Developing Sixth Graders’ Inquiry Skills to Construct Explanations in Inquiry-based Learning Environments

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Abstract

The purpose of this study is to investigate how sixth graders develop inquiry skills to construct explanations in an inquiry-based learning environment. We designed a series of inquiry-based learning activities and identified four inquiry skills that are relevant to students’ construction of explanation. These skills include skills to identify causal relationships, to describe the reasoning process, to use data as evidence, and to evaluate explanations. Multiple sources of data (e.g., video recordings of learning activities, interviews, students’ artifacts and pre/post tests) were collected from two science classes with 58 sixth graders. The statistical results show that overall the students’ inquiry skills were significantly improved after they participated in the series of the learning activities. Yet the level of competency in these skills varied. While students made significant progress in identifying causal relationships, describing the reasoning process, and using data as evidence, they showed slight improvement in evaluating explanations. Additionally, the analyses suggest that phases of inquiry provide different kinds of learning opportunities and interact with students’ development of inquiry skills.
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Introduction

Engaging students in inquiry-based learning is a cornerstone of current efforts at science education reform in Taiwan (Ministry of Education [MOE], 1999). The new curriculum outlines published in 1999 emphasized that students from grades 1 to 9 should develop skills to conduct scientific investigations (Abd-El-Khalick et al., 2004). Instead memorizing definitions and facts, students should develop meaningful understandings and construct scientific explanations by exploring natural and scientific phenomena (MOE, 1999). Explanation plays a central role in current inquiry-based reforms in science education. Formulating, evaluating, and communicating explanations have been identified as essential features of classroom inquiry (National Research Council [NRC], 1996, 2000). However, most middle school students have difficulty constructing scientific explanations of phenomena. They tend to generate incoherent explanation from personal ideas (Driver, Guesne, & Tiberghien, 1985; Driver, Leach, Millar, & Scott, 1996) and are not able to make logical relationships between evidence and explanations (Kuhn, Amsel, & O'Loughlin, 1988).

Intellectual skills, such as selecting and controlling variables, planning procedures, and interpreting patterns of evidence, are required for students to construct explanations and to engage in inquiry-based learning (Kuhn Black, Keselman, & Kaplan, 2000; Shimoda, White, & Frederiksen, 2002; Windschitl, 2000). These rudimentary intellectual skills necessary for inquiry learning are defined as inquiry skills in this study. Although studies on inquiry learning have recognized the importance of developing students’ inquiry skills (e.g., White & Frederiksen, 1998), they provided little guidance about what inquiry skills are needed for explanatory
activities and how students’ inquiry skills evolve over time. This study identifies four inquiry skills that are critical for students to develop scientific explanations: to identify causal relationships, to describe the reasoning process, to use data as evidence, and to evaluate explanations. The purpose of this study is to understand how sixth graders develop inquiry skills to construct scientific explanations throughout a series of inquiry-based learning activities.

The research questions that guide the study are: (1) How do students develop their inquiry skills throughout a series of inquiry-based activities? (2) How does the development of inquiry skills interact with phases of inquiry (e.g., asking questions, conducting investigations, and analyzing data)? (3) Does the teacher’s role change throughout the series of activities? If so, how? This study will provide insight into the design of learning environments in which students develop competent inquiry skills and actively engage in inquiry-based learning.

Theoretical Framework

Inquiry has been viewed as an approach to learning science that involves a process of exploring the natural or material world (Tamir, 1983; NRC, 1996). This study defines inquiry as a question-driven learning process involving conducting scientific investigations, documenting and interpreting narrative or numerical data, and summarizing and communicating findings. To help students learn science through inquiry, we develop a framework for inquiry learning that involves three dimensions: (1) phases in an inquiry process, (2) features of inquiry learning, and (3) intellectual skills required for inquiry learning. Explanatory activities play a particular important role in the latter two dimensions. In this section, we will describe phases involved in inquiry, outline the definitions of scientific explanations, and discuss the inquiry skills required in explanatory activities.
Developing Sixth Graders’ Phases in an Inquiry Process

Scientific inquiry is a “multifaceted” activity (NRC, 1996, p. 23) and can take many forms. Inquiry learning moving away from the traditional approach of a universal and procedural scientific method is to encourage students to participate in a range of activities in which students construct and evaluate scientific knowledge (McGinn & Roth, 1999). What types of activities might be involved in inquiry learning? What are the important aspects of inquiry that ought to be supported in a learning environment? Following NRC (2000) and Krajcik et al. (1998), we identify seven phases in an inquiry process: (1) asking and deciding questions, (2) searching for information, (3) designing investigations (4) carrying out investigations, (5) analyzing data and making conclusions, (6) creating artifacts, and (7) sharing and communicating findings. These phases are not steps to take in a linear fashion and students can go through the phases in complex ways. For example, students can reframe their research question and redesign their investigation after recognizing that their data cannot answer their questions. Additionally, due to the nature of inquiry some scientific investigations do not involve all seven phases. For example, analyzing data from a weather database and constructing explanations of phenomena such global warming and climate change could be an interesting project for inquiry although students do not collect empirical data by themselves, nor do they carry out hands-on experiments. Students should be provided with opportunities to appreciate and understand various forms of scientific inquiry.

Features of Inquiry Learning and Scientific Explanations

Having identified the phases of inquiry, more questions arise: What counts as a good question to ask? What kinds of artifacts or knowledge productions do students create through inquiry? NRC (2000) indicates five essential features of classroom inquiry that emphasize
questions, evidence, and explanations within a learning context. The features include asking scientifically oriented questions, using evidence to formulate and evaluate explanations that address the questions, considering and evaluating alternative explanations, and communicating and sharing explanations (p. 25). In classroom inquiry, one of the major knowledge productions created through inquiry learning is explanations that address scientifically oriented questions and are supported by empirical evidence. Students not only learn science from explanations provided by teachers and textbooks but they also participate in explanatory activities that involve formulating, evaluating, and communicating explanations.

Explanations are more than descriptions of phenomena and can be viewed as answers to “why” questions (Horwood, 1988). According to Hempel (1965) and his deductive-nomological model (known as the D-N model), a scientific explanation is formulated as a deductive argument that consists of statements of specific antecedent conditions and general laws (explanans), and description of the empirical phenomenon to be explained (explanadum). A D-N explanation for a question of “why is the sky blue” should include the statements below:

A clear cloudless daytime sky is blue [the empirical phenomenon to be explained] because the Earth’s atmosphere is composed of gas molecules mainly of nitrogen and oxygen [antecedent/initial conditions], and the gas molecules scatter light. The amount of light scattered for any given color depends on the wavelength of that color [relevant laws]. Blue light’s short wavelength causes it to be scattered the most [relevant law], so the blue in the sky we see is scattered blue light.

However, not all explanations used in science are deductive and general laws are not always involved in explanations (Scriven, 1988). A second type of explanation is teleological and sometimes functional. Biologists explain characteristics of an organism by referring to certain
purposes but not a cause. For instance, why do plants contain chlorophyll? A common explanation is that plants contain chlorophyll in order to photosynthesize. In this teleological explanation (Hempel & Oppenheim, 1988), a present event is explained by referring to a goal or a function. A third type of explanation is a causal-mechanical one (Salmon, 1984) that is formulated to capture a physical process such as the motions of two balls after a collision. In a physical process, spatio-temporal locations of objects are continually changing and more than one causal relationship is involved. This type of explanation illustrates interactions among objects involved in process and explains an event by tracing causal processes and interactions leading up to (or making up) the event.

The three types of explanations outlined above present philosophers’ views of scientific explanations. Although this classification of explanation provides a useful framework for defining scientific explanations, it requires modifications when used to examine students’ explanations in classrooms. The adequacy and completeness of an explanation depend on the knowledge available to the explainer and the knowledge assumed to be available to the explainee (Achinstein, 1971; McEwan & Bull, 1991; Wong, 1996). The explanation of “why the sky is blue” shown previously is a complete scientific explanation according to the D-N model but it cannot be fully understood by learners at the middle school level. Given their limited understandings about the underlying concepts (e.g., wavelength and light scattering), constructing such explanation could be even harder for middle school learners. Therefore, within a learning context where students are explainers and have limited conceptual knowledge about the phenomenon explained, definitions of scientific explanation need modified and some pedagogical considerations (e.g., the nature of content taught, students’ prior knowledge, and teachers’ supports) need to take into account. In this study, considering that the concepts
covered in the learning activities were mainly in physics science, we focus on students’ causal explanations that include four parts: (1) a description of the phenomenon explained, (2) a causal relationship or process, (3) a logical argument linking the description and the relationship, and (4) empirical data used as evidence. Yet, formulating such explanations is not an easy task for sixth graders.

*Inquiry Skills Required in Explanatory Activities*

Children’s explanations about natural and scientific phenomena have been of interest to researchers in science education. There are two main approaches to the studies of children’s explanations. One focuses on the content of the explanations and students’ conceptual understandings revealed by their explanations in particular scientific domains (Andersson, 1986; Watson, Prieto, & Dillon, 1997). A second approach emphasizes scientific reasoning and the process of constructing explanations (Kuhn, 1989; Kuhn & Dean, 2004). Following the latter approach, this study aims at understanding how students learn to generate explanations.

Students’ difficulties in constructing explanations are well documented. Many students generate incoherent explanation from personal ideas (Driver, Guesne, & Tiberghien, 1985; Driver, Leach, Millar, & Scott, 1996) and are not able to make logical relationships between evidence and explanations (Kuhn, Amsel, & O’Loughlin, 1988). Students tend to use linear causal reasoning and attribute the cause of a phenomenon to the existence of an agent (Andersson, 1986). Secondary students do not consider all relevant variables in a problem and often rely on anthropomorphic explanations in their understandings of the natural world and attribute human agency or non-human organisms (Clough & Wood-Robinson, 1985). A majority of middle school students in Abrams, Southerland and Cummins (2001) were not able to provide a causal explanation to a why question about biological changes and could not make a distinction
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between explanations that involve causal relationships in the changes and explanations that address the rationales of the changes. Additionally, many students in the middle grades confuse explanatory claims with evidence and have difficulty making logical inferences (Kuhn, 1989).

Part of students’ difficulties stem from their lack of inquiry skills. When students engage in explanatory activities and inquiry learning, they are believed to develop a set of intellectual skills that enable them to construct understandings about science (Windschitl, 2000). If students lack these essential skills, inquiry learning may not be productive and lead students to frustration, and students may generate conclusions that are not empirically proved. For example, Kuhn and her colleagues (Kuhn et al., 1988; Kuhn et al., 2000; Kuhn & Pearsall, 2000) focused on the coordination of theory and evidence, and suggested that students should posses skills to interpret patterns of evidence, to understand the type of evidence that could support or contradict that theory, and to justify the selection of competing theories that explain the same phenomenon. Kuhn (1989) argued that these skills are the “most central, essential, and general skills that define scientific thinking” (p. 674).

In explanatory activities, students are required to construct an explanation that include a description of the phenomenon explained, a causal relationship or process, a logical argument linking the description and the relationship, and empirical data used as evidence. Additionally, students should participate in the evaluation of the explanations and understand that explanations could be modified and discarded based on the evidence (Sandoval & Reiser, 2004; Thagard, 1988). Therefore, when students construct scientific explanations, they are expected to demonstrate the following skills: (1) identifying causal relationships, (2) describing the reasoning process, (3) using data as evidence, and (4) evaluating explanations. The development of these skills throughout a series of inquiry-based learning activities is the foci for our analysis. To
understand the potential interactions among the three dimensions of inquiry (i.e., processes, features, and inquiry skills), this study also examines in which phase of inquiry students develop the inquiry skills. The analyses of the interactions could help us understand the kinds of opportunities provided in each inquiry phase.

Teacher’s Role in Inquiry-based Classrooms

One factor that could affect students’ development of inquiry skills is teachers’ instruction (Eick & Reed, 2002; Rop, 2002). When using an inquiry approach to science teaching, teachers are expected to support students’ exploration of phenomena and to engage them in constructing meaningful scientific understandings (Hogan & Berkowitz, 2000). Teachers need to shift the emphasis from textbooks to exploring questions and topics that are student-centered (Keys & Kennedy, 1999). They also need to facilitate students building on their current knowledge and revising their understanding (Eick & Reed, 2002; NRC, 1996). Flick (2000) identified elements of cognitive scaffolding provided by teachers that supported inquiry learning. Theses elements of scaffolding included transforming the task accessible to students, structuring opportunities for learning, organizing a task for presentation, and identifying approximations of successfully completing a task. Although the teachers in Flick (2000) demonstrated various elements of scaffolding, their scaffolding “focused on using inquiry skills and not on learning the skills themselves nor how and when to employ those skills in scientific problems” (p. 122). Thus, teachers have to communicate inquiry expectations and provide instructional supports to develop skills that are important for performing inquiry.

Teachers play varied roles in supporting students’ development of inquiry skills. These roles include modeler, guide, diagnostician, facilitator, mentor, and collaborator that indicate a varied amount of structure and scaffolding teachers build into an activity (Crawford, 2000;
Developing Sixth Graders’ Communication Skills (Osborne & Freyberg, 1985). For example, as a guide, a teacher provides specific directions for developing students’ skills and strategies. When a teacher plays a role of collaborator, he or she does not provide scaffold but allows students to take a role of teacher. In this study, we follow Crawford’s categorization of teachers’ roles to examining teaching practice. In doing so, we can understand how a teacher changes his or her role to support learning when students become more skillful at doing inquiry.

Methods

This study was conducted in two sixth grade science classrooms at a public elementary school in northern Taiwan. Fifty-eight sixth graders (n=58, 29 girls and 29 boys; average age 12 years) participated in the study. The students had a range of academic abilities and the majority of them were middle-class. Both classes (Class I: 28 students, 14 girls; Class II: 30 students, 15 boys) were taught by the second author who held a master degree in science education and had taught science at elementary schools for four years. In each class, six students were nominated by the teacher for intensive observation. Among the 12 target students, seven of them were girls.

The teacher designed six learning activities to engage students in constructing scientific explanations (Table 1). Because the students had no prior experience in inquiry-based learning, the students needed guidance in undertaking inquiry. To support students learning, the teacher coached students into the inquiry process through planned steps during the first three activities. He also limited the scope of inquiry when the activities involved new concepts. For example, during Activities 3, 4, and 5, students did not design their own experiments but engaged in discussions and explorations designed by the teacher so that students could concentrate on learning new ideas. The six activities covered topics of motion, force, and electromagnetism and took a total of 15 class periods (over 6 weeks) to finish.
In Activities 1, 2, and 3, students identified variables that affected a runner’s speed (e.g., height and weight) and the movement of a ping-pong ball. They designed experiments to examine the causal relationships between the variables, carried out the investigations, collected data, and shared their findings. During Activities 4, 5, and 6, students built electric motors, investigated factors that influenced the rotation speed of a motor, and created posters to share their findings.

When presenting their experimental findings in Activities 2 and 6, students were given an evaluation worksheet and asked to score each other’s explanations. The evaluation sheet contained several guiding questions: Does the group clearly state their argument or a causal relationship? Does the group clearly describe the process of their investigation? Does the group include data or graphs in their presentation? Does the group present the evidence to support their argument? After considering these questions students gave a score from one to three for each question and wrote down their comments on the presentations.

Data Collection

Multiple sources of data were collected over six weeks including: classroom video recordings, field notes, students’ artifacts, pre- and post-tests, and interview transcripts. Every class period was videotaped and fieldnotes were taken to capture classroom activities. The classroom video recordings illustrated students’ development of inquiry skills and the teacher’s instructional supports. Students’ artifacts including reports, posters, and worksheets were also collected to evaluate students’ inquiry skills.

An inquiry skill test was designed to assess students’ inquiry skills before and after the activities. The test contained questions created by the authors and modified questions from the Test of Integrated Process Skills (Burns, Okey, & Wise, 1985) and TIMSS 2003 Special
Developing Sixth Graders’ Initiative in Problem Solving and Inquiry (International Association for the Evaluation of Educational Achievement, 2005). A group of specialists, including one university professor and three elementary school teachers, reviewed the test items to ensure that the content and format of the test items were in alignment with the nature of inquiry skills. The final version of the test contained 20 items, which were grouped into the four skills. The reliability coefficient was estimated at 0.72 using the Juder-Richardson Formula 20 (KR-20).

To assess whether students developed competent skills, target students (a total of 12 students including 7 girls and 5 boys) were interviewed individually. Each target student was interviewed three times, before the Activity 1, after the Activity 2, and after the Activity 6. In each interview, two questions were asked. For each question, students were asked to use materials or analyze data to identify causal relationships and formulate explanations. For example, for one interview question, target students were provided with a spring scale, a small bag, and an inclined plane, and asked to explain the relationship between the height of the inclined plane and the amount of force needed to pull the bag to the top of the inclined plane. Each interview was about twenty minutes and conducted outside of the science classroom. The interviews were later transcribed and coded by the scheme shown in Table 2.

Data Analysis

The quantitative data (i.e., pre- and post-tests) were analyzed by SPSS 11.0 (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 item into one of the inquiry skills. The alpha level used as criterion was $p < 0.01$. 
Several analytic steps were taken to analyze the qualitative data (Erickson, 1986). We transcribed the classroom video recordings into a text format. Each class period was then segmented into episodes. In each episode, a classroom activity centered on the same conceptual theme and had coherent interaction (Jordan & Henderson, 1995). Interviews were also transcribed. These transcripts were imported into a database and organized by the NUD*IST analysis software (Qualitative Solutions, Melbourne, Australia). Using the constant comparative method (Glaser & Strauss, 1963), we coded the transcripts based upon a coding scheme that included phases of inquiry, inquiry skills, and the teacher’s roles. Each inquiry skill was categorized into four levels. According to students’ responses and performances, their inquiry skills were coded as high, adequate, low, and none. Table 2 shows examples of the codes.

Students’ artifacts were assessed using a set of scoring rubrics. The causal relationships, arguments, explanations generated by students were analyzed at multiple levels using the rubrics.

When analyzing data, we reviewed the data corpus repeatedly to search for confirming and disconfirming evidence for findings (Erickson, 1986). Each finding was warranted by multiple sources of data. For example, the data from artifacts was used to triangulate assertions generated from the analysis of classroom videos and interviews. To establish the reliability, we used audio or video recording devices so qualitative data could be collected in detail, instead of relying on our memory or fieldnotes. We had three researchers analyze the same set of data. The interrater agreement among three coders was 0.88.

Findings

This section consists of three parts and follows the research questions. The first part presents statistical results and analyses of qualitative data regarding the development of students’ inquiry skills. We then describe the interactions between the development of inquiry skills and
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The results of pre-test (n = 58, M = 6.70) and post-test (n = 58, M = 7.97) indicate that students’ inquiry skills to construct scientific explanation improved after they engaged in a series of inquiry-based activities. A paired two-sample t-test for mean shows a statistically significant difference between the means of pre- and post-tests (t(58) = 10.3, p < .01). Moreover, the effect size indicates that the average score on the post-test was 0.34 standard deviations greater than the average score on the pre-test (effect size = 0.34). This shows a medium effect of the inquiry-based learning activities.

An item analysis was also conducted to examine students’ performances on the tests. Each item was categorized as one of the inquiry skills and the statistical comparison results are shown in Table 3. The results indicate that students made significant progress in three of the four skills: identifying causal relationships, describing the reasoning process, and using data as evidence. The effect size shows a large effect of the treatment on describing the reasoning process. Although in the pretest students tended to make a claim without describing the connection between the claim and the data, they were able to verbalize their reasoning process in posttest. However, students did not perform better on evaluating explanations. It seems that while students became more skillful in identifying and describing elements of explanations, they did not learn more about critiquing explanations constructed by others.

Analyses of the qualitative data provide detailed information about students’ development of the inquiry skills throughout the series of inquiry-based activities. Figures 1, 2, 3, and 4 show groups’ and target students’ performances during class activities and interviews.
In general, students in both classes improved substantially on the four skills; however, the level of competency in these skills varied. Analyses of the qualitative data reveal that although all students groups reached a high or adequate level of skill in identifying causal relationships, describing the reasoning process, and using data as evidence, two groups still demonstrate a low skill level in evaluating explanations. This finding echoes statistical results that for the sixth graders, evaluating the validity and quality of explanations provided by others seemed the most challenging skill to develop. Below we provide detailed descriptions of students’ development of inquiry skills.

*Identifying causal relationships.* While one of student groups were able to accurately describe a causal relationship during Activity 1, all of them could describe a causal relationship and include data in their description in Activity 6 (Figure 1). Students’ artifacts show that over 70% of the causal relationships identified by students were simple, bivariable relationships and did not involve scientific concepts. A typical example is: “we found that when the motor coil was two centimeter lower [and closer to the magnet], the motor ran 60 rotations [per minute]. When the coil was higher, the motor ran only 40 rotations. So we can know from the data that the position of the coil affects the speed of the motor. The lower the coil, the higher the speed.”

Target students’ interviews show a similar pattern that target students improved substantially in their skill to identify causal relationships. Below we present two interview segments to show a typical example. During the interviews, target students were provided with a spring scale, a small book bag, and an inclined plane, and asked to explain the relationship between the height of the inclined plane and the amount of force needed to pull the bag to the top of the inclined plane. The interviewed students were allowed to use a blackboard to write down their ideas or draw diagrams if they needed.
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(Segment 1: Yi-Jay’s first interview)

Interviewer: Here is an inclined plane and you can change the height if you want. Could you tell me why you need less pulling force when the inclined plane is lower?

[Yi-Jay hooks the spring scale to the bag and pulls the bag up the plane. He stops and then pulls the bag up the plane again.]

Interviewer: Could you tell me what you’re doing?

Yi-Jay: I don’t know…

Interviewer: Do you want to use the blackboard?

Yi-Jay: Yes. [On the board, Yi-Jay draws a hill and a little person standing on the hill].

Yi-Jay: This is…well…you can feel…that walking up a steeper hill is more difficult [pointing to the hill]. When the hill is lower, it’s easier.

Interviewer: Anything else?

Yi-Jay: No. That’s it.

(Segment 2: Yi-Jay’s third interview)

Interviewer: Here is an inclined plane and you can change the height if you want. Could you tell me why you need less pulling force when the inclined plane is lower?

[Yi-Jay hooks the spring scale to the bag and pulls the bag up the plane. He changes the height of the plane and pulls the bag up the plane again. He records the readings on the board. He also draws a simple line graph]
Interviewer: Could you tell me what you’re doing?

Yi-Jay: When…when the hill is low, I use 1.5 kg force [pointing to the graph]. When the hill is steep, I use 2 kg force. Uh…this shows that when the height of the inclined plane is lower, the pulling force is decreasing. That’s why a flat inclined plane makes work easier.

In the first interview, although Yi-Jay manipulated materials and tried to come up with an explanation, his manipulation did not seem purposeful. His response was rather intuitive, mainly drew upon his experience (walking up a hill), and lacked of data to support his claim. During the third interview, Yi-Jay was able to record readings in a more systematic way and used a graph to illustrate the relationship between the height of the inclined plane and the amount of pulling force. Additionally, he included quantitative data as evidence to validate his claim. Yi-Jay’s responses suggested his improvement in identifying a causal relationship as well as in using data as evidence.

Describing the reasoning process. During the first activity, none of student groups described how they analyzed or interpreted data in order to generate their causal argument and conclusion (Figure 2). For example, during their first group presentation, without describing the process of data analysis, Lin-Fen jumped into a conclusion that “the taller the people, the faster they run” even though some of the data did not support this finding. Among the ten groups in
the two classes, seven groups (including Lin-Fen’s group) ignored data that did not fit into their existing ideas (Chinn & Brewer, 1993). To help students reason about data, the teacher provided timely scaffolds (Krajcik, Czemiak, & Berger) when students engaged in inquiry-based learning activities. The classroom recordings show that supported by the teacher, students began to reason about data, to describe patterns shown in graphs, and to include their interpretation of data in their explanation or argument. Pei’s second group presentation is a typical example.

(Segment 3: Pei’s group presentation)

Pei: The results of our activity...here is the table [pointing to the table]. All data is here [the table]. We transformed it into a graph. We found that the steeper the inclined plane, the faster the ball runs.

Pei: Oh, we also found that the data show [showing three worksheets but some data on the worksheets are irrelevant to their conclusion] the steeper the inclined plane, the faster the ball runs.

Teacher: Could you tell us about the pattern shown in your graph?

Pei: When the plane is inclined at an angle of 15 degree, the time is 18 seconds. When the plane is inclined at an angle of 30 degree, the time is 10 seconds. [Pei reads through the data recorded in the table.]

Teacher: What do these numbers mean?

Pei: They mean that when the plane angles are higher, the fewer the seconds, the higher the speed [pointing to the graph].

Teacher: Does the result support your hypothesis?

Pei: Yes.
At the beginning of the segment, Pei pointed to their data and graph but did not elaborate on them. She repeated their conclusion twice without describing how they reached the conclusion. The teacher’s questions played an important role in supporting her to describe the reasoning process. During their presentation in the activity 6, without the teacher’s prompt, Pei’s group described their interpretation of the data and included quantitative data to support their argument. They also identified outliers and provided possible causes for errors. It seems that the process of describing how they reasoned about the data provided students with opportunities to externalize their thoughts, to reflect on the data, and to reorganize their existing ideas.

After engaging in the series of inquiry-based activities, all student groups could describe their reasoning process adequately, whereas three target students were still below the adequate skill level when they were interviewed individually (Figure 2). The discrepancy between group and individual performances was also found in other inquiry skills (Figures 1, 2, and 3). This suggests that in this collaborative learning environment, not all group members were on the same skill level and that not all group-developed skills were internalized by each group member (Forman & Larreamendy-Joerns, 1995; Lumpe & Staver, 1995).

*Using data as evidence.* Figure 3 shows that in Activity 1, none of the student groups included data as evidence during their group discussion and presentation. As they had more experience in inquiry learning, they learned to use data to support their explanations and conclusions. For example, in one of the interview segments shown previously, Yi-Jay used numerical data and a graph to support his explanation about how the height of an inclined plane affects the pulling force. Students’ artifacts also showed that 80% of the student groups included numerical data collected from their first-hand investigations in their explanations. In addition to the numerical data, four groups included second-hand information from textbooks or authorities.
to strengthen their arguments. For instance, in one of their presentations, Li-Lin’s group made an argument that the position of the coil affects the speed of the motor. After describing the data and their argument, they added “also, we asked Ms. Chen [a science teacher] and Ms. Chau [a science teacher] for their opinion. Both of them think that the lower the position of the motor coil the higher the speed.” These groups learned to include information from multiple sources to support their explanation. They used information gathered from two teachers to support their claim but did not evaluate the validity the information and the quality of evidence.

Encouraged by the teacher, all student groups showed at least one representation in their posters. The most frequently used representations were graphs and data tables. Yet, the way that students used representations as evidence was superficial. In Pei’s presentation shown previously, she first displayed a graph without any interpretation. Under the teacher’s request, Pei then explicitly referred to numerical quantities, identified the pattern shown in the graph and made a claim through the pattern. Students’ artifacts also showed that although a majority of the student groups included graphs as evidence, they rarely make references to the graphs in the text (Wu & Krajcik, 2006). These sixth graders may need explicit guidance from the teacher in using graphs as meaningful evidence.

Evaluating explanation. During their presentations in Activities 2 and 6, students were asked to evaluate each other’s explanations. Consistent with what we found from the statistical results, however, the analysis of their responses only showed a slight improvement in the skill (Figure 4). Although the number of students’ comments increased from Activity 2 to Activity 6, students’ comments on the evaluation worksheets focused on the loudness of voice and the clarity of expression during the presentations instead of the content and the quality of
Developing Sixth Graders’ explanations. Only one group in Activity 2 and two groups in Activity 6 mentioned a lack of evidence in other groups’ presentations.

Throughout the series of activities, students’ performances on evaluating explanations did not improve as much as their performances in other skills. This may be because students had fewer opportunities to evaluate each other’s work. As shown in Table 1, students demonstrated their evaluating skill in two activities but they learned about other three inquiry skills in three or more activities. Additionally, analyses of the classroom observation suggested that the lack of improvement might be attributed to the design of the evaluation activities. While students worked in groups to construct explanations with the teacher’s support, they participated in evaluating activities through individually filling out the worksheets. They did not receive timely feedback or scaffold from the teacher. Nor did they have a group or class discussion about how to evaluate explanations. It seems challenging for students to develop evaluating skills with limited time, supports, and peer interactions.

Interactions between the development of inquiry skills and the phases of inquiry

To examine the interactions between the development of skills and the phases of inquiry, we used NUD*IST to count frequencies of instances in which students demonstrated a skill in a certain inquiry phase (e.g., identifying causal relationships when analyzing data). We find that all student groups frequently demonstrated the four skills when sharing findings (36 observed instances per activity) and creating artifacts (27 observed instances per activity). Yet, the frequencies were relatively low in other inquiry phases. When carrying out investigations and analyzing data students focused on following procedures, recording data, and graphing data rather than constructing explanations. The observed frequencies were 10 and 8 in the phases of carrying out investigations and analyzing data, respectively. Students rarely engaged in
explanatory activities when asking/deciding questions (2 observed instances per activity) and searching for information (1 observed instances per activity).

This finding indicates that each phase of inquiry provided students with different kinds of learning opportunities to develop inquiry skills. Among the phases of inquiry, creating artifacts and sharing findings offered many opportunities for students to recast their findings and construct explanations. Additionally, the finding suggests a need for explicit instruction on explanatory activities. As novice inquiry learners, students did not use inquiry skills spontaneously unless the learning activities or the teacher required them to do so. When students created artifacts and shared findings, the teacher requested them to include data, graphs, and explanations in the artifacts as well as their presentations. On the other hand, when asking questions, analyzing data and conducting investigations, students were not asked to construct explanations although they were provided with time and opportunities to do so. Without explicit instruction, it is not surprising that students did not engage in discussions about causal relationships and evidence.

Change of the teacher’s role

The teacher’s role slightly changed throughout the series of activities. Table 4 shows that during Activity 1, the teacher frequently played the role of guide and diagnostician. As a guide, he directed and led students in identifying causal relationships and interpreting data. When playing the role of diagnostician, the teacher did not give structured instruction but provided suggestions and commented on students’ ideas when they analyzing data, discussed preliminary findings, and presented results. For example, in Segment 3, the teacher played a role of diagnostician and used questioning to help students identify patterns of the data.
As students engaged in a more complex inquiry activity (Activity 2), the teacher took on more the role of modeler, demonstrated how to plan and design investigations, and modeled how to construct explanations based on the data students collected. In the same activity, the teacher also guided students to design and create artifacts that demonstrated their understandings. As a mentor, he supported students’ inquiry process and provided assistance when students needed it.

During Activity 6, the students had more opportunities to take on the role of teacher. In addition to giving direction and correcting errors made by students, the teacher listened to students, participated in students’ group discussions, exchanged ideas with them, and played a role of collaborator. Below is an example of collaborator in which the teacher participated in a group discussion. Instead of providing answers, the teacher invited students’ ideas and expressed genuine interest in students’ ideas.

Segment 4: Group discussion with the teacher

Students are looking at their worksheets and discussing whether their results confirmed their hypothesis. The teacher stopped by and joined the conversation.

Teacher: Using the large rubber band runs fast [reading students’ worksheet]…What did you do? Large rubber band and what?

Wendi: Small rubber band.

Teacher: Okay, let’s think about it. You found that a large rubber band makes the ball run faster?

Jay: Yeah.

Teacher: But why?

Wendi: Maybe the tension of the band?

Teacher: That’s a good idea. You mean that different bands provide different
Developing Sixth Graders’ amounts of tension, right? Any other idea?

The teacher’s role indicates a varied amount of structure teachers build into an activity. Although the major roles played by the teacher in the activities (i.e., modeler and guide) suggest that inquiry practiced in the two classrooms was in a form of guided inquiry (NRC, 2000), the shift in the teacher role indicates that some of the scaffolds were fading when students became skillful in constructing explanations and doing inquiry. As the teacher’s role changed from modeler to collaborator, students gained more independence in learning.

Discussion and Conclusions

This study shows that through a series of inquiry-based activities, sixth graders were able to develop adequate inquiry skills for constructing scientific explanations although the growth patterns of the skills could vary. Additionally, the phases of inquiry interacted with students’ development of inquiry skills. Each phase of inquiry provided students with different learning opportunities to develop inquiry skills. Furthermore, the teacher’s timely and ongoing scaffolds played a critical role when students engaged in explanatory activities. As students gained more experience in doing inquiry, they took more responsibilities for their own learning and the teacher took on more the role of collaborator.

While students made significant progress in identifying causal relationships, describing the reasoning process, and using data as evidence, they showed slight improvement in evaluating explanations. As in Krajcik et al. (1998), this study shows that engaging students in critiquing and evaluating each other’s work is a challenge for teachers in an inquiry-based classroom. The learning environment needs to provide more supports or explicit instruction so that students can make constructive comments on improving the quality of explanations. One way to encourage
students’ participation in evaluating activity is through introducing them to the criteria by which their work is evaluated (White & Frederiksen, 1998). In addition to the guiding questions used in this study, worksheets could include descriptions of appropriate learning performances and examples of scientific explanations to help students understand the characteristics of explanatory activities and assess the quality of explanations.

Judging the quality of explanations is not an easy task (Sandoval & Millwood, 2005). Drawing from studies of science and research on student argumentation, Sandoval and Millwood developed an analytical framework to examine high school students’ written explanations that involved important biology concepts. Although the components of the framework (i.e., the warrant of explanatory claims, the sufficiency of the evidence, and the rhetorical use of inscription) are useful for evaluating students’ epistemic practices in explanatory activities, it requires modification before used in a middle school science classroom. As we discussed previously, the adequacy and completeness of an explanation depends on the knowledge available to the explainer and the knowledge assumed to be available to the explainee (Achinstein, 1971). To involve students in evaluating activities, researchers and teachers could use part of the framework created by Sandoval and Millwood (2005) as a template and engage students in creating their own reflective assessment when students become more skillful in constructing scientific explanations.

Although students’ lack of improvement in evaluating skill could be attributed to the design of the activities and curriculum materials, the findings also suggest that the inquiry skills for constructing explanations might involve different levels of difficulty and complexity. For example, after their participation in Activity 1, students made a significant progress in describing the reasoning process and identifying causal relationships in Activity 2. Other skills were still
scaffolded heavily by the teacher and were not performed adequately until Activity 6. This suggests that some of the skills might be more conceptually complicated and sophisticated to these students. As shown in research on scientific reasoning (e.g., Kuhn, 1989; Kuhn, Amsel, & O’Loughlin, 1988), many students have difficulty coordinating their claims and evidence and making a logical relationship between evidence and explanations.

To ease students’ difficulty and facilitate the development of inquiry skills, the curriculum and teachers should provide ongoing and timely scaffolds. This study shows that the teacher’s support was crucial and students’ initial participation in inquiry activities required co-participation of more competent others. Consistent with the characteristics identified by Crawford (2000), inquiry teaching in this study involved probing for reasoning, asking for elaboration, and fostering ownership of students. The teachers provided scaffolds through questioning, guiding, and modeling to support students’ engagement of explanatory activities. On the other hand, scaffolds are not necessarily in a form of discursive interactions between teachers and students. They could be provided by curriculum materials or learning technologies (Fretz, Wu, Zhang, Krajcik, & Soloway, 2002). Technological tools such as ExplanationConstructor (Sandoval & Reiser, 2004) have been designed to foster high school students’ construction of explanations. Some features of the tool might be transformed into teaching practice to engage middle and elementary school students in explanatory activities.

Explanatory activities could be a core of inquiry learning. This study indicates that through participating in a series of inquiry-based activities students developed important inquiry skills to construct scientific explanations. The findings provide insight into the design of learning environments in which students develop competent skills to engage in the inquiry learning.
References


Developing Sixth Graders’


Authors Note

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### Table 1

**Inquiry Skills and Inquiry Phases Involved in the Six Learning Activities**

<table>
<thead>
<tr>
<th>Activity title and description</th>
<th>Inquiry skills demonstrated</th>
<th>Inquiry phases involved</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Who runs faster?</strong>&lt;br&gt;Students identified variables that affect a runner’s speed, make claims based on the data provided by the teacher, identify relationships between the variables, and presented their findings.</td>
<td>(1) Identifying causal relationships&lt;br&gt;(2) Describing the reasoning process&lt;br&gt;(3) Using data as evidence</td>
<td>(1) Asking and deciding questions&lt;br&gt;(5) Analyzing data and making conclusions&lt;br&gt;(7) Sharing and communicating findings</td>
</tr>
<tr>
<td><strong>2. What makes a ping-pong ball run faster?</strong>&lt;br&gt;Students discuss how to measure the speed of a ball, make hypotheses about how to make a ball run faster, design experiments and collect data, transform the data into a table or a graph, generate explanations, create posters to present findings, and evaluate explanations.</td>
<td>(1) Identifying causal relationships&lt;br&gt;(2) Describing the reasoning process&lt;br&gt;(3) Using data as evidence&lt;br&gt;(4) Evaluating explanations</td>
<td>(1) Asking and deciding questions&lt;br&gt;(2) Searching for information&lt;br&gt;(3) Designing investigation&lt;br&gt;(4) Carrying out investigations&lt;br&gt;(5) Analyzing data and making conclusions&lt;br&gt;(6) Creating artifacts&lt;br&gt;(7) Sharing and communicating findings</td>
</tr>
<tr>
<td><strong>3. How can we “draw” a motion?</strong>&lt;br&gt;Students observe the movement of a ball, identify possible factors that influence the direction and the speed of the moving ball, and represent the movement by lines and arrows.</td>
<td>(1) Identifying causal relationships</td>
<td>(7) Sharing and communicating findings</td>
</tr>
<tr>
<td><strong>4. What’s inside an electric motor?</strong>&lt;br&gt;Students identify the main components of an electric motor, and find out the relationship between the current-carrying coil and the magnetic field.</td>
<td>(1) Identifying causal relationships&lt;br&gt;(2) Describing the reasoning process&lt;br&gt;(3) Using data as evidence</td>
<td>(4) Carrying out investigations&lt;br&gt;(5) Analyzing data and making conclusions&lt;br&gt;(7) Sharing and communicating findings</td>
</tr>
<tr>
<td><strong>5. Let’s build an electric motor.</strong>&lt;br&gt;Students work in groups to build an electric motor, identify the main components of a motor, and explain how an electric motor works.</td>
<td>(1) Identifying causal relationships&lt;br&gt;(2) Describing the reasoning process</td>
<td>(4) Carrying out investigations&lt;br&gt;(5) Analyzing data and making conclusions&lt;br&gt;(7) Sharing and communicating findings</td>
</tr>
<tr>
<td><strong>6. How can we increase the rotation speed of an electric motor?</strong>&lt;br&gt;Students discuss and identify several factors which affect the rotation speed of a motor</td>
<td>(1) Identifying causal relationships&lt;br&gt;(2) Describing the reasoning process&lt;br&gt;(3) Using data as evidence&lt;br&gt;(4) Evaluating explanations</td>
<td>(1) Asking and deciding questions&lt;br&gt;(2) Searching for information&lt;br&gt;(3) Designing investigation&lt;br&gt;(4) Carrying out investigations&lt;br&gt;(5) Analyzing data and making conclusions&lt;br&gt;(6) Creating artifacts&lt;br&gt;(7) Sharing and communicating findings</td>
</tr>
</tbody>
</table>
Table 2

*Levels for Coding Inquiry Skills*

<table>
<thead>
<tr>
<th>Inquiry Skill</th>
<th>High</th>
<th>Adequate</th>
<th>Low</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identifying causal relationships</td>
<td>Students accurately describe a casual relationship and include data in their description.</td>
<td>Students accurately describe a casual relationship.</td>
<td>Students indicate either a cause or an effect in a causal relationship, but cannot provide a complete description of the relationship.</td>
<td>Students do not indicate any causal relationship.</td>
</tr>
<tr>
<td>Using data as evidence</td>
<td>Students include sufficient data to support their explanation and use information from other reliable sources to strengthen their explanation.</td>
<td>Students include sufficient data to support their explanation.</td>
<td>Students include some empirical data in their explanation but the data do not fully support their explanation. Or students uncritically use information from authorities as evidence.</td>
<td>Students do not include any evidence in their explanation.</td>
</tr>
</tbody>
</table>
### Table 3

*The Statistical Results of Students’ Pre- and Post-tests (n=58)*

<table>
<thead>
<tr>
<th>Inquiry skills</th>
<th>Pre-test</th>
<th>Post-test</th>
<th>t-value</th>
<th>Sig.</th>
<th>Effect size</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td></td>
</tr>
<tr>
<td>Identifying causal relationships</td>
<td>1.59</td>
<td>0.50</td>
<td>2.19</td>
<td>0.45</td>
<td>4.82 &lt;0.001**</td>
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<tr>
<td>Describing the reasoning process</td>
<td>0.554</td>
<td>0.39</td>
<td>1.32</td>
<td>0.50</td>
<td>6.90 &lt;0.001**</td>
</tr>
<tr>
<td>Using data as evidence</td>
<td>3.06</td>
<td>0.50</td>
<td>3.96</td>
<td>0.50</td>
<td>4.18 &lt;0.001**</td>
</tr>
<tr>
<td>Evaluating explanations</td>
<td>0.43</td>
<td>0.50</td>
<td>0.50</td>
<td>0.51</td>
<td>0.85 0.399</td>
</tr>
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Table 4

*Change of the Teacher’s Role in the Series of Inquiry-based Learning Activities*

<table>
<thead>
<tr>
<th>Activity</th>
<th>Modeler</th>
<th>Guide</th>
<th>Diagnostician</th>
<th>Mentor</th>
<th>Facilitator</th>
<th>Collaborator</th>
<th>Total</th>
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<tr>
<td>1</td>
<td>Instances</td>
<td>6</td>
<td>25</td>
<td>13</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>13%</td>
<td>54%</td>
<td>28%</td>
<td>4%</td>
<td>0%</td>
<td>0%</td>
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<tr>
<td>2</td>
<td>Instances</td>
<td>20</td>
<td>50</td>
<td>16</td>
<td>10</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>20%</td>
<td>49%</td>
<td>16%</td>
<td>10%</td>
<td>4%</td>
<td>2%</td>
</tr>
<tr>
<td>6</td>
<td>Instances</td>
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<td>33</td>
<td>13</td>
<td>5</td>
<td>5</td>
<td>8</td>
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<tr>
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<td>18%</td>
<td>42%</td>
<td>17%</td>
<td>6%</td>
<td>6%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Guided inquiry    ←  →  Open inquiry
Figure Captions

Figure 1. Students’ performances in identifying causal relationships: (a) groups’ performances during classroom activities; (b) target students’ performances during interviews

Figure 2. Students’ performances in describing the reasoning process: (a) groups’ performances during classroom activities; (b) target students’ performances during interviews

Figure 3. Students’ performances in using data as evidence: (a) groups’ performances during classroom activities; (b) target students’ performances during interviews

Figure 4. Students’ performances in evaluating explanations: groups’ performances during classroom activities
Figure 1. Students’ performances in identifying causal relationships: (a) groups’ performances during classroom activities; (b) target students’ performances during interviews.
Figure 2. Students’ performances in describing the reasoning process: (a) groups’ performances during classroom activities; (b) target students’ performances during interviews
Figure 3. Students’ performances in using data as evidence: (a) groups’ performances during classroom activities; (b) target students’ performances during interviews
Figure 4. Students’ performances in evaluating explanations: groups’ performances during classroom activities