so on.

Lemke (1990) showed how the way that teachers and students talk science in school communicates a set of values suggesting scientific knowledge is authoritarian, objective, and incontrovertibly factual. This science talk is reinforced by the way in which students do science in school, performing predesigned laboratory activities divorced from any particular question and predestined to achieve a certain result. This final form science (Duschl, 1990) prevents students from developing robust ideas of scientific theories and theory building. This form of instruction skews the relation between theory and evidence too heavily toward evidence, and evidence is seen as objective rather than as theoretically constrained (Hodson, 1988; Lemke, 1990). It is not surprising to find that students thus tend to view science as the accumulation of objective, isolated facts about the world, rather than an effort to explain the world (Carey & Smith, 1993; Driver et al., 1996; Lederman, 1992). In our work, like others interested in promoting and supporting science inquiry, we are trying to change the ways that students do science and talk science. One of the goals of the present study is to see whether this leads to changes in how students talk about science. Does students' engagement in valued epistemic practices foster change in their epistemological conceptions?

Students' Scientific Epistemologies and Inquiry

Lederman (1992) pointed out that understanding the nature of science and scientific activity has been a goal of science instruction for nearly a century, and the past 50 years have seen much research on students' and teachers' conceptions of the nature of science. Lederman's review of this work paints a consistent picture of these ideas: namely, that both students and teachers have inadequate conceptions about the nature of science, especially in failing to recognize the tentative nature of scientific knowledge. Instead, scientific knowledge is often seen as absolute truths about the world. More recent studies have refined the view somewhat. Driver et al. (1996) described three levels of students' views of the nature of science: (a) a process of making observations about the world, (b) inducing generalizations from observations, and (c) testing models and theories. This latter level was held by few of the subjects they studied, and only by high school students (the oldest subjects in their sample). Carey and colleagues similarly characterized three distinct levels of scientific epistemology. None of their middle school students, across several studies, have shown evidence of holding the highest level view, similar to Driver et al.'s and including explicit notions of tentativeness and the socially constructed nature of scientific practice (Carey, Evans, Honda, Jay, & Unger, 1989; Carey & Smith, 1993; Smith, Maclin, Houghton, & Hennessey, 2000).

Little work has explicitly addressed the relation between students' scientific epistemologies and their inquiry. Linn and Songer (1993) found that students with a dynamic view of science were more successful at integrating formal conceptions of heat and temperature with their everyday ideas, but apparently did not explore whether these views influenced how students explored available microcomputer-based laboratories. Hammer (1994) found that more successful college physics students expected that physics concepts had to cohere, and therefore worked actively to make sense of them. On the other hand, Roth and Roychoudhury (1994) reported that students in their open-ended inquiry physics course could appreciate the value in constructing knowledge from their own inquiry experiences while maintaining objectivist views of science. There is other, indirect evidence that an understanding and appropriation of valued epistemic goals for inquiry positively affects students' investigation strategies. Dunbar (1993) found that students instructed to generate their own explanations for data rather than verify a given hypothesis more systematically and effectively experimented in a simulated genetics microworld. This manipulation in goals presumably encouraged students to evaluate data more carefully in relation to potential causal explanations, an important epistemic practice for science. Similarly, sixth graders receiving explicit instruction about the goals of experimentation (e.g., to isolate causal relationships) were more able to design controlled experiments (Schauble, Glaser, Duschl, Schulze, & John, 1995).

These findings relate to students' epistemologies of science because the goals for scientific experimentation (and inquiry more broadly) derive from epistemological commitments. For example, controlled experimentation as a methodology is valued precisely because it allows for the isolation of causal relations, an epistemic goal. It follows that students' epistemologies of science, their beliefs about what science is, directly influence their own goals during inquiry, and thus the reasoning strategies that they pursue. This has been our position in the development of a technology-supported curriculum to guide students' inquiry into phenomena of evolution by natural selection. We have explicitly designed technological and curricular scaffolds to emphasize the nature of scientific causal explanation, and the criteria to which such explanations are held (Reiser et al., 2001).

Assessing Students' Scientific Epistemologies

Early research into students' conceptions of the nature of science consisted of fixed-choice survey responses, which provide little insight into the conceptions underlying students' responses (Lederman, 1992). More recently, researchers have turned to open-ended interview assessments to probe students' ideas. In several studies, Carey and colleagues articulated a three-level characterization of students' epistemologies of science, using the Nature of Science interview (Carey et al., 1989; Carey & Smith, 1993; Smith et al., 2000). A Level 1 epistemology, the lowest level of their scheme, sees the purpose of science as the discovery of facts about the world, including the discovery of solutions to human problems, such as curing diseases. On this view, there is no distinction between experiments and the ideas they are meant to test. Experimental results are the answers, not evidence for or against a particular idea. A Level 2 epistemology is one in which ideas and experiments are seen as distinct, and the purpose of science is seen as testing ideas, but does not yet necessarily recognize that such ideas are tentative or that theories are socially constructed and constrain the kinds of experimentation scientists might do (Carey & Smith, 1993). The highest level, Level 3, is characterized as knowledge problematic and is consistent with modern philosophies of science regarding an explicit acceptance of the tentative nature of theories, their influence on experimentation, and the role that social interaction has in determining what science gets done and how scientific claims are evaluated. Smith, et al. (2000) recently refined the broad Level 2 characterization of earlier work, to distinguish between a simplistic differentiation of ideas and experiments in which ideas are still considered ultimately provable and what they call a more constructivist epistemology that begins to acknowledge the complexity inherent in developing theories and their consequent tentative status. They referred to this as a transitional, Level 2.5 epistemology.

Studies using this interview have shown that students can learn more sophisticated conceptions of science through instruction. Carey et al.'s (1989) study shifted some students from a Level 1 toward a simple Level 2 view in only 3 weeks, although most students' expressed ideas did not change. Smith et al. (2000) compared the views of sixth-graders from a highly constructivist classroom in which epistemological notions were taken up at length with a comparison group and found that students in the constructivist classroom had significantly more sophisticated conceptions of science and scientific practice. The teacher in Smith et al.'s study engaged in several inquiry-oriented practices that have been shown to be related to positive changes in students' epistemological conceptions (Lederman & Druger, 1985). It is important to note that in Smith et al.'s study, the students had the same science teacher from first through sixth grade.

We wondered what effects, if any, students' engagement in rich, complex investigation and explanation construction would have on their beliefs about science, without explicit instruction about epistemology. We felt it possible that because students' experiences in this unit involved them in generating data, using those data to explain specific problems, and mapping their explanations into the theory of natural selection, they might develop their ideas about how theories change and the relationships between theory and experimentation. Would students spontaneously recognize their own inquiry as scientific work, and would that lead them to change their professed ideas about the nature of such work? Change in students' epistemological conceptions from this unit would suggest that engaging students' in key epistemic practices during their inquiry was sufficient to develop epistemological ideas. A lack of change would suggest that inquiry experiences need to be augmented with explicit epistemological discourse for students to develop robust epistemological frameworks. We chose the Nature of Science interview because it focuses exclusively on formal ideas of the relations between theories and experimentation (see Appendix A) and was thus independent of our intervention, and because it is a well-known instrument in this area.

Context of the Study

The context of the present study was a 4-week unit on evolution implemented in a suburban high school of a major Midwestern city during the spring semester of 1998. The centerpieces of this unit were two computer-based investigation environments that we developed to enable children to explore examples of natural selection and evolution. These problems of guided inquiry were integrated with other curricular activities developed collaboratively with our participating teachers. The software tools we developed and our general approach to curriculum integration are described in more detail elsewhere (Reiser et al., 2001; Tabak, Smith, Sandoval, & Reiser, 1996). The first week of the unit included a lecture about Darwin's theory of evolution and several labs in which students measured individual variations in various attributes of populations and graphed these in ways consistent with what they would later see in the computer investigations (e.g., scatterplots, histograms). Students spent the second week working on the first inquiry problem, described below. This was followed by three periods of labs chosen by the teachers about human evolution (e.g., sorting hominid skulls according an evolutionary chronology and justifying the sort). After these labs students worked on the second inquiry problem. After this, students spent the last three periods of the unit in various discussion activities to relate their particular inquiry investigations with the broader theory of natural selection.

Each of the computer inquiry projects asked students to explain a complex problem of natural selection. In the first, students were asked to explain an episode of natural selection among finches on a Galápagos island [based on Grant (1986)]. The second, which spanned the third and fourth weeks of the unit, asked students to explain how *M. tuberculosis* bacteria are able to develop resistance to antibiotics. Each investigation is an example of guided inquiry. In each, students worked collaboratively in groups of 3 or 4 to generate an answer for a complex question posed by the environment. For example, in the Galápagos Finch (GF) problem, students were told that over the course of 1 year most of the finches on a small island died, and they were asked to explain how the surviving finches were able to survive. In the TBLab, students were introduced to the problem of bacterial resistance to antibiotics and asked to explain how bacteria were able to become resistant to antibiotics. Neither problem was specifically introduced as an example of natural selection. Students worked on each of these problems for 4–5 hours of class time.

The GF program simulated the environment of the Galápagos island of Daphne Major and provided tools for students to explore the island's climate and several aspects of the finch population. Students could connect changes in the island's environment to differential survival in the finches, and observed trait differences to their selective advantage [see Reiser et al. (2001) and Tabak et al. (1996)]. The TBLab simulated a microbiology laboratory in which students could observe the effects of a set of antibiotics on different strains of the bacteria that cause tuberculosis, run assays to see how antibiotics attack cells, and discover genetic differences through DNA sequencing to explain how single gene mutations confer antibiotic resistance. Each program included specific scaffolds to provide strategic guidance for their investigations, and each program logged the data students created, allowing them to work over several days. The GF and TBLab programs enabled students to explore scientifically important and pedagogically useful problems of natural selection that they otherwise could not, because of access and, in the TBLab case, potential danger. The investigation environments were supported by a software program specifically designed to help students organize their work and write their explanations. Students recorded their questions in this software, wrote explanations for each question, and were able to select specific pieces of data from an investigation environment (e.g., a scatterplot of beak sizes, a DNA sequence) and link them into their explanation texts as evidence for claims [for details see Sandoval (2003) and Sandoval & Reiser (under review)]. As with the investigation environments, students' work was saved daily and their final electronic journals, including the questions they recorded, candidate explanations, and all of the data they selected as evidence, were printed out and turned in at the end of each investigation.

During each investigation, the teachers and researchers present encouraged students to record explanations, use data to support their claims, and justify why selected data were good evidence. In addition, at the midpoint of each investigation, student groups reviewed each other's explanations using a rubric we developed with the teachers. This rubric directed students to attend to the clarity and causal specificity of explanations, the use of data as evidence, and whether alternative explanations might be offered. At the end of each investigation, students self-assessed the limitations of their explanations using the same rubric. Thus, students spent 2 of the 4 weeks of this unit trying to make sense of large complex sets of data to explain specific events of natural selection. They were entirely responsible for generating possible causal explanations from their interpretations of the data they collected through each investigation environment. Through their explanations and peer reviews they were encouraged to articulate the relation between the data they looked at and their developing ideas about what was happening in each case. Because students' own ideas about what was happening directed their efforts to generate data, and because new data changed their ideas about what was happening, we thought that these efforts to coordinate data with causal explanations might change their ideas about the relations between theories and experimentation in formal science. We expected that if any of their ideas about formal science as assessed by the Nature of Science interview changed, this would show in their responses to questions about theories and theory change.

The unit was taught in four classrooms by two teachers. Mr. G. taught two honors level classes of introductory biology. Mr. B. taught introductory biology to two regular level classes. Students were admitted into the honors classes on the basis of a writing test unrelated to biology. Pretests of their knowledge of evolution showed no differences between students in any of the four classes. There was a total of 87 students in the four classes, 44 boys and 43 girls. Each teacher was experienced with this course, although Mr. B. was teaching our unit for the first time. Mr. G. was teaching our unit for the third consecutive year and had been a consultant on its development. We found no differences between any of the classes in students' performance on the specific investigations they conducted or in what they learned about evolution (Sandoval, 1998, 2001).

Methods

Participants

Before the intervention we asked students to volunteer to be interviewed before and after the unit. From this pool of volunteers, we asked each teacher to select 5 students from one of their classes, such that the 10 students included roughly equal numbers of girls and boys and represented the range of abilities in their classrooms, as measured by first-semester grades for the course. Each class, one from each teacher, was the focus of other data collection efforts in the intervention. We chose a subset of students to interview because it simply was not feasible to interview all of the participating students. Ten students were originally selected, but two students from Mr. G.'s class were unable to complete the postinterview and were dropped from our analyses. Of the 8 students who completed both the pre- and postinterviews, 4 were girls and 4 were boys. To be clear, apart from these interviews, these students experienced the same intervention as all other students.

Materials

We used a version of the Nature of Science interview developed by Carey and colleagues (Carey et al., 1989; Carey & Smith, 1993). The Nature of Science interview is composed of 21 questions around several clusters of themes including the goals of science; the types of questions that scientists ask; the nature of experiments, hypotheses, and theories; the influence of theories and ideas on experiments; and processes of theory change. We asked students 16 questions from the interview related to these themes (see Appendix A for the questions, and our justifications for omissions).

Procedures

Each student was interviewed twice, before and after the unit. The preinterview occurred a few days before the start of the unit and the postinterviews were conducted during the last 2 days of the unit. Students were interviewed individually, by the first author, mostly during free periods although a few students were pulled out of their biology class for the interview. Interviews were conducted in a small conference room in the school's science department offices. The Nature of Science portion of these interviews took about 25 minutes for each student.

At the preinterview students were told nothing of the purpose of the interview other than that we wanted to find out what they thought "science is all about." They were explicitly told that the interview was not a test, that there were no right answers, and that their teacher would not see their responses to any of the questions. We then asked each question in turn, probing when we felt we did not understand any part of a response. The Nature of Science interview is semistructured, with only the initial questions being scripted. We asked follow-up probes to elicit expansion on students' initial responses or to clarify responses that were ambiguous. For example, if after being asked how scientists answer their questions a student responded, "Research," we asked what they meant by "research." Probes either asked them to unpack their responses in this way or sometimes paraphrased our interpretation of a response to elicit clarification or greater detail.

The postinterviews were conducted similarly, 4 weeks after the preinterviews. Students were again informed that their answers would be confidential and that we wanted to know if their ideas had changed since the first interview. We explicitly told students that we did not want them to try to remember their previous responses, and reminded them that we did not consider these questions to have right or wrong answers. All of the interviews, before and after, were audiorecorded and transcribed for subsequent analysis.

Theme Development

Although the original analyses from this interview considered students' responses in terms of three epistemological levels (Carey et al., 1989; Carey & Smith, 1993), more recent studies using this interview have looked more closely at themes that students express in response to certain clusters of questions (Smith et al., 2000). Smith and colleagues developed an extensive coding manual to identify and describe the themes in students' responses to four clusters of questions: the goals of science, the types of questions scientists ask, the nature of experiments, and processes of theory change. One of the first challenges for our analysis was that many of the questions we were interested in, relating to the nature of theories and the relationships between theories and experimentation, did not yet have themes. Our first effort was thus to develop our own themes that we could use to analyze these questions.

We developed themes for seven questions on the interview, Questions 9–11 and 13–16. We did not attempt to put these questions into clusters, as it was not entirely clear to us what clusters would be appropriate (cf. Smith et al., 2000). Instead, we developed themes for each question independently. To do this, we randomly selected 4 interview transcripts from a double-blind set of 16 (i.e., we did not know the identity of the student or time of the interview). Both authors collaborated to develop themes until we had a set that we felt captured the responses from the four interviews. We each then coded all 16 interviews independently, double-blind, including all of the interview questions. After this first round of coding it was clear that some of the students' responses had not been seen in the first subsample or anticipated by us. We added new themes as appropriate (see Appendix B) and recoded the entire sample again, double blind, but only Questions 9–16.

Once we had developed a full set of themes, we assigned each theme to a level in the scale used in previous studies with this interview (Carey & Smith, 1993; Smith et al., 2000), to support comparisons with that earlier work. Responses that made no distinction between ideas and experiments or were too vague to allow this distinction to be made were coded as Level 1. Responses that clearly distinguished between ideas and experiments and that experiments are for testing ideas were coded as Level 2. If responses suggested a recognition that testing ideas was complex, requiring more than one test for an idea, we coded these responses at Level 2.5, following Smith et al. Finally, Level 3 responses were those that indicated the tentative nature of ideas and distinguished theories as being broader sorts of ideas than hypotheses.

Analysis

Our initial rater agreement on level assignments for question clusters described by Smith and colleagues (2000) about the goals of science, scientists' questions, and the nature of experiments was 72%. Agreement on themes was slightly lower. On a fourth cluster of questions described by Smith et al. on change processes in science, level agreement was only 50%, although theme agreement was slightly higher. This fourth cluster, however, was excluded from further analyses. On the seven questions we developed themes for, initial level assignment agreements averaged 78% for Questions 9–11, 13, 14, and 16, but was only 50% for Question 15, which was subsequently dropped from analysis. Our interrater agreement is comparable to previous studies using this interview (Carey et al., 1989; Smith et al., 2000). Disagreements among themes usually occurred when one rater overlooked or discounted part of a response that the other rater scored. Less commonly, we disagreed because of differing interpretations of the intent behind students' responses. All theme disagreements were resolved through discussion to assign a final level score for each cluster and question. These final level scores were used to compute an overall level score for each interview, excluding Question 15 and the cluster on change processes (Questions 17–19). All of these theme and level assignments were made double-blind.

Results

We present our results in three parts. First, we present findings regarding students' general beliefs, as reflected in their overall levels both before and after the intervention. For comparison, we then summarize students' responses to the portion of the interview analyzed in previous work (the goals of science, scientists' questions, and the nature and purpose of experiments). We then present in more detail our findings concerning areas of students' beliefs that we expected could change owing to students' inquiry experiences: the relations between theories and experiments.

General Beliefs

Pre- and postinterview level scores for each question and cluster, and overall, are shown in Table 1. We present Questions 9–16 individually because this study is the first using this interview to analyze responses to these questions. Consequently, we are hesitant to decide a priori that the questions cluster in particular ways. Paired-sample *t* tests yielded no significant differences between the pre- and postinterview level scores for any cluster or question, or overall. (Given the small sample, we did not statistically compare students from different classes.) Students' ideas about formal science did not seem to change as a result of our intervention. Overall, these students are just below Level 2 of this interview, indicating that they understand that the purpose of science is generally to explain things, and that the role of experimentation in this process is to test ideas.

Table 1 shows that the levels scores for different clusters are different, suggesting different epistemological views expressed in response to different questions. Figure 1 shows the pattern of individual students' responses across both interviews. We want to draw attention to two features of these patterns. First, students rarely gave responses at the same epistemological level across questions in a particular interview, except for S6 on the preinterview and S2 and S4 on the postinterview. Second, students' responses to particular questions change considerably across interviews. Together, these patterns undermine assumptions that students possess stable, coherent epistemological frameworks.

Figure 1 shows that students responses fluctuate mostly between Level 1 and 2 ideas, depending on the questions and time of interview. A clear modal epistemology (cf. Smith et al., 2000) does not emerge from these students, and none of them individually can be definitively said to have a certain level of epistemological sophistication. Rather, there seem to be competing conceptions of the nature of scientific work. One, consistent with a Level 1 epistemology, is that experiments directly generate answers to scientific questions. A second, consistent with a Level 2 epistemology, is that experiments provide definitive evidence about whether a scientist's idea is

Table 1
Level scores for questions and clusters

	Pre		Post	
	M	*SD*	*M*	*SD*
Goals of Science	1.69	0.46	1.69	0.53
Scientists' Questions	2.00	0.29	2.00	0.41
Nature of Experiments	1.75	0.53	1.94	0.62
Choosing Experiments (Q09)	1.19	0.37	1.25	0.46
Hypotheses (Q10)	1.21	0.27	1.36	0.48
Ideas & Experiments (Q11)	1.69	0.70	1.75	0.71
Theories (Q13)	2.00	0.58	2.43	0.53
Theories & Experiments (Q14)	2.19	0.46	1.94	0.42
Unexpected Results (Q16)	2.00	0.46	1.81	0.53
Overall[a]	1.76	0.23	1.84	0.22

[a]Excludes scores for Cluster 4 (Nature of Change Processes) and Question 15.

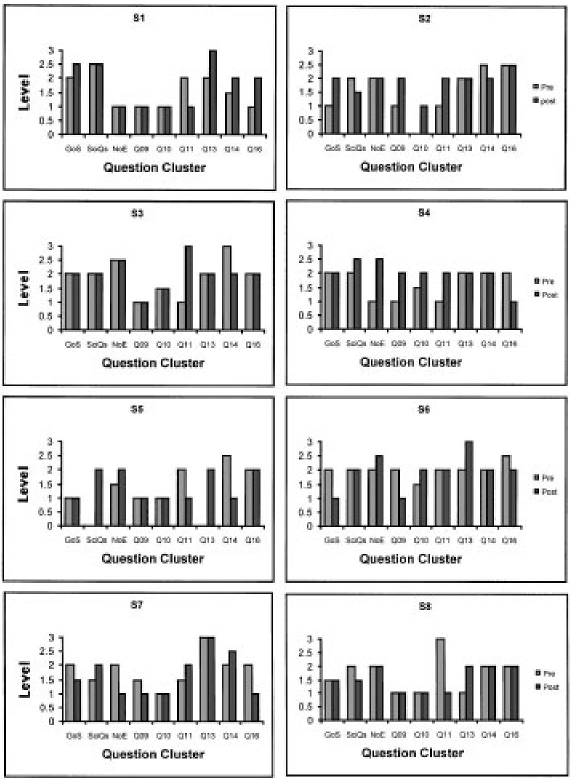

Figure 1. Individual pre- and postinterview level scores across question clusters (GoS = Goals of Science; SciQs = Scientists' Questions; NoE = Nature of Experiments) and the questions for which we developed themes.

right or wrong. In the following sections we look at how these competing positions were expressed by students in this interview.

Goals of Science, Scientists' Questions, and Nature of Experiments

Smith et al. (2000) defined three conceptual clusters about students' ideas about (a) the goals of science (Questions 1–3), (b) the kinds of questions that scientists ask (Questions 4 and 5), and (c) the nature and purpose of experiments in science (Questions 6–8). For brevity's sake, we merely summarize students' responses to these questions. Most students said in at least one of the interviews that scientists want to build explanations or test ideas. Students saw scientists' questions as mainly concerned with explanations of how things work or why they happen, but they often did not elaborate much on these responses. This suggests that perhaps students have been taught that scientists ask "how" or "why" kinds of questions but lack direct knowledge of such questions themselves. Students had a difficult time describing a general process of how scientists answer their questions. Most students mentioned vague, unelaborated procedures such as "doing experiments," "doing research," "asking other scientists," or "looking at books." When probed, they usually could not expand on what experiments or research were like. This raises the question of whether students saw their inquiry experiences in the unit as real science or school science, as they do not seem to have seen their own doing research during the unit in ways that could help them answer these questions.

The Nature of Experiments

Students' ideas about what experiments are and why scientists do them were mixed. Five of the 8 students suggested during the postinterview that scientists do experiments to test ideas but 4 students also suggested that experiments are means to find a direct answer for questions. In this latter idea, the experimental results are the answer, rather than being evidence for or against a prior idea. For those students that considered experiments as ways to test ideas, their responses to the questions in this cluster (6 and 8) did not make clear whether they saw such tests as being definitive or as lending tentative support for an idea. Students' responses were not clear or elaborate regarding these questions, and we gained a distinct impression that students had not thought much about the relations between ideas and experimentation until we asked them.

Ideas about Theories and Experimentation

Several questions in this interview ask for students' views of the relationships between ideas and experimentation. These include questions about what hypotheses (Question 10) and theories (Question 13) are, how scientists choose experiments (Question 9), how their ideas influence their experimentation (Questions 11 and 14), and whether scientists try to falsify hypotheses (Question 16). In the following sections we describe the themes that students expressed regarding these questions during the pre- and postinterviews. Besides conveying what students said, we want to explore in more detail the issues of coherence suggested by Figure 1.

Experiments Are for Proving Things. We asked students how they think scientists decide what experiment to do and what hypotheses are (Questions 9 and 10, respectively). Together, these questions suggested that students did not seem to have clear ideas about the purposes of experiments or the nature of hypotheses. At the preinterview all of the students said scientists choose experiments that will find or give them the answer to a question, and that hypotheses are guesses about what would happen. Only two students, S2 and S4, gave more sophisticated responses on the postinterview (Figure 1), but only S4 clearly indicated that experiments test ideas and that hypotheses are the ideas that are being tested.

Students had little insight into how scientists might choose their experiments (elisions represent pauses in speech, not omissions):

> S2: I don't know, like reasoning, just the question and then logic to see whatever seems the best way to get evidence for it.
>
> I: So, if they have a question . . . there's a logical way they could find . . . there's always going to be a single right experiment to do first?
>
> S2: No, not a single right, but there will be . . . you have to do . . . I don't know how you would decide . . . you test something to see if it supported your theory. (S2, post)

Although S2 is clear that scientists start with a question and a theory, in his words, he is unable to articulate anything more than a general need to choose an experiment that would be the best way to get evidence for an idea. Here and elsewhere, this vague generality in students' responses may result from the abstract nature of the interview questions.

We expected that students' ideas about how scientists choose experiments would have been informed by their own efforts to do just that during the Finch and TB investigations of the unit. Students' conversations during collaboration suggested that they were able to seek specific data to test their own ideas (Sandoval, 2003; Sandoval & Reiser, under review), but these specific efforts did not help them answer this question generally.

Ideas Bias Experimentation. Two questions asked students whether they thought scientists' ideas influenced their experiments. Question 11 seems phrased in a way to elicit ideas about experiment choice, whereas Question 14 seems designed to elicit ideas about interpretation of experimental results. We found, however, that students interpreted either question variously as about choice or interpretation of experiments. In answering both questions, students interpreted the influence of ideas in terms of scientists' goals. Students tended to argue either that scientists want to be right, personally, or that they want their ideas to be right. Students said that scientists would be "lenient" on "borderline" results that would confirm their ideas or "give them the results that they want," without clarifying whether the results are the answer or evidence for an idea. Students also repeated answers similar to their responses for how scientists choose experiments (Question 9), saying that scientists will do experiments to "prove or disprove your theory," or "that they think they can find the answer they want to."

Theories Are Proven Hypotheses. Far and away, the most common definition of a theory (Question 13) was that they are proven hypotheses that have been tested "many, many times." There was no sense from these responses that theories are more encompassing than hypotheses. Two students, S5 and S7, also suggested that theories are strongly held beliefs. This may represent a notion that hypotheses achieve a personal strength of belief from their stature of being "proven many times." Only three students explicitly mentioned the idea that theories have explanatory power, and that theories are bigger epistemological entities than hypotheses and provide a basis for further ideas. One student, S8, went on to say that theories are encompassing explanations in development, that can be advanced over time in the light of new data. This view of theories as proven hypotheses may be promoted by the simplistically linear model of the scientific method presented in most science classrooms.

Science Progresses through Right Answers. When asked whether a scientist would deliberately try to prove himself wrong (Question 16), students generally argued that this would be unproductive. Students generally received this question with skepticism and they did not appear to believe that a scientist would set out to show himself wrong. Instead, it was more likely that he would try to show another scientist wrong. Most students, 6 of the 8, suggested during at least one of the interviews that a scientist might set out to show an idea was wrong if he already suspected it might be, as a way of eliminating possibilities. The following quotations illustrate the range of responses.

> To make sure that idea . . . maybe to see if it's wrong. I can't explain. If the idea was wrong, they have to make their experiment to see if it is true that it was wrong, or it could be turned around to make sure their theory is right. (S5, post)
>
> Probably not . . . because it's time-consuming . . . they don't really . . . I don't know . . . it's just . . . it's just they're not going to do it because they're trying to get someplace not put themselves backwards. (S7, post)

> Well, I guess, because if they're . . . if they haven't even looked at other options, then if they publish it, then, I guess someone could say . . . oh, well, I have this and this experiment proves your theory wrong. (S8, post)

Two students, S1 and S8, recognized that social pressure might lead a scientist to attempt to refute himself because the failure to do so might make a scientist look bad if someone else later showed his idea to be wrong. We coded this as Level 2 because it accounts for the notion that there might be alternative ideas about the same phenomenon, but the implication in these students' responses was that the goal is still to be right, and the need to consider alternatives is to make sure that somebody else is not right at your expense. More than that, as S7 suggested, being wrong moves scientists backward; progress comes only from right answers.

Discussion

We began these analyses to find out whether engaging students in substantive inquiry would change their ideas about the relationship among theories, evidence, and the ways in which data might be generated (e.g., experimentation). We found that students' ideas, as assessed by the Nature of Science interview, did not change through our intervention. Instead, we discovered something of a paradox in students' responses during this interview. On the one hand, individual students' responses to different questions varied widely across levels. On the other hand, across students there emerged consistent themes about scientific theories and experimentation. This paradox leads us to consider two questions. First, how best can we characterize students' epistemological conceptions? We try to answer this by examining squarely the apparent paradox of our data. Our findings reinforce previous empirical work in terms of the generally objectivist view of science expressed here, but weaken the assumption that students' epistemological conceptions are coherent frameworks. Second, how can we best explain, and thus support, the development of students' scientific epistemologies? Although students' inquiry experiences in our unit focused them on making and justifying claims about particular problems, students may not have connected such effort to formal science, or these questions may not have elicited such a connection. Making such a connection may require an explicit epistemic discourse in the classroom, in which particular inquiry experiences are embedded. We consider the implications of such a discourse for science teaching and the use of technology to support inquiry.

Science as a Search for Right Answers

Several common themes running through students' responses to these questions paint an epistemological view of science as a search for answers about the world, with the notion that certain answers are right and others are wrong. Students' responses did not always make clear whether they thought that ideas are constructed by scientists to explain the world, or whether there are right answers out there in the world. This latter view is what Carey et al. (1989) called a correspondence view of theories: theories describe the world as it is. On this view, experiments test ideas, but the nature of ideas is that they are conjectures about an objective, knowable reality. This means that ideas are either right or wrong. Although students mention a notion of testing ideas in their responses to many questions, the way they talk about the effects experiments have on these ideas suggests that experimental data are not only epistemically privileged, but are definitive. Experimental results trump hypotheses. Such a view is not unreasonable, it is consistent with prevailing conceptions of scientific practice. What it fails to capture, however, is the theory-bound nature of not only scientists' interpretations of data, but the decisions they make about the kind of data that is worth generating (e.g., Kuhn, 1970). Experimental results are not objective in the sense that these students' responses would suggest.

Moreover, these students' views of science, at least as reflected in their responses to these questions, ignore a consideration of the socially constructed nature of science, including a recognition that the questions, methods, and standards of scientific disciplines are constituted through the people who practice in those disciplines (Latour, 1987). Their view of the social nature of science appears essentially competitive: Scientists vie to be right, try to prove each other wrong, and consider alternative viewpoints only to avoid embarrassment. Such social aspects are sometimes a part of actual scientific practice, but the socially constructed nature of science extends much more deeply to the idea that scientific facts themselves are constructed (Latour & Woolgar, 1986). One important consequence of the socially constructed nature of scientific theory is that alternative theoretical perspectives can lead to different interpretations of the same data. The meaning ascribed to particular data come from theory, not from the data themselves. When mentioned here at all, students asserted that if two scientists held alternative interpretations of the same data, one must be wrong or each must be part right and part wrong. Data are generally seen as objective.

Epistemological Framework or Fragments?

Implicit in the Nature of Science interview is the idea that each level represents a distinct, coherent epistemological framework, and that students might be confidently placed at one level or another (Carey et al., 1989; Carey & Smith, 1993; Smith et al., 2000). In their recent study, Smith et al. argued that the consistency in their sixth-grade students' responses across clusters is evidence for coherent epistemological frameworks. In our admittedly small sample, we did not find convergence across students or see consistency in individual students' responses across interviews. Thus, although it is certainly possible to assign these students to an overall level, doing so masks substantial variation in the ideas they express.

It seems important to take this variation seriously in our theoretical accounts of students' epistemological ideas and their development. The coherence evidenced by students in Smith et al.'s constructivist classroom may be an instructional outcome. Similarly to our data, Roth and Roychoudhury (1994) found that the high school students in their study concurrently held incommensurate beliefs about the nature of scientific knowledge, with some ideas commensurate with an objectivist epistemology and others with a constructivist epistemology. As with other intuitive conceptions, students' intuitive epistemological ideas may be "knowledge in pieces" (diSessa, 1993) rather than intuitive theories. Hammer and Elby (2001) recently argued that epistemological beliefs should be thought of as a collection of relatively independent resources that get activated in specific contexts, rather than coherent frameworks. They presented several candidate resources for personal epistemology, such as a view of "knowledge as stuff," "knowledge as accumulated," and others. Students here may invoke specifically scientific resources to answer our questions, such as "experiments give answers," "experiments prove or disprove ideas," or "scientists want to be right."

Testing the resources view further suggests that assessments of students' epistemological ideas ought to be more closely grounded in students' actual experiences. We wonder, for example, whether asking students to explain their reasons for making certain claims or selecting certain evidence for their own explanations of the problems they investigated here would have uncovered different epistemological conceptions than the Nature of Science interview seemed to tap. A combination of techniques grounded in students' actual work paired with more formal instruments such as the Nature of Science interview would paint a fuller picture of students' active epistemologies, the epistemic ideas they actually reason with during inquiry, and thus are most likely to be influenced by inquiry-based instruction.

Developing Epistemic Practice in School Science

Smith et al. (2000) described the features of an exemplary elementary science classroom they believed explained the sophisticated constructivist science epistemology developed by the sixth graders they interviewed. Those students had a significantly different science learning experience from most students, including ours. First, they had the same exceptional science teacher from first through sixth grade. Their science classroom was characterized by authentic inquiry into centrally important and deep scientific questions. Perhaps most important with respect to students' epistemological beliefs is that Smith and colleagues reported that the discourse of science in this classroom was one in which students had a large degree of responsibility in the construction and defense of ideas, and their teacher supported a high level of metacognitive discourse about what they were learning and how they knew what they knew. These young students, then, learned a markedly different scientific discourse than is typical, and it shows in their epistemological conceptions. Sustained, explicit epistemic discourse seems crucial to developing sophisticated scientific epistemologies (cf. Rosebery, Warren, & Conant, 1992).

Thus, to develop students' epistemological ideas, the nature of the discourse surrounding students' inquiry may be more important than the inquiry itself. In our intervention students were engaged in authentic inquiry into problems of natural selection, and their work focused them on articulating causal explanations that could be justified in terms of evidentiary support (Sandoval, 2001, 2003). During their inquiry, students actively considered epistemic issues, including what questions they were trying to answer, what specific data meant, and deciding when an explanation was complete or should be abandoned. They were also able to assess themselves and their peers' explanations in epistemically appropriate terms: They noticed when claims were unsupported; they noticed when causal mechanisms were not clearly articulated; and they were aware of the limits to their explanations given the data they had available (Sandoval & Reiser, under review). Yet, students' discussions of claims and their support may have been driven by their own goals to get the right answer. Such a perspective is typical of science classroom discourse (Lemke, 1990). We are not suggesting that students' inquiry should not lead them to sensible answers, but that developing criteria for deciding what is right or better than an alternative is an important instructional goal.

It is worth bearing in mind that our inquiry curriculum was only 4 weeks out of a school year, against a history of several years of school science. In hindsight, epistemological change was a remote possibility. Still, our intervention was not unlike other inquiry-oriented approaches to science education reform. With scaffolds, students can conduct productive inquiry in these settings and learn important science ideas and investigation skills (e.g., Linn, Bell, & His, 1998 White, 1993; White & Frederiksen, 1998). Investigating authentic problems is not necessarily enough to raise epistemological issues, even when epistemic criteria are made explicit, as here. Students can apparently engage in sustained open-ended inquiry, appreciate its benefits for their personal construction of knowledge, but maintain objectivist views of formal science (cf. Roth & Roychoudhury, 1994). Students may not see their experiences as real science, despite the way we researchers see it. The important epistemic discourse, then, is to relate students' inquiry experiences directly to the practice of professional science. This raises two key issues for inquiry-based approaches to science education, especially those using technology to support students' inquiry.

Teacher as Epistemologist

For students to engage in a sophisticated epistemological discourse, teachers must be prepared to facilitate such a discourse. For this, teachers themselves need to have sophisticated epistemological understanding, and many do not (Lederman, 1992). The situation suffers from a vicious recursion. Prospective science teachers have not typically had educational experiences that include scientific inquiry, and are thus ill-prepared to guide their own students through it. Ideally, inquiry and scientific epistemology would be a part of an undergraduate science education, but at the least teacher education should address this. In our classrooms, neither teacher supported an epistemic discourse. In fact, one of the teachers summarized students' inquiry projects by organizing classroom discussions around making sure that everyone, regardless of their group explanations, got what he considered to be the right answer for the problem (Sandoval, Daniszewski, Spillane, & Reiser, 1999). Such a move diminishes the authenticity of students' inquiry by reestablishing authority with the teacher and mitigates the possibility of epistemological change.

Epistemic Artifacts

An epistemic discourse requires that students' inquiry produce artifacts of their knowledge that can become the focus of epistemic consideration. The key here is that such artifacts need to be reasonably variable, and thus open to debate about what makes one explanation (or argument, model, or theory) better than another. Debates over such artifacts seem to help students to learn scientific concepts (Bell & Linn, 2000). We have found, however, that creating and sustaining such public conversations on the epistemological aspects of student-generated artifacts is difficult, especially within the constraints of a crowded high school science curriculum. Any solution to this lies in seeing epistemic and content ideas as inseparable, that what we know in science is inseparably tied to how we know what we know.

Conclusions

We have described the epistemological conceptions expressed in interviews with eight high school students before and after a 4-week technology-supported inquiry unit on natural selection and evolution. Students' epistemological ideas did not appear to change as a result of their inquiry experiences, but we found that this sample of ninth graders distinguished ideas from experiments and saw the purpose of experimentation as testing ideas. As a group, students' views were largely "knowledge unproblematic" (Carey & Smith, 1993): Science is a search for answers, and experiments provide definitive evidence for or against ideas. Yet, the variability within individual students' responses undermines previous assumptions that students' epistemological beliefs are coherent frameworks. Instead, we suspect that students' epistemological ideas are fragmented, appropriated in an incoherent way from the implicit epistemology of the authoritarian, objectivist discourse of the typical science classroom.

Hogan (2000) suggested that students' formal knowledge about the nature of science has little influence on their inquiry. We suggest that students' inquiry has little influence on their formal understanding of the nature of science without explicit attention being paid to epistemological ideas. Yet, simply asking students to explain their views of the relationships among epistemological entities such as theories, hypotheses, and experiments may downplay their ability to work with theories, build explanations, and conduct experiments. Doing and talking science are not the same as talking about science. Efforts to support students' inquiry, including our own, need to do more to develop an epistemic discourse that can help students articulate their epistemological conceptions in ways that would support their development of more sophisticated scientific epistemologies.

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Appendix A

The Nature of Science interview, with the questions asked in this study in italics. Some questions were dropped after piloting suggested that they did not discriminate students (e.g., all students answered "Yes" to Question 7, and the first parts of Questions 10 and 13). Others were omitted because of limited time and they seemed to not easily tap into students' ideas about theory development and change (Questions 2, 12, 20, and 21). The headings represent question clusters, taken from Smith et al. (2000).

Goals of Science

1. *What do you think science is all about?*
2. What do you think the goal of science is?
3. *What do you think scientists do?* How do they achieve the goals of science?

Types of Questions

4. *Do you think scientists ask questions? What sorts of questions do you think scientists ask? IF NO, go to Question 6.*
5. *How do scientists answer their questions? Can you give an example of a scientist's question and what he or she would do to answer it?*

Nature and Purpose of Experiments

6. *What is an experiment?*
7. Do scientists do experiments? IF NO, skip to Question 10.
8. *Why do scientists do experiments? IF "to test ideas" THEN: How does the test tell the scientist something about the idea?*

Role of Ideas: Conceptions of Hypotheses and Theories

9. *How does a scientist decide what experiment to do?*
10. Have you ever heard the word "hypothesis"? *IF NO, explain: A hypothesis is an idea scientists have, an idea about how an experiment would turn out. IF YES, ask: What is a hypothesis? IF "educated guess" or "guess" THEN ask: Do you think a hypothesis is the same as a guess or do you think there is a difference? What is the difference?*
11. *Do you think a scientist's ideas influence the experiments he or she does? IF YES: How? IF NO: Do scientists ever test their ideas?*
12. How do you think scientists come up with their ideas?
13. Have you ever heard the word theory? *IF YES: What is a theory? Do you think scientists have theories? IN ALL CASES, EXPLAIN: "A theory is a general idea about how and why things happen the way they do. For example, biology is a theory about living things."*
14. *Do you think a scientist's theory influences his or her ideas about specific experiments? How?*

Unexpected Results and Disproving Ideas

15. *If a scientist does an experiment and the results are not as he or she expected, would the scientist consider this a bad result? Why or why not? Can they learn anything from this? What?*
16. *Say a scientist is going to do an experiment to test his or her idea. Would a scientist do an experiment that might prove this idea is wrong? Why or why not?*

Nature of Change Processes

17. *What happens to a scientist's ideas once he has done a test?*
18. *Do scientists ever change their ideas? IF YES: When would they do that and why?*
19. *Do scientists ever change their whole theories? IF YES: When would they do that and why?*

Achieving Goals and Making Mistakes

20. Do scientists always achieve their goals? If not, why not?
21. Can scientists make mistakes or be wrong? How?

Appendix B

Themes developed to analyze Questions 9–16. Levels indicated in parentheses are drawn from the coding manual used by Smith et al. (2000) and generously provided to us by Carol Smith.

Question 9: How Does a Scientist Decide What Experiment to Do?

1. Unelaborated Relatedness (Level 1)

These responses claim some vague unspecified relationship between a scientist's interests and the experiment he chooses to perform. Student does not mention testing ideas or answering questions.

2. Find an answer or solve a problem (Level 1b)

Student says scientists do an experiment to find an answer or solve a problem. There is no indication that the scientist had a hypothesis that is being tested by the experiment.

3. Best way to get answer or evidence for a question (Level 1b or 1.5)

These responses claim that scientists choose the best experiment available to help them answer their question or solve a problem. Central to this theme is that the scientist has an initial question or problem that motivates the experiment. There are two levels of answer in this theme, differing in whether the experimental results are the answer (Level 1b) or help find one (Level 1.5).

4. Test ideas, test explanations (Level 2 or 2.5)

In this theme, the scientist has an initial idea, and the purpose of the experiment is to test the idea. The experiment either definitively proves or disproves an idea (Level 2) or provides partial evidence (Level 2.5).

Question 10: What Is a Hypothesis?

1. Prediction of experimental outcome (Level 1)

In these responses a hypothesis is a prediction about the result of an experiment.

2. Educated guess with some basis for it (Level 1 or 2)

This theme captures variations in the common response that a hypothesis is an educated guess. The guess was vague (Level 1) or about how or why something works (Level 2).

3. Conclusion induced from experimental results or observations (Level 1.5)

These responses suggest that a hypothesis is an explanation about observations or experimental results. The hypothesis is something the scientist imposes on the data: the data come first, then the hypothesis.

4. Initial explanation that is the basis for testing an idea (Level 2)

This theme is the classic definition of a hypothesis: an initial idea about how something works, or why things are the way they are. In this theme, the hypothesis comes before any experimentation.

Question 11: Do a Scientist's Ideas Influence the Experiments He or She Does?

1. Experiment is truth (Level 1)

In this theme, ideas do not influence experiments in any way, because experiments tell you the truth or give you the answer.

2. Relatedness: Ideas determine process (Level 1.5)

In this theme, a scientist's ideas will determine what experiment to do. Student does not mention that the intent of the experiment is to test the idea, just that ideas tell you what experiment to do.

3. Prove you are right (Level 1b or 2)

The scientist performs experiments to prove that he or she is right. The level of the response is determined by how clear it is that an idea is being tested: general goal to be right (Level 1b) or prove an idea right (Level 2).

4. Test ideas (Level 2 or 2.5)

Here the scientist has an idea and designs an experiment to test the idea. The scientist's goal in doing experiment is to see if his or her idea is right or wrong. Responses that suggest that a single experiment definitively shows an idea to be right or wrong are scored as Level 2. Responses that say that experiments could be interpreted as providing partial evidence for or against an idea are scored as Level 2.5. We also scored as Level 2.5 responses that clearly discuss a multistep bidirectional relationship between ideas and experiments: that ideas influence experiments, but experimental results can change ideas and suggest new experiments.

5. Ideas affect interpretation of experimental results (Level 2.5)

In this theme, a scientist's ideas will affect how she or he interprets experimental results, especially if results are borderline or not clear.

Question 13: What Is a Theory?

1. Strongly held belief or personal opinion (Level 1)

Responses in this theme define theory in the everyday meaning with which it is often used, as a strongly held personal belief, not open for testing.

2. Something like a fact (Level 1)

In this theme, the nature of a theory is vague but its epistemological status is that of a fact, so true that it is taken as a given by people or other scientists.

3. A proven hypothesis (Level 2)

A theory is simply a hypothesis that has been proven many times.

4. An explanation (Level 2)

A theory is a way of explaining natural phenomena or experimental results. Student might say theory cannot be proven but it is a logical explanation.

5. A basis for ideas; a theory is bigger than an idea or hypothesis (Level 3)

The pertinent distinction in this theme is that a theory involves a lot of information or covers a broad topic, and that it is conceptually bigger than hypotheses.

6. An encompassing explanation that is in development (Level 3)

This theme goes beyond theory as explanation (Theme 4) and beyond theory as bigger than idea (Theme 5), because the student also offers that since the theory is based on a lot of information or evidence, the theory can change or advance as new discoveries and findings are made.

Question 14: Does a Scientist's Theory Influence His Ideas about Specific Experiments?

1. Vague Relationship (Level 1)

Student says ideas and experiments are related but is not specific about how they are related.

2. Experiment influences idea (Level 1.5)

Students say that experiment will influence scientist's ideas, that the ideas come from the experiment.

3. Experiment is designed to prove or test idea (Level 2)

Scientist designs experiment to prove his or her theory, get support for it, or test it.

4. Theory influences interpretation (Level 2.5 or 3)

In this theme, students say that a scientist's theory will influence his or her interpretation of data. This theme has two levels: a scientist's theory will influence his interpretation of his own data, either as a simple bias (i.e., he wants to) or more theoretically (Level 2.5); or different scientists can interpret the same data differently because they hold different theories (Level 3).

Question 15: If a Scientist Does an Experiment and the Results Are Not as He Expected, Would the Scientist Consider This a Bad Result?

1. Experiments show the answer (Level 1)

In this theme, unexpected results are not bad because the results show the answer.

2. Experiments generate ideas (Level 1.5)

In this theme, unexpected results are not bad because they lead to the creation of new ideas.

3. Experimental error (Level 1)

In this theme, unexpected results occur only from experimental, procedural errors; the scientist did something wrong.

4. Results refute one possibility (Level 2 or 2.5)

Here, results can show that an idea was wrong but do not necessarily provide a definite conclusion about what is right. Either results provide a definitive refutation (Level 2) or a tentative one that requires more testing (Level 2.5).

Question 16: Would a Scientist Do an Experiment That Might Prove His Idea Is Wrong? Why?

1. No, it is unproductive. (Level 1)

In this theme, responses are unequivocal that a scientist would never purposely set out to prove himself wrong because that is not helpful in finding the right answer to a question.

2. Ambiguous "it" works or does not work. (Level 1)

Student mentions "it" might not work or might work. Not clear what "it" is; no clear differentiation between the idea and the experiment.

3. Yes. Reverse proof. (Level 2)

In this theme, a scientist might try to prove himself wrong as a reverse proof. If a scientist cannot prove the idea is wrong, that means the idea is right.

4. Yes. Eliminate possibilities (Level 2)

In this theme, a scientist would try to prove himself wrong to eliminate one of several possibilities.

5. Yes. Get support for overall question (Level 2.5)

In this theme, knowledge is complex, with questions and subquestions, or big ideas that are made of parts. The student might explain that part of an idea could be wrong, or that an idea could be partly wrong.

6. Yes, social pressure to consider alternatives (Level 2.5)

Responses in this theme say that a scientist might be made to look bad if he does not consider alternative ideas and attempt to refute them.

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