Exploring the Development of Fifth Graders’ Practical Epistemologies and Explanation Skills in Inquiry-Based Learning Classrooms

Hsin-Kai Wu · Chia-Lien Wu

Abstract The purposes of this study are to explore fifth graders’ epistemological views regarding their own experiences of constructing scientific knowledge through inquiry activities (i.e., practical epistemologies) and to investigate possible interactions between students’ practical epistemologies and their inquiry skills to construct scientific explanations (i.e., explanation skills). Quantitative and qualitative data including interview transcripts, classroom video recordings, and pre- and post-tests of explanation skills were collected from 68 fifth graders in two science classes. Analyses of data show that after engaging in 5-week inquiry activities, students developed better inquiry skills to construct scientific explanations. More students realized the existence of experimental errors, viewed experimental data as evidence to support their claims, and had richer understanding about the nature of scientific questions. However, most students’ epistemological beliefs were still naïve (the beginning level); they could not differentiate between experimental results and scientific knowledge and believed that the purpose of science is doing experiments or research. The results also show that students who held a more sophisticated epistemology (the intermediate level) tended to develop better inquiry skills than those with naïve beliefs. Analyses of classroom observations suggest possible explanations for how students reflected their epistemological views in their inquiry practices.

Keywords Epistemology · Explanation skill · Inquiry

Introduction

In recent years, inquiry-based approaches have been recommended by many reports in science education (Abd-El-Khalick et al. 2004). In Taiwan, inquiry-based learning is a
central strategy in science education reform (Ministry of Education 1999), and in the United States, National Research Council [NRC] (1996, 2000) places inquiry as a cornerstone of science education. Engaging in inquiry allows students to experience the activities and thinking processes used by the scientists (NRC 2000), supports the development of inquiry skills (Wu and Hsieh 2006), and encourages epistemological understandings of how inquiry results in scientific knowledge (Sandoval 2003).

Research in science education has found that students’ epistemological views and beliefs could affect their ability to solve problems (Lin et al. 2004), knowledge integration (Songer and Linn 1991), and their attitude towards science learning (Tsai 1999); however, “there is a gap between what is known about students’ inquiry practices and their epistemological beliefs about science” (Sandoval 2005, p. 634). To shed a light on this issue, this study investigates possible interactions between students’ inquiry skills and their scientific epistemologies.

Additionally, a number of studies in students’ epistemologies indicated that although in inquiry-based classrooms students engage in activities that share similarities with those done by practicing scientists, students still hold naïve epistemological views and their epistemological ideas seem difficult to change through inquiry practices (Meichtry 1992; Sandoval and Morrison 2003). One reason might be that what these studies examined were students’ epistemological beliefs for professional science (i.e., formal epistemology), rather than their own views and ideas generated during inquiry practices from school science (i.e., practical epistemology; Sandoval 2005). Therefore, this study responds to Sandoval’s (2005) distinction between formal epistemologies and practical epistemologies, and explores students’ practical epistemologies during inquiry-based learning. Practical epistemologies refer to students’ epistemological beliefs that are used to construct their own scientific knowledge through inquiry activities in science classrooms. The purposes of this study are to explore fifth graders’ practical epistemologies in inquiry-based learning classrooms and to investigate a relationship between students’ inquiry skills and their epistemologies.

**Theoretical Background**

**Epistemology of Science**

Epistemology has been one of the fundamental themes in science education. Although its definitions are varied among scientists, scientific educators, philosophers, and historians of science, this study follows the definition commonly used in science education (Lederman et al. 2002). Scientific epistemology refers to students’ beliefs and views about how scientific knowledge is developed and justified, and involves a set of ideas and assumptions about the nature of science that students have (Hogan and Maglienti 2001; Sandoval 2005). Students rely on these beliefs to decide which claims they should believe, accept, deny, or revise.

According to American Association for the Advancement of Science [AAAS] (1993), the nature of science includes three aspects: the scientific worldview, scientific inquiry, and the scientific enterprise. Considering that classroom inquiry activities may not provide students with direct learning experiences about the scientific enterprise (e.g., science is organized into content disciplines and conducted in various institutions; scientists participate in public affairs both as specialists and as citizens), in this study we focus on students’ ideas about the nature of scientific knowledge and the methods to generate and evaluate scientific knowledge.
Carey, Smith and their colleagues characterized students’ epistemological ideas about the nature of science into three levels (Carey and Smith 1993; Smith et al. 2000; Smith and Wenk 2006). These levels “distinguished three qualitatively different epistemologies of science, each of which involves a set of different concepts for describing both the structure of scientific knowledge and the processes of knowledge acquisition in science” (Smith et al. 2000, p. 356).

At the beginning level, students cannot differentiate between evidence, hypotheses, and theories. They focus on procedures (i.e., the purpose of science is to do things) and results (i.e., experiments are designed to produce a good result), and have a strong belief in the certainty of scientific knowledge (i.e., scientific knowledge is unproblematic and unchanging).

At a second level, students start making an initial differentiation between scientists’ ideas, procedures, and results; they define experiments as tests of hypotheses, view theories as well-tested hypotheses, and believe that knowledge is uncertain. Additionally, students realize that scientists design experiments to test their initial ideas and that one purpose of science is to understand questions about why something happens.

At a more sophisticated level, students view a scientific theory as an explanatory framework and make a distinction between a theory and a hypothesis that can be tested within a theory. Students realize the theory-guided nature of scientific inquiry and view knowledge as uncertain (i.e., scientific knowledge is tentative and can be revised and changed as new understandings are learned). The three levels provide a framework for this study to categorize students’ epistemologies.

Inquiry Learning and Practical Epistemology

Inquiry-based learning is believed to be one of the effective approaches to developing a sophisticated and informed view of science (NRC 2000) because inquiry is a question-driven learning process that allows students to formulate researchable questions, design informative investigations, gather and give priority to evidence, and propose persuasive explanations (Krajcik et al. 1998). Through engaging in inquiry practices, students would be aware of the process of producing, testing, and revising scientific knowledge and the criteria of evaluating scientific knowledge claims (Smith et al. 2000).

However, some studies have shown that even if students engage in inquiry practices that are very similar to the ways in which scientists study the world, many of their epistemological beliefs are unaffected and they tend to hold a naïve epistemological view (Khishfe and Abd-El-Khalick 2002; Meichtry 1992). For example, Sandoval and Morrison (2003) explored how high school students constructed scientific explanations and examined their ideas about the nature of science during a biology inquiry unit. They found that after a 4-week inquiry unit, students still believed that the purpose of science is to search for right answers about the world. Similarly, Moss et al. (2001) showed that even though the 11- and 12-grade students in their study participated in project-based learning activities throughout an academic year, most of their epistemological views remained unchanged.

To explain how students develop their scientific epistemological beliefs in inquiry-based classrooms, Sandoval (2005) argued for a distinction between students’ epistemological ideas about their own inquiry and their views towards professional science. These two types of epistemological views might be affected to different extent by instruction. For instance, in Moss et al. (2001), having direct learning experiences about how scientific knowledge is constructed in a series of project-based activities, students developed better understandings about the nature of scientific knowledge than the nature of the scientific enterprise.
Therefore, inquiry practices could have an impact on some aspects of students’ epistemologies. What remains unchanged might be students’ epistemology about professional science and scientific community, that is different from a set of ideas students have while engaging in inquiry activities or producing science knowledge (Sandoval 2005).

To distinguish this difference, Hogan (2000) and Sandoval (2005) identified two types of students’ epistemologies. The first category called distal knowledge of the nature of science (Hogan’s term) or formal epistemology (Sandoval’s term) means students’ beliefs or ideas for professional science. Interviews and questionnaire are popular assessments to explore students’ formal epistemologies, and students are directly asked questions such as: What is science? What is the goal of science? What is theory? How does the theory affect the experiment? These assessments examine students’ understandings about the nature of professional science enterprise, the nature of scientific knowledge generation, and scientists’ epistemological commitments.

On the other hand, proximal knowledge of the nature of science or practical epistemology refers to the ideas or views that students hold regarding their own experiences of constructing or encountering scientific knowledge (Hogan 2000; Sandoval 2005). Practical epistemology involves the ideas for the nature of scientific knowledge, the approach of producing scientific knowledge, and the criteria of evaluating scientific knowledge claims that could reflect students’ decision and criteria of the construction and evaluation of scientific knowledge in their own learning practices. In order to uncover students’ practical epistemology, researchers need to analyze students’ discourse and artifacts during their inquiry activities, and to ask students about their ideas for their own inquiry activities (Sandoval 2005). As a substantial amount of research has investigated students’ formal epistemology by using questionnaires, relatively few studies investigated students’ practical epistemologies. Thus, this study examines classroom discourse and students’ interview responses to understand students’ practical epistemological views in inquiry-based classrooms.

Epistemology and Science Learning

Research has found that students’ epistemologies could interact with their engagement in science learning. In Songer and Linn (1991), students who held dynamic epistemological beliefs and viewed science as understandable and interpretive were more likely to be active learners and developed better conceptual understandings than those who had static beliefs about science. Additionally, Tsai (1999) showed that students with constructivist epistemological beliefs used more meaningful learning strategies and explored deeply the concepts involved in laboratory activities, which in turn resulted in richer understandings about science. In contrast, students who held an empiricist epistemology of science concentrated on following experimental procedures and tended to believe that laboratory activities were a means to memorize scientific concepts.

However, as some interactions between students’ epistemologies and their approaches to learning have been explored, relatively little is understood about how students’ epistemological ideas play a role in the development of inquiry skills. Inquiry skills are rudimentary intellectual skills necessary for inquiry learning such as selecting and controlling variables, planning procedures, and interpreting patterns of evidence (Kuhn et al. 2000; Shimoda et al. 2002). Without them, students are not able to productively engage in inquiry, which in turn might interfere with students’ ideas about how scientific knowledge is constructed or vice versa. Additionally, because formulating, evaluating, and communicating explanations have been identified as essential features of classroom inquiry.
(NRC 2000), this study mainly focuses on students’ inquiry skills for explanatory activities. According to Wu and Hsieh (2006), three inquiry skills are critical for students to develop scientific explanations (called explanation skills in the study): identifying causal relationships between variables, describing the reasoning process, and using data as evidence. To understand how students’ epistemological ideas interact with their inquiry process, this study investigates the development of their inquiry skills and explores the possible interactions between their epistemologies and these skills.

Methods

Design

This study takes a mixed-methods approach and involves two fifth-grade classes taught by the same teacher. Because relatively few studies have investigated students’ practical epistemologies, this study is exploratory in nature. Qualitative methods including interviews and classroom observations were used to probe for the existence of alternative epistemologies in students that were not identified in previous research. Additionally, to capture the process of how students developed inquiry skills and epistemologies, the period of data collection lasted over 5 weeks.

Research questions that guide the study were: (1) Do students improve their inquiry skills to construct scientific explanations after a series of inquiry-based activities? (2) What are students’ practical epistemologies during and after the inquiry activities? (3) What are the interactions between students’ inquiry skills and their practical epistemologies? The findings of this study will help design classroom activities that support students to build understandings of how scientific knowledge is constructed through inquiry.

Participants

The study was conducted at a public elementary school in Northern Taiwan. Sixty-eight fifth graders (n=68, 32 boys and 36 girls; average age 11 years) from two science classes participated in the study. These students had a range of academic abilities and the majority of them were middle-class. Both classes (Class I: 34 students, 18 girls; Class II: 34 students, 16 boys) were taught by Mr. Chen who had been teaching science in elementary and junior high schools for more than 5 years. Mr. Chen received a B.S. degree in biology and held a masters degree in educational technology. For intensive observation, 23 students from four student groups (Class I: 11 students; Class II: 12 students) were nominated as target students in the two classes. Among them, 12 of them were girls.

Activities

To engage students in constructing scientific explanations, Mr. Chen and the second author designed ten learning activities (Table 1). The ten activities covered topics of force and motion, and took a total of 15 class periods (over 5 weeks) to finish. In these activities, students explored the effects of force, designed experiments to examine the relationship between force and the length of a spring, collected and analyzed their experimental data, and presented and shared their findings. Each activity involved one or more inquiry phases suggested by Krajcik et al. (1998) such as asking and deciding questions, designing investigation, creating artifacts, and sharing and communicating findings. Because students...
Table 1 Explanation skills and practical epistemology involved in the six learning activities

<table>
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<tr>
<th>Activity title and description</th>
<th>Explanation skills demonstrated</th>
<th>Practical epistemology involved</th>
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<tbody>
<tr>
<td>1. Exploring the effect of force</td>
<td>(1) Identifying relationships between variables</td>
<td>Nature of Experiments</td>
</tr>
<tr>
<td>Students explore the effects of force and discuss the effect of increasing forces on the length of a rubber band.</td>
<td>(2) Describing the reasoning process</td>
<td>Evidence Generation and Evaluation</td>
</tr>
<tr>
<td>2. Measuring the amount of force I</td>
<td>(3) Using data as evidence</td>
<td></td>
</tr>
<tr>
<td>Students design an experiment to examine the relationship between the number of coins and the length of a spring. Students are asked to make predictions, collect data, and share findings with others.</td>
<td>(1) Identifying relationships between variables</td>
<td>Nature of Experiments</td>
</tr>
<tr>
<td>3. Measuring the amount of force II</td>
<td>(2) Describing the reasoning process</td>
<td>Evidence Generation and Evaluation</td>
</tr>
<tr>
<td>Students use a spring scale and counterweights to measure the amount of force. By reviewing their previous experiment and using different measuring tools, they discuss why a spring can be used as a scale. They design an experiment to re-examine the relationship between the weight of the added mass and the length of a spring.</td>
<td>(3) Using data as evidence</td>
<td></td>
</tr>
<tr>
<td>4. Representing the force data</td>
<td>(1) Identifying relationships between variables</td>
<td>Evidence Generation and Evaluation</td>
</tr>
<tr>
<td>Students present their experiment data collected from their previous experiments. They learn to use a computer software tool to transform their data into a data table or a graph. They also use these representations to present results and describe the patterns they find from the data.</td>
<td>(2) Describing the reasoning process</td>
<td>Nature of Scientific knowledge</td>
</tr>
<tr>
<td>5. What a force can do? The movement of objects</td>
<td>(3) Using data as evidence</td>
<td>Types of Scientific Questions</td>
</tr>
<tr>
<td>Students observe how a force can change the shape of a rubber band, and move or stop an object. They conduct an experiment to find out how the amount and direction of force affects the movement of an object.</td>
<td>(1) Identifying relationships between variables</td>
<td>Nature of Experiments</td>
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<tr>
<td>6. Composition of forces I: a tug of war</td>
<td></td>
<td>Evidence Generation and Evaluation</td>
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<tr>
<td>Students experience the strength and direction of different forces through playing a tug of war outside of the classroom.</td>
<td>(1) Identifying relationships between variables</td>
<td></td>
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<tr>
<td>7. Composition of forces II</td>
<td>(2) Describing the reasoning process</td>
<td></td>
</tr>
<tr>
<td>The teacher introduces concepts about gravity, force, speed, and motion. He uses two visualization tools to demonstrate composition of forces. Students discuss the speed and direction of an object and the combined effects of two or more separate forces.</td>
<td>(1) Identifying relationships between variables</td>
<td></td>
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<tr>
<td>8. Motion and speed</td>
<td>(2) Describing the reasoning process</td>
<td>Nature of Experiments</td>
</tr>
<tr>
<td>The teacher engages students in a discussion of how to measure and represent “speed.” Students compare and interpret different graphs in the textbook and use a software tool to create distance-versus-time graphs.</td>
<td>(3) Using data as evidence</td>
<td>Evidence Generation and Evaluation</td>
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had no prior experience in inquiry-based learning, it was difficult for them to accomplish learning tasks without the teacher’s guidance. To help students learn, the teacher provided support and guidance through asking questions, demonstrating the use of tools, modeling how to analyze data, and providing oral feedback during inquiry activities. Inquiry practiced in the two classrooms was in a form of guided inquiry.

Data Collection

Quantitative and qualitative data were collected over 5 weeks consisting of classroom video recordings, fieldnotes, students’ artifacts, pre- and post-tests for explanation skills, and semi-structured interview transcripts. We videotaped every class period and wrote fieldnotes for all classroom activities. The classroom video recordings captured target student group discussions and illustrated students’ practical epistemologies.

A paper-and-pencil test was designed to assess students’ explanation skills before and after the inquiry-based learning activities. Based on the design patterns of assessment suggested by Songer and Gotwals (2004), the test contained items created by us and modified items from TIMSS 1995, TIMSS 1999 and TIMSS 2003 (International Association for the Evaluation of Educational Achievement 2003). After the test was created, one university professor and one elementary school scientific teacher reviewed the test items to ensure that the content, format and description of the test items were suitable for students and aligned with the nature of explanation skills. The final version of the test contained 7 open-ended questions and a total of 15 sub-questions. 100 sixth-grade students piloted the test and their answers were classified to construct scoring rubrics. The rubrics included three levels of explanation skills, and high, adequate, and low-level answers were respectively scored as 2, 1, and 0 point. Twenty-five randomly selected answer sheets were independently coded by two researchers using the rubrics, and the estimation of intrarater agreement between them was 0.95. The internal consistency was moderately high (Crobach’s $\alpha=0.77$).
To further assess students’ explanation skills and practical epistemologies, 23 target students were interviewed individually outside of the science classroom before and after they participated in the ten learning activities. Each interview lasted about 40 min and included two parts. In the first part, six questions were presented with experimental data and used to evaluate students’ explanation skills. Students were asked to analyze data, identify relationships between variables, and formulate explanations based on the given data and the situation. For example, one interview question asked students to explain how different variables affect the growth of beans. They were provided with data of several variables such as size of beans, amount of sunlight received, and height of bean sprouts. Students had to explain relationships between the height of the bean sprouts and other variables, to use data as evidence, and to describe how they used data to reach their conclusion (reasoning process).

In the second part, interview questions were to probe into students’ practical epistemological views about the nature of scientific knowledge and scientific inquiry. Students were asked about the experiments that were conducted in their science class. Some interview questions included: (1) What question was your experiment designed to answer? Do you think the question is a scientific one? What is a scientific question? (2) What conclusion did you generate from the experiment? Does your conclusion count as scientific knowledge? Why or why not? What is scientific knowledge? (3) How do you know that the experimental data you collected are accurate? If the experimental results are different from your predictions, what would you do? Students were frequently asked to elaborate their answers and any unclear responses were questioned further.

Data Analysis

The quantitative data (i.e., pre- and post-tests) were analyzed by SPSS 12.0 (the Statistical Package for the Social Sciences). A paired two-sample *t*-test for means was used to determine the significance between students’ performances on the pre- and post-tests. For the item analysis, we categorized each sub-question into one of the explanation skills, and students’ answers were classified and graded by the scoring rubrics developed in the pilot testing. The alpha level used as criterion was *p*<0.01.

Students’ interviews and classroom video recordings were transcribed into a text format, imported into a database, and organized by the NVivo analysis software (QSR International, Doncaster, Victoria, Australia). Two sets of codes were developed to analyze the transcripts and generated through an iterative process. The first set of codes was used to evaluate students’ explanation skills. The codes were adopted from Wu and Hsieh (2006) and the categories and levels of explanation skills were modified for the present study (Table 2). Compared to their answers on pre- and post-tests, students’ interview responses provided richer information about their explanation skills. It allowed us to classify their responses into four levels rather than three levels in the tests. Because of the differences in the number of levels, we did not do any quantitative comparisons between test and interview results.

The second set of codes was developed to characterize students’ practical epistemologies during interviews and when they engaged in learning activities. We adopted the framework in Smith and Wenk (2006) for initial coding. We then compared and examined the data line by line to develop and revise levels and categories of students’ epistemologies. Because none of the students in the study held a sophisticated epistemology (i.e., Level 3 in Smith & Wenk’s study), there were two levels in our coding scheme: beginning and intermediate (Table 3). Additionally, due to the nature of data, the beginning and intermediate levels in this study did not directly correspond to Level 1 and 2 in Smith and Wenk (2006).
each level, five categories emerged from the data: (1) Goals of science, (2) Nature of scientific knowledge, (3) Types of scientific questions, (4) Nature of experiments, and (5) Evidence generation and evaluation.

After a trial coding, we refined both sets of codes for another trial coding and repeated the refining process until the codes accurately portrayed students’ performances and responses. Two researchers independently analyzed one-third of the qualitative data, and the interrater agreement was 0.90.

Finally, we compared the test scores and levels of students’ explanation skills before and after the learning activities to examine the improvement of students’ skills. To explore the interactions between students’ explanation skills and their epistemological views, we generated analytical notes and visual displays. The coded data, notes, and displays were reviewed several times to generate findings and to search for confirming and disconfirming evidence for findings (Erickson 1998). Each finding was warranted by multiple sources of data.

Findings

This section consists of three parts and follows the research questions. The first part shows statistical results and analyses of qualitative data regarding the development of students’
inquiry skills for constructing scientific explanations. Then we describe students’ practical epistemologies during interviews and the inquiry-based learning activities. The final part presents interactions between students’ inquiry skills and their practical epistemologies.

Students’ Explanation Skills

Statistical results of the pre-test \((n=68, M=5.60)\) and post-test \((n=68, M=8.24)\) showed that students’ inquiry skills for constructing scientific explanations were improved throughout a series of inquiry-based activities. A paired two-sample \(t\)-test for means indicated a statistically significant difference between students’ performances on the pre- and post-tests \((t(67)=5.04, p<.01)\). Additionally, we categorized each sub-question as one of the explanation skills and examined students’ performances on different skills. The results showed that students made significant progress in describing the reasoning process \((\text{Mean difference} = 1.99, t(67)=8.63, p<.01)\) but did not perform better on identifying relationships between variables and using data as evidence.

An analysis of interviews also suggested that in general students’ explanation skills were improved after the inquiry-based learning activities. As Fig. 1 shows, more students’ performances were categorized into Levels 3 and 4 during the post-interviews. Students improved the most in identifying relationships and describing reasoning where the number of students in Levels 3 and 4 increased by 21.7 and 17.4\%. This finding is partially consistent with the statistical results of the pre- and post-tests by showing that students made much progress on describing the reasoning process. In post-interviews, 11 of the

<table>
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<th>Levels and categories for analyzing practical epistemologies</th>
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<tr>
<td>Category</td>
<td>Beginning level</td>
</tr>
<tr>
<td>Goals of Science</td>
<td>The purpose of science is to do things (e.g., doing experiments, doing research, and making observations). Doing science involves following procedures and getting expected results.</td>
</tr>
<tr>
<td>Nature of Scientific Knowledge</td>
<td>Scientific theories and experimental results are the same. Scientific knowledge is something that scientists do or know, or something presented in textbooks and taught by teachers. Scientific knowledge is unproblematic and unchanging.</td>
</tr>
<tr>
<td>Types of Scientific Questions</td>
<td>Scientific questions are descriptive or factual questions (e.g., what happens when we add acid to water? what is a black hole?).</td>
</tr>
<tr>
<td>Nature of Experiments</td>
<td>There is only one way to do an experiment. There should be correct results for every experiment which could be obtained by asking teachers and repeating experiments.</td>
</tr>
<tr>
<td>Evidence Generation and Evaluation</td>
<td>Evidence could come from any source (e.g., asking teachers or others). There is no need to evaluate the accuracy of results; people should trust their results or ask others for correct answers.</td>
</tr>
</tbody>
</table>
target students were able to describe how they applied concepts or used experimental data to identify relationships between variables (Levels 3 and 4). Yet, while the test results showed no significant difference in students’ performances on identifying relationships between variables, interview data (Fig. 1) suggested that students had considerable improvement in this skill after engaging in inquiry-based activities.

To understand the possible reasons that caused different patterns in the tests and interviews and to examine students’ difficulties in identifying relationships between variables and using data as evidence, we conducted a content analysis of students’ interview responses and test answers. The analysis showed that after engaging in inquiry-based activities over 60% of students could correctly identify a bi-variable relationship when two variables were given. However, when the number of variables in a question was more than two, some students had difficulties in eliminating irrelevant variables and controlling one of the variables. Keeping one variable constant and allowing the others to vary seemed challenging to these fifth graders, which in turn undermined their performances on accurately identifying relationships between variables. Therefore, one reason that affected students’ skill in identifying relationships might be that compared to the interview questions the tests contained more items that included three or four variables. Additionally, students were given prompts and asked for elaboration during interviews while they worked individually without any support during the tests. Students’ post-interview responses were more complete and elaborated than their post-test answers. This might also explain why students seemed to improve more on identifying relationships during interviews.

Furthermore, the content analysis showed students’ difficulties in using data as evidence. When students were asked to use evidence to support their claims during the pre-test and pre-interview, approximately one third of them (22 in pretest; 9 in pre-interview) provided answers such as “you can see it from the data table,” “I’ve done the experiment,” or “because the results show it.” It seems that these students did not understand what counts as evidence and believed that because their claims were developed from a data table or an experiment, the source itself was evidence. Although more students started using data to support their ideas in the post-test and post-interview, connecting evidence to their claim...
and judging the quality of evidence were still challenging for them. Some students started including data in their answers but did not explicitly relate the data to their claims. Additionally, although five target students directly referred to experimental data in their post-interview responses and used them as evidence, only one of them included more than 3 sets of data points and others thought one or two sets of data points were convincing enough to justify their claims. This suggests that after the inquiry-based activities, some students realized the importance of using data as part of their explanations. However, this skill was not fully developed, and they needed guidance to evaluate the quality and the strength of evidence.

To summarize, these results showed that students’ explanation skills were improved substantially after they engaged in inquiry-based learning activities. Yet, their skills were differentially developed and they still had difficulties in controlling variables, identifying relationships among multiple variables, distinguishing evidence from information sources, and using data to develop convincing evidence.

Students’ Practical Epistemologies

Students’ practical epistemologies were categorized into two levels and five categories (Table 3). Below we present findings from the analyses of students’ interview responses, their classroom activities and conversations, and the teacher’s instruction. Quotation marks are used when directly quoting participants’ words.

Goals of Science Most of students’ ideas about what science is fell into four main types (Fig. 2). In pre-interviews, 22% of students thought that science is to invent and discover new stuff and 26% of students believed that science is doing research and experiments. Instead of viewing science as doing something, some students focused on other purposes of science such as improving people’s lives and solving problems. When prompted to elaborate on their responses, however, students provided very few details about the goals or the nature of these scientific activities. And some students used examples from scientists to describe what science is (e.g., “scientists try different things to see if they work”).

After the inquiry activities, students’ views about science as doing things seemed to be enhanced (Fig. 2). Many of students’ interview responses concentrated on practical purposes of science and what scientists do, which suggested an epistemology at the beginning level. A majority of the target students did not realize the complex nature of science and believed that the process of doing science is linear by “following the procedures.” Only two students (S215 and S216) were aware that “scientists’ ideas would influence their work.”

Students’ ideas about purposes of science and what scientists do might be partially affected by the teacher’s instruction. During Activity 6, for example, the classes watched videos about scientists and inventors. After the videos, the teacher used Newton’s example to illustrate that scientists are focused, like to think, and pay attention to things that other people might think trivial. The class discussions focused on scientists’ personalities rather than the complicated and social nature of scientific practices. Additionally, in Activity 8, the two classes discussed the history of transportation. The teacher presented a cumulative view of science and technology by showing how the shape of tyres has been changed historically and how the invention of rubber tyres made a great contribution to modern transportation. The teacher also mentioned several inventors (e.g., the Wright brothers and James Watt) and indicated how their inventions have improved human life. These discussions might shape students’ views of what science is and what scientists do.
Nature of Scientific Knowledge Analyses of students’ interview responses showed that almost all students held a naïve view toward scientific knowledge during pre-interviews (Fig. 2). Forty seven percent of the target students viewed scientific knowledge in terms of either experimental results (30%) or something that scientists do or know (17%). Rather than providing a definition of what scientific knowledge is, some students gave examples of

Fig. 2 Target students’ practical epistemologies about goals of science, scientific knowledge, and scientific questions. pre = pre-interview; post = post-interview
scientific knowledge, such as gravity, television, airplane, and the formation of black hole. These responses were categorized as “Other.”

As shown in Fig. 2, students’ ideas somewhat changed after they engaged in inquiry activities; fewer students held a view of scientific knowledge as experimental results. Also, one target student indicated a tentative view of knowledge and stated that one experiment is not enough because “a piece of knowledge should be proved by different experimental results.” However, more students viewed scientific knowledge as something owned by authorities (i.e., something that scientists do or know, and something presented in textbooks and taught by science teachers). It was disappointing to find that more students held such a view in post-interviews and that no classroom discussion explicitly addressed the definition of scientific knowledge.

Types of Scientific Questions In pre-interviews, half of the target students could not answer the question about the nature of scientific questions (Fig. 2), whereas during post-interviews, over 70% of students could express their ideas on scientific questions and provided at least one example. Their responses could be classified into three types. One type of scientific questions was to understand why things happen, such as “why does an apple fall” and “why are there bubbles in soda.” Some students believed that scientific questions were about how things work, and their questions included “how can we balance the lever” and “how can we light a bulb.” A third type of question was descriptive and relevant to observable phenomena: “can we use a microscope to observe small things” or “will a heavier water bottle move a longer distance.” According to Smith’s work (Smith et al. 2000; Smith and Wenk 2006), the first two types of questions indicate a higher level of epistemology because they are explanatory, open-ended, and involve scientific processes or principles. Figure 2 shows that after engaging in inquiry activities, more students were able to formulate better questions and had a richer understanding about the nature of scientific questions.

In the two guided-inquiry classrooms, all experiment questions were given by the teacher (NRC 2000). Students did not have opportunities to ask their own questions; however, their understandings about scientific questions improved. This suggests that through exploring these questions, students may realize the nature of scientific questions although the teacher did not explicitly provide criteria to evaluate the quality of scientific questions.

Nature of Experiments During the pre-interviews, about the same number of target students believed that students and scientists had multiple methods to carry out an experiment (Fig. 3). Yet, in post-interviews, some students changed their ideas, held a more naïve view toward own inquiry, and believed that there was only one method to conduct their experiments. On the other hand, students’ views about how scientists conduct an experiment remained unchanged. It appears that students held different views about how learners and scientists do an experiment.

Analyses of students’ conversations and classroom instruction showed that although students designed their experiments in Activities 3, 5, and 9, they did not compare the methodological differences between their own experiment and the experiments designed by other groups. In Activity 9, the teacher suggested two groups to change their measurements of time and distance in order to collect data accurately, but he did not explicitly indicate different methods or designs to conduct the experiment. Additionally, in this guided-inquiry learning environment, because the research questions given by the teacher were not complicated, the experiments designed by students were relatively simple and followed similar procedures; students did not have opportunities to explore different approaches.
Thus, the teacher’s instruction and their learning experiences may lead students to hold a more naïve view toward their own experiments.

Another aspect in the nature of experiments concerns possible sources of experimental errors. During the pre-interviews, over 45% of the target students identified human errors as a major source of experimental error while 26% of them were not able to provide any answer. After the inquiry-based activities, more students indicated the existence of instrument errors but there were still three students who believed that scientific experiments were always accurate without any error.

Fig. 3 Target students’ practical epistemologies about nature of experiments. pre = pre-interview; post = post-interview
An analysis of students’ classroom conversations indicated that at least four groups of students realized the importance of reducing human errors during the inquiry activities. For example, one student (S434) in the target group asked his group members to stop shaking the table when they were measuring the distance of a rolling ball. In Activity 9, another target group had a discussion about how to accurately measure the length of a spring scale. This discussion might help one of the group members (S430) to realize the existence of human and instrument errors. In the pre-interview S430 believed that there should be “no error in a scientific experiment,” while during the post-interview she indicated possible errors that could affect the accuracy of experimental results. Additionally, in Activities 5 and 9, the teacher reminded students to pay attention to the sources of error when they did measurements. He used examples to model how to measure time and distance consistently, how to reduce errors by keeping the instrument stable, and how to prevent human errors by doing an experiment collaboratively. These lessons may also help students realize that errors would be part of a scientific experiment.

A third aspect of the nature of experiments is how to improve experiments. In response to a question of what they would do to improve experiments, students gave answers such as reducing experimental errors, repeating experiments, and asking scientific teachers or others (Fig. 3). In post-interviews, more target students realized the existence of errors but some students still relied on teachers to provide answers.

Analyses of students’ interview responses suggested that a majority of the target students seemed to believe that there should be correct results for every experiment. Students stated that reducing errors was “a way to make an experiment accurate” and that repeating experiments could improve an experiment because “doing it again would correct our previous mistakes” which in turn could help them obtain “right results.” Asking authorities including science teachers for suggestions or solutions was also an approach to helping them know “whether our results are right or wrong.” The findings above are consistent with what we observed in classroom activities. When students encountered difficulties in designing or carrying out experiments, target groups usually turned to the teacher and asked for help. They seldom discussed with other groups and did not look for solutions by themselves.

Evidence Generation and Evaluation During interviews, students were asked about how to collect evidence to support their claim. Some target students believed that doing an experiment could “prove that their claim is right,” and more students (28% in pre-interviews and 35% in post-interviews) held this view after the activities (Fig. 4). Students’ responses showed their limited understanding about evidence, and only two students (S215 and S208) indicated that they would use experimental data as evidence to support their claims. Consistent with their development of inquiry skills, during post-interviews, some students considered using data as evidence but still did not fully understand the relationship between evidence and their claim.

During Activities 2, 5, 9 and 10, the teacher reminded students to use data to verify their hypotheses. The teacher asked students to “keep your hypotheses in mind” and “remember to check whether your idea is right” when they conducted their experiments. Yet, the teacher did not explicitly define what evidence is. Neither did he indicate what it meant to test their hypotheses and what students should do if the results were different from their hypotheses. This might explain why students’ views about evidence generation did not change much after inquiry activities.

Additionally, we explored students’ ideas about how to evaluate the accuracy of experimental results. Their interview responses included asking teachers or others,
repeating experiments, identifying errors, comparing results with other groups’, and trusting their own results (Fig. 4). If students directly gave examples (e.g., “using fire to test the existence of carbon dioxide”) without indicating an evaluation process, their responses were categorized as “Other.” After the inquiry activities, fewer students decided to ask teachers for accurate results. More students thought that repeating experiment would help them determine how accurate their experimental results were (Fig. 4); these students seemed to believe that experimental results would be unproblematic if they followed procedures correctly and “the experiments were done right.” Only one target student (S430) expressed a more informed view and stated that “although my group’s result is different from others, both of them could be accurate.”

Analyses of classroom instruction showed that during Activity 9, the teacher engaged the classes in a discussion of how to process their experimental data and how to improve the accuracy of results. The teacher guided students to think about “whether we should average the data or take one data reading” and “why we should use averages.” He then suggested students do multiple measurements of a quantity and average their data. The teacher also explained how these methods would help them filter out “unreasonable data.” During the interviews, however, target students seemed to interpret “doing multiple measurements” as repeating experiments and none of the students mentioned averaging data as a strategy to ensure the accuracy of results. Students might have forgotten about these strategies or did not connect them to epistemological purposes.
According to analyses of classroom observations, at least three target groups did repeat their experiments when results were different from their predictions. For example, in Activity 5, one of the target groups used spring scales to measure the amount of pulling force. A student noticed that the reading on their scale was lower than he expected so his group redid the procedure and read the data again. Additionally, two groups attempted to explain their anomalous data. When students examined a relationship between the weight of the added mass and the length of a spring, S214 noticed that the length did not increase much and discussed with S215 about possible reasons. S215 explained that the length did not change significantly because the object was too light. There were also three occasions when the teacher noticed that students’ readings were unreasonably high or low and asked students for explanations. The teacher modeled what they should do when they found anomalous data. However, the group and class discussions focused on identifying and reducing experimental errors rather than on developing alternative explanations of their results. This might explain why in post-interviews students still had a naïve view and believed that there existed correct and unproblematic results for their experiments.

Taken together, the analyses of students’ interviews showed that 9 of 23 target students had epistemological beliefs at the beginning level in all categories, while the others held more informed views in at least one of the categories. The former group of students was coded as “beginning” and the latter group was coded as “mixed.” Below we present a relationship between students’ epistemological beliefs and their development of explanation skills.

Interactions Between Explanation Skills and Practical Epistemologies

In order to examine a possible interaction between explanation skills and practical epistemologies, we compared levels of students’ inquiry skills before and after the inquiry activities and found that while some students improved one to three levels, few of them regressed by one level. We then divided students on the basis of their epistemological views and created Fig. 5. It shows that students with more epistemological beliefs at the

![Fig. 5 Interactions between the development of students’ inquiry skills and their epistemological views. B Beginning; M Mixed](image)
intermediate level (the mixed group) made more progress in developing explanation skills than their peers with naïve beliefs (the beginning group). Particularly, half of the students with mixed beliefs improved their skills to describe a reasoning process whereas none of the students at the beginning level showed improvement in this skill.

Analyses of classroom observations provided possible explanations for this interaction and showed how students reflected their epistemological views in inquiry practices. First, compared with their peers, students with mixed views tended to believe that science is to explain how and why some phenomena happen (nature of scientific questions) and raised more “why” and “how” questions during inquiry activities (7 students with mixed views). We found that a majority of group discussions were initiated by these questions, which in turn supported students to elaborate more on their reasoning processes.

Second, when experimental results were different from their hypotheses, students with naïve views tended to redo the experiment and searched for correct answers. They focused on doing experiments, ignored the concepts or principles behind the results, and did not interpret data. On the other hand, at least five students with mixed views attempted to interpret the anomalous data. Instead of judging the correctness of data, they applied the concepts learned to generate interpretations. This process supported them to realize the relationships between variables and to externalize their reasoning.

Third, because students with mixed views focused more on interpretation of data rather than the correctness of data, they usually combined their ideas with data when reporting experimental results. On the other hand, students at the beginning level seldom linked their data to an argument or a relationship. Therefore, in order to explain their ideas or reinterpret data, students with mixed views performed better on using data to support their claims.

Discussion and Conclusions

This study expanded on early attempts to understand how students develop their explanation skills and epistemological views in inquiry learning environments. The analyses of tests, interviews and classroom observations showed that guided-inquiry learning activities could help fifth graders develop rudimentary inquiry skills to construct scientific explanations, view experimental data as evidence to support their claims, realize the existence of experimental errors, and have a richer understanding about the nature of scientific questions. The study also examined interactions between practical epistemologies and explanation skills and suggested possible explanations of how students may reflect their epistemological views in their inquiry practices. However, after 5 weeks of inquiry activities, many of the students’ epistemological views were still naïve, such that science is doing things, experimental results are scientific knowledge, and there exists only one method to conduct an experiment. In the following, the findings are discussed in light of how to support students’ development of explanation skills and sophisticated epistemological beliefs through inquiry learning.

Consistent with previous research, this study found that students’ explanation skills were differentially developed (Wu and Hsieh 2006; McNeill et al. 2006). Although students’ performances were significantly improved in the pre- and post-tests, some of them still had difficulties in controlling variables, identifying relationships among multiple variables, distinguishing evidence from information sources, and using data to
develop convincing evidence. These findings raise issues regarding how students develop and perform explanation skills and how these skills are examined (Songer and Gotwals 2004). First, we found that when the number of variables increased, students would need an understanding about control of variables in order to identify relationships accurately. This suggests crucial elements of inquiry skills need to be taught when students engage in explanatory activities that involve more than two variables. These elements include eliminating irrelevant variables, keeping one variable constant, and allowing the others to vary, which need to be enhanced so that students could participate in more complicated inquiry activities (Kuhn 2007). Second, the results indicated differences between the level of skills apparent in students’ tests and those articulated during their interviews. Student interviews seemed to permit a fine-grained view of their inquiry skills. As more and more attention has been placed on how to develop students’ skills to engage in inquiry in recent years (NRC 2000), how to accurately evaluate and characterize students’ inquiry skills would be a methodological issue to explore further.

Previous research has indicated the importance of investigating students’ epistemological ideas about their own inquiry (Hogan 2000; Sandoval 2005). In order to uncover their ideas for their own inquiry and their approach to producing scientific knowledge, this study analyzed students’ artifacts and discourse, and collected data from students’ interviews as well as classroom observations. These observational data provided rich information about how the teacher presented and represented the nature of science and how students performed their epistemological views in inquiry activities. Yet, the analyses also showed that students did not have many opportunities to verbalize their epistemological views during inquiry activities and some of their views remained unchanged. Particularly, the classroom discussions focused more on the nature of scientific inquiry rather than on the nature of scientific knowledge. Engaging students in discussions of the latter dimension requires more support from teachers and the design of learning activities.

Additionally, explicit classroom discourse and a reflective instructional approach may be necessary in order to support students’ development of epistemologies. Khishfe and Abd-El-Khalick (2002) indicated that students who engaged in inquiry activities followed by explicit and reflective discussions made measurable changes in their epistemological beliefs, whereas students in the group that took an implicit instructional approach showed no change in their views. However, similar to what we found in this study, some students in the explicit group still held naïve epistemological views (Khishfe and Abd-El-Khalick 2002; Khishfe 2008). Effective instructional methods are still needed to support students’ development of sophisticated and informed views toward the nature of science.

In recent years, more and more studies were designed to understand and bridge the gap between epistemology and inquiry (Sandoval and Morrison 2003; Schwartz et al. 2004). By taking a notion of practical epistemology, this study made an effort to emphasize and reveal a close relationship between students’ epistemological views and their inquiry practices. The findings showed that guided-inquiry learning activities could provide students with opportunities to discuss the nature of science in context and reflect their epistemological views in inquiry activities. However, although this study shed light on how students’ epistemological views may be transformed into inquiry practices, some questions are still left unanswered, such as: How do students’ inquiry practices shape their epistemological views? How do students generalize their practical epistemologies into their knowledge of formal epistemologies? Future research could consider exploring these questions.
References


