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Acquisition of Physics Content Knowledge and Scientific Inquiry Skills in a Robotics Summer Camp

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Abstract

Despite the growing popularity of robotics competitions such as FIRST LEGO League, robotics activities are typically not found in regular K–12 classrooms. We speculate that, among other reasons, limited adoption is due to the lack of empirical evidence demonstrating the effect of robotics activities on curricular goals. This paper presents a mixed methods study exploring the impact of a summer robotics camp on middle school students' physics content knowledge and scientific inquiry skills. It was found that the camp enhanced students' physics content knowledge but failed to improve their skills in conducting scientific inquiry. Qualitative data provided an explanation of the findings. (Keywords: educational robotics, scientific inquiry, problem-based learning, constructionism.)

INTRODUCTION

Recent years have witnessed an increasing interest in the educational use of robotics. International competitions such as RoboCup (The RoboCup Federation, 2006), FIRST LEGO League (2006), and RoboFesta (2006) have attracted children and young adults around the world to participate in various challenges. Many universities and schools have been offering robotics summer camps and enrichment programs to K–12 students. The commercial market of educational robotics is also growing. Recent research by Japan Robotics Association, United Nations Economic Commission, and the International Federation of Robotics (cited in Kara, 2005) indicates that the market growth for personal robots, including those used for entertainment and educational purposes, has been tremendous. This trend may continue in the next several decades.

Despite their growing popularity, robotics activities are usually not found in regular K–12 classrooms. One of the reasons might be that there is limited empirical evidence to prove the impact of robotics activities on curricular goals. Most of the literature on robotics use in education is anecdotal and descriptive in nature (e.g., Ford, Dack, & Prejean, 2006; Lau, Tan, Erwin, & Petrovic, 1999). A few exploratory studies have revealed positive perceptions of the educational value of robotics activities among teachers and students (Petre & Price, 2004; Robinson, 2005). This is encouraging, but measurable evidence is needed to convince educators of the positive impact of robotics activities on curricular goals.

Educational theorists such as Papert (1993) believe that robotics activities have tremendous potential to improve classroom teaching. Educators have started to generate ideas and develop activities to incorporate robotics into the teaching of diverse subjects, including math, science, and engineering (Bratzel, 2005; Wang, 2004). However, without research evidence to support their direct impact on students' academic performance, robotics activities may continue to be kept out of regular classrooms. As an effort to fill the gap in the literature, this article reports on a study that examines the effect of a two-week robotics summer camp on middle school students' physics content knowledge and scientific inquiry skills. Findings from this study not only offer support for the educational use of robotics to achieve curricular goals, but also provide guidance on how to design and implement educational robotics programs.

REVIEW OF THE LITERATURE

In this section, we first present constructionism as the theoretical base for designing robotics activities for educational purposes. We then review the literature on science teaching and inquiry to support the use of robotics activities in teaching science content knowledge and scientific inquiry skills. Finally, we present existing studies on educational robotics to identify the gap in the literature.

Constructionism

Constructionism is a learning and instructional theory rooted in the philosophical tradition of constructivism, which emphasizes the active role of the learner in collaboratively constructing knowledge in a rich context (Duffy & Cunningham, 1996). Papert (1991) clarifies the relationship between constructionism and constructivism:

> Constructionism…shares constructivism's connotation of learning as "building knowledge structures" irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe. (p. 2)

Constructionism shares similarity with other constructivist theories such as situated cognition (Brown, Collins, & Duguid, 1989) and cognitive flexibility theory (Spiro, Coulson, Feltovich, & Anderson, 1988). However, constructionism is unique in that it emphasizes "learning by making" as the key aspect of the learning activity. The artifacts to be created are "objects to think with" (Papert, 1993, p. 11). They provide tangible means for learners to evaluate and modify their understanding of science concepts while collaboratively designing, building, evaluating, and modifying artifacts meaningful to them and the community (Puntambekar & Kolodner, 2005). Learning occurs when learners are engaged in the process of creating artifacts and communicating about their design.

Constructionism has informed a series of studies in which technology is used to create a context that enables "learning by making" and "learning by design." Primary research projects in this area include those that use Logo programming in teaching mathematics (Papert, 1993), involve children in designing computer games (Kafai, 1996), engage members of a virtual community to create objects and space (Bruckman & Resnick, 1996), and facilitate learning with programmable bricks (Sargent, Resnick, Martin, & Silverman, 1996). Research on programmable bricks has led to the commercial product of LEGO Mindstorms robots (LEGO Group, 2006).

Science Teaching and Inquiry

Scientific inquiry is considered the centerpiece of science teaching. This belief is reflected in the National Science Education Standards (NSES), which position scientific inquiry as a core standard and stipulate that appropriate subject matter knowledge be incorporated in inquiry-based teaching (National Research Council, 1996). NSES defines scientific inquiry as

> … the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world. (National Research Council, 1996, p. 23)

Inquiry skills include the abilities to conduct and understand scientific inquiry, including "asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments" (National Research Council, 1996, p. 105).

Robotics activities are ideal for teaching scientific inquiry skills. In inquiry-based learning, students need a rich context to investigate questions and develop scientific argumentation skills (Baumgartner & Reiser, 1998; Kolodner et al., 2003). This context is usually not available in the traditional classroom. Robotics activities may be a promising alternative. They may provide a rich context needed for students to identify and investigate problems, generate hypotheses, gather and analyze data, and to determine findings and interpret results. In addition, developing robots may provide an opportunity for learners to acquire science content knowledge since mathematics and physics are the foundation for engineering and programming, which are required in robotics development.

Research on Robotics in K–12 Education

Limited research has been conducted as to the impact of educational robotics activities on K–12 students' learning. Much of the literature on educational robotics focuses on describing the activities in robotics educational programs with some discussion of their effectiveness based on the anecdotal evidence (e.g., Ford, Dack, & Prejean, 2006; Lau, Tan, Erwin, & Petrovic, 1999). Only a few studies have employed qualitative or quantitative methods to explore the impact of robotics activities (Barker & Ansorge, 2007; Nourbakhsh et al., 2005; Petre & Price, 2004; Robinson, 2005; Sklar, Johnson, & Lund, 2000).

Both anecdotal and research literature indicates that robotics activities have educational values, but most of the research depends on observation and interview data without any quantitative measures of the direct impact of the activities on students' learning. For example, Robinson (2005) interviewed three science teachers who used Robolab, a Mindstorms robotics program, to teach 8th grade physics. The teachers perceived that robotics activities may promote inquiry, increase students' interest in physics, and provide opportunities for expanding English vocabulary for English as Second Language (ESL) students. Sklar, Johnson, and Lund (2000) interviewed teachers at RoboCup Junior 2000, an international event, about their perceptions of the educational value of the challenges. Most of them believed in the effectiveness of RoboCup in enhancing academic skills and personal development.

Other researchers approached their studies a little differently. Instead of interviewing teachers, they focused on the learners' perceptions. Petre and Price (2004) conducted interviews and observations of children attending RoboCup Junior (ages 6 to 18) and RoboFesta (ages 12 to 14) competitions. Children reported that they learned programming, problem solving, teamwork, hardware, and electronics while building and programming robots. Nourbakhsh and colleagues (2005) gathered comprehensive self-report data from high school students in a full-time, seven-week, eight-hour-per-day course on robotics. The primary data source was the weekly survey that students filled out anonymously. The initial survey that was administered on the first day of the class gathered data on students' technological background, their expectations for learning from the class, and their plans for college and beyond. In the following weeks, students filled out a written survey every Monday to rate the performance of their team, describe the effectiveness of specific course activities, and discuss the problems they encountered and the discoveries they made. In the final survey that was completed during the last week of the class, students reflected on what they have learned. Analysis of the surveys indicated that students found the class interesting and the activities effective. At the beginning of the class, most of them expected to learn about mechanics and programming related to robotics and only a small percentage of participants expected to achieve learning goals related to teamwork, problem solving, and self identification with science and technology (interest in technology, confidence to work with technology, and aspiration in pursuing education and careers in science and technology). Interestingly, at the end of the seven-week class, the majority of the students reported learning not only about mechanics and programming, but also about teamwork, problem solving, and self identification with science and technology.

We found only two studies that went beyond gathering self-report and observation data and used quantitative measures to evaluate the impact of robotics on student learning. One (Barker & Ansorge, 2007) aimed to determine the effects of an after school robotics science intervention on students' (ages nine to eleven) achievement in science, engineering, and technology as measured by a 24-item multiple-choice instrument. It was found that students in the robotics intervention improved significantly from the pretest to the posttest, whereas students in the control group did not improve significantly. In addition, the multiple-choice instrument was found to be valid and reliable in this study. Another study (Wagner, 1998) intended to identify whether the use of robotics in science curriculum has greater effect on children's (ages eight to twelve) problem solving skills and performance in science achievement tests than the use of battery powered (non-robotic) manipulatives or no manipulatives in the science curriculum. It was found that compared to the use of manipulatives, the robotics intervention did not significantly improve science achievement or general problem solving, but did improve programming problem solving. In addition, both robotics and battery-powered manipulatives were superior to the traditional instruction in improving science achievement. These studies were encouraging; they provided some empirical support for the use of robotics in science education. However, none of the studies explicitly measured scientific inquiry skills as an outcome of the intervention. This study attempts to close this gap through an effort to assess students' acquisition of scientific inquiry skills and science content knowledge.

RESEARCH PURPOSES AND QUESTIONS

An educational research center in a southern research/teaching university offered a robotics summer camp to teach physical science to middle school students. The camp ran for two and a half hours each day for a period of two weeks in the summer of 2006.

The purposes of the study were to evaluate the impact of a robotics summer camp on students' physics content knowledge and scientific inquiry skills and to explore various factors that might have contributed to the impact of the program. Findings from the study may not only provide empirical support for stakeholders to adopt educational robotics programs but also inform the design and implementation of these programs. The following research questions guided the study:

1. Do student participants exit the summer robotics program with increased content knowledge?
2. Do student participants exit the summer robotics program with better scientific inquiry skills?

METHODS

Mixed methods guided data collection and analysis for this study. As a complement to traditional qualitative and quantitative research, mixed methods research bridges the schism between the two. It is considered as the third research paradigm in educational research, with the first two being quantitative and qualitative methods (Johnson & Onwuegbuzie, 2004; Onwuegbuzie & Leech, 2004). Mixed methods were appropriate for this study, which aimed not only to examine whether the summer camp led to increased physics content knowledge and better scientific inquiry skills, but also to explore various factors that might have contributed to the impact of the program. The dual purposes of the study to measure and to understand the effect of the summer camp called for mixed methods design in which both quantitative and qualitative data were gathered to confirm, cross-validate, and corroborate the impact of robotics activities on students' physics content knowledge and scientific inquiry skills. Quantitative data were gathered to answer quantitative research questions; qualitative data helped supplement and explain the quantitative findings.

The Context and Participants

The two-week robotics camp consisted of a mix of whole group and small group activities with hands-on work and discussions. Students worked in small groups to complete several challenges such as the Mars Rover Challenge, Tug-of-war Challenge, and Creature Bot Challenge. They used LEGO Mindstorms robotics kits and Robolab programming environment to complete the challenges. At the end of each day, whole group debriefing provided an opportunity for groups to share ideas and show work in progress. To support students to complete the challenges, we provided tutorials on robotics programming, light sensors, and gears, and facilitated activities such as analyzing sample robotic toys and devices.

Participants of the study included 21 middle-school students who enrolled in the robotics summer camp and their 10 facilitators. We sent an advertisement about the summer camp to various schools in the geographic area, and posted it in a local newspaper. The first 21 students who applied were admitted. Among the middle-school students, 18 were boys and three were girls. They were entering sixth to eighth grade in the fall semester of 2006. Many of the students had familiarity with LEGO bricks, but only a few had experience with the LEGO Mindstorms robotics kit. Students were assigned to a two or three member team guided by a facilitator. Among the 10 facilitators, seven were females and three were males, including five teacher candidates, three doctoral students in a cognitive science program, and two teacher educators with K–12 experience.

The Quantitative Methods

A single group of 21 summer camp participants was pretested, exposed to the summer camp program, and posttested to answer the research questions.

Measurement and Data Collection

For each student participant, a factual knowledge measure and a scientific inquiry measure were given both before and after the robotics intervention. The *physics content knowledge measure* included twelve multiple-choice items developed by our team to assess students' understanding of Newton's Laws of Motion. The *scientific inquiry measure* included five questions, based on an instrument developed by researchers at Harvard Graduate School of Education (Dede & Ketelhut, 2003). In the scientific inquiry measure, students were provided with problem scenarios and then asked to respond to questions. For example, students were given this scenario: "After many observations, you find that your bicycle tires look flatter on cold winter days than they do on hot summer days—even though you fill them with the same amount of air." Then, students answered three questions that required them to describe the problem in the scenario and to develop the hypothesis and the procedure that they would take to test the hypothesis. Another more complex scenario was also provided to students along with two questions that required them to generate a hypothesis and describe the procedure to test the hypothesis.

Data Analysis

In order to answer research question one, "Do student participants exit the summer robotics program with increased content knowledge?" a two tailed paired t-test was calculated to compare the pretest and posttest scores on the *physics content knowledge measure*. In order to answer research question two, "Do student participants exit the summer robotics program with better scientific inquiry skills?" a two tailed paired t-test was calculated to compare the pretest and posttest scores on the *scientific inquiry measure.*

The Qualitative Methods

An ethnographic study was carried out to explain the quantitative data. Insights gained from facilitator focus group interviews, individual facilitator interviews, facilitator reflections, and researcher field notes helped further examine and explain the impact of the summer camp on students' acquisition of physics content knowledge and scientific inquiry skills.

Data Sources

Facilitator focus group interviews. We conducted daily focus group interviews with facilitators at the end of each day. During the interviews, the group discussed various issues that arose in the camp and the strategies they used to address the issues. Field notes were taken to record the key ideas that emerged in the focus group interviews.

Facilitator interviews. We conducted individual interviews with four facilitators after the camp to understand their experience in the camp and their perceptions of students' learning. We emailed a request for an interview to all seven participants who turned in reflections and four of them were able to participate in the interviews; thus they were a convenience sample. The interviews were recorded and transcribed.

Facilitator reflections. Seven out of 10 of the facilitators submitted daily reflections of their camp experience. Researchers sent out a list of question prompts to guide the facilitator reflections. These questions focused on the effect of the robotics summer camp on students' learning and the effectiveness of the facilitation strategies.

Researcher field notes. A researcher kept daily field notes of observations and reflections of the camp experience. The researcher was introduced to the facilitators and students at the beginning of the summer camp. She was there every morning during the entire two weeks. At the beginning and end of each day, she helped the facilitators set up the equipment and clean up the classroom. During the camp activities, she had no responsibilities in the classroom; she focused on data collection.

Data Analysis

We imported interview transcripts, field notes, and facilitator reflections into NVivo 7, a software package that helps manage and analyze qualitative data. Miles and Huberman's (1994) procedures guided data analysis. First, in the data reduction step, we coded the transcripts, reflections, and field notes into conceptual chunks and grouped them into categories. Next, in the data display step, we ran queries to make sense of the relationship among the categories. Finally, we wrote up conclusions and verified them. Please note that pseudonyms are used to refer to the facilitators in this paper.

FINDINGS

Physics Content Knowledge

Statistical analysis indicates a significant difference on the *physics content knowledge measure* from pretest to posttest $t(20) = -3.275$, $p = .004$ ($M_{pre} = 8.40$; $M_{post} = 9.75$). That is, the robotics summer camp had a statistically significant impact on students' gains in physics content knowledge.

In this robotics summer camp, various activities might have provided opportunities for students to experiment with physics concepts. For example, the downhill racer task allowed the students to determine the impact of various variables on the movement of vehicles. The variables included the weight, the angle of the ramp, diameters of the wheels, the friction between the wheel and the surface, and the location of the weight. In the robotic mouse activity, the students discussed how the flow of energy was changed with a "whisker" switch, a touch sensor that alters the direction of a robotic mouse.

Short lessons, tutorials, and debriefings embedded in the problem solving activities might have helped students make the connection between experience and scientific concepts. For example, Madison, the lead facilitator, introduced Newton's Three Laws of Motion to the whole class during the camp. In later debriefings when several students presented their design of a robot powered by balloons, they cited Newton's Laws to explain the driving force behind the movement of the balloons. In a mini problem solving activity, students created paper devices to stay aloft as long as possible. At the debriefing, students discussed concepts such as kinetics, gravity, velocity, and weight to explain their design. A tutorial on gears might have also contributed to students' learning of scientific concepts. In this activity, students moved through stations to explore various gears and read about their strengths and weaknesses. The tutorial encouraged several groups to use gears in the design of their robots.

Although short lessons and tutorials embedded in the robotics summer camp might have contributed to students' acquisition of physics content knowledge, facilitators reported that students generally showed less interest in lessons and tutorials as compared to robotics building and programming tasks. During debriefing, several facilitators mentioned that these activities might be more interesting to students if they were offered in a more just-in-time manner. For example, the robotic mouse activity was meant to help students understand how a touch sensor works, but some students were not interested. The lead facilitator, Madison, suggested that the activity would have been more meaningful if it were presented when the students had a need to use touch sensors on their robots. Similarly, although some groups added gears to their robots after going through the tutorial on gears, one facilitator commented that the tutorial might have been offered too late, because his team had already completed the design of the robot when they studied the tutorial. Several facilitators made similar comments on the robotic toy analysis activities. At the beginning of the summer camp, students moved through stations to analyze a variety of robotic toys. They were given a list of questions concerning the capabilities and features of the robots to guide their analysis. Although students were fascinated by these toys, they showed less interest in the analysis task. During facilitator debriefing, it was recommended that these toys should not only be presented at the beginning of the summer camp to stimulate interest, they should also be made available throughout the summer camp to encourage students to analyze the toys to generate solutions to their design challenge. With a specific purpose in mind, students might find the robotics toy analysis more relevant.

The impact of the robotics summer camp on students' physics content knowledge might go beyond what was reflected in the content knowledge assessment. It is hoped that the summer camp experience will impact students' future learning of physics or other science subjects. A facilitator, Brook, reflected on the significance of this learning experience:

> Watching these students today helped me to realize that any type of experience is valuable and that the goal isn't to create an immediate product. The students working today may not have understood or remembered the formulas or physics theories we discussed but they will create a memory of their experience. Later, when these students are in a physics or science class, they can match what is learned in the classroom to the experiences they have developed through this camp. (Brook, Daily Reflection, Day Eight)

Another interesting finding related to content acquisition was that a couple of students who would be considered as low performing students in regular classrooms also improved in the physics content knowledge assessment. Although they were not as engaged in the activities as other students, they might have acquired some physics concepts from peer observations, group discussions, debriefings, lessons and tutorials, as well as the customized activities tailored to meet their special needs. For example, the robotics activities seemed to be too challenging for a child diagnosed with attention deficit hyperactive disorder (ADHD). His facilitator, Nicole, pulled him aside and asked him to complete a very structured robotic building task by following step-by-step instructions on a manual. Nicole reflected on the child's progress in a positive tone:

> He still needed support to begin and occasionally in progress, but he was able to complete a couple of tasks on his own. I think this was great progress for him... Also note that he was FULLY engaged when watching what others were doing. He was OBSERVING. Something was happening. That is NOT a bad thing. (Nicole, Daily Reflection, Day Nine)

Inquiry Skills

No statistically significant difference was found when comparing pretest and posttest scores from the *scientific inquiry measure*: $t(20) = -1.870$, $p = .077$ ($M_{pre} = 3.50$; $M_{post} = 4.28$). This result initially appeared to conflict with the qualitative data. For example, throughout facilitators' reflective journals and interviews, their discussions of physics content knowledge were sporadic as compared to their numerous discussions on problem solving. Ironically, quantitative data demonstrated that students made significant progress in their physics content knowledge yet failed to demonstrate significant improvement in their performance on the assessment of scientific inquiry skills.

Further analysis of the qualitative data related to problem solving and scientific inquiry helped us make sense of the finding. Even though the scientific inquiry process was introduced in the camp, students predominantly used the trial and error method to solve problems. For example, Brook described how her students failed to go through the scientific inquiry process. Instead, they worked through an intuitive procedure by trying various ideas for the alert system and addressing problems as they arose. Joshua stated that his students either skipped some of the inquiry steps, or did not have a systematic plan for isolating and testing variables to find the solution.

Several factors might have contributed to students' failure to follow the scientific inquiry process. First, the excitement and novelty of building robots might have rendered the design challenges less appealing. Some students had difficulty focusing on any specific design goals or problems. Brook was frustrated that her students kept ignoring the design challenges and the scientific procedure. Instead, they built their robots without a clear sense of what they wanted to achieve. Justin suggested providing an opportunity for students to explore the LEGO robotics kit before requiring them to work on a design challenge. They might be ready to solve the problem "after the novelty of new materials and a new project were over."

Second, the difficulty of some challenges might not have encouraged explicit application of the scientific inquiry process. During the follow-up interview, Joshua described how some robotics activities might not be challenging enough to require explicit thinking on every step of the scientific inquiry process. He stated,

> He almost saw exactly what it needed to be, and all the steps in between he just didn't see as necessary. It is kind of hard to tell somebody to slow down, take it step by step, whenever he knows it is just a matter of intuition… (Joshua, Follow-up Interview)

Third, the development of the scientific inquiry skills might be a long-term process that requires much more than a two-week summer camp. For example, Justin reflected that acquisition of scientific inquiry method might be a gradual process; it might take students years to integrate scientific inquiry into their problem solving process. Madison had similar thoughts. She wondered whether students' inability to use the scientific process was influenced by their level of development.

Fourth, facilitators in the camp might not have had enough knowledge and skills related to the scientific inquiry process to facilitate its use. In teachers' reflective journals, only Madison specifically mentioned the term scientific inquiry process, and what the process entails. Does this indicate that the facilitators themselves might not have had a deep understanding of the scientific inquiry process? Their lack of knowledge and skills in the scientific inquiry process might have impacted their ability to encourage and model the use of the process in the design challenges.

The last possible explanation of the non-significant finding was that the scientific inquiry assessment may not be robust enough to discern a difference. The Harvard research group who created the scientific inquiry instrument used in this study recently questioned its validity (Ketelhut & Dede, 2006). In a new study, they added another measure in which students wrote an authentic report in the format of a letter to describe their hypothesis, experimental design, findings and recommendations for solving a city's health problems. Researchers found that students who scored low on the original survey-based measure wrote letters with similar quality as those written by students who scored high on the original measure. This finding indicates that the original measure was not sensitive enough to detect students' learning of scientific inquiry. More authentic assessment of scientific inquiry skills may be needed in the future.

How can the learning environment be structured to encourage students to follow the scientific inquiry process? Justin was wondering how educators could balance between giving students the freedom to explore but at the same time directing them toward the scientific process for solving problems. He wrote,

> I wonder about the issue, which seems to be coming up in most or all of the groups, of resistance to being methodical and to writing things down. I'm not sure to what extent it's beneficial to them for us to try to work against this. Maybe they're at a point where they're going to learn better by being more exploratory and less structured — or maybe they'd do better being reined in and directed more. Of course there's a balance, but I'm not sure where that balance should be. There's definitely a short-term cost in working against their natural inclination; I'm not sure about the longer term cost/benefit. (Justin, Daily Reflection, Day Four)

Quite a few facilitators described the dilemma of choosing either to let students follow their instinct to solve the problems or to interrupt students' thought process and ask them to clarify their hypothesis and data gathering procedure. When a child is deeply engaged in problem solving, it is difficult to stop them to ask for clarification.

CONCLUSIONS

This study found that the summer robotics camp enhanced middle-school students' physics content knowledge. This finding is consistent with the literature. In the previous studies, teachers' perception data (Robinson, 2005; Sklar, Johnson, & Lund, 2000), learners' self-report data (Nourbakhsh et al., 2005; Petre & Price, 2004), and direct measures of achievement (Barker & Ansorge, 2007; Wagner, 1998) showed that robotics programs increased learners' science content knowledge. This study provides more support for this finding. Moreover, this study explored the various summer camp components that might have contributed to students' acquisition of physics content knowledge. These components include activities that allowed students to experiment with various scientific concepts as well as lessons, tutorials, and debriefing sessions that helped students make connection between the activities and scientific concepts.

This study also found that the summer robotics camp failed to improve students' skills in conducting scientific inquiry. This finding seems to be at odds with results in the previous studies in which teachers and students perceived that robotics programs promoted inquiry and problem solving. However, we argue that this finding does not contradict the existing literature; rather, it adds to the body of knowledge related to the educational use of robotics. Although students and teachers in several previous studies (Nourbakhsh et al., 2005; Petre & Price, 2004; Robinson, 2005; Sklar, Johnson, & Lund, 2000) believed that students learned problem solving from robotics programs, only one of them (Robinson, 2005) explicitly stated that such programs may promote scientific inquiry. These studies focused on a set of problem solving skills that are unrelated to the scientific inquiry skills measured in our research. In the study that does refer to inquiry, teachers reportedly perceived that the robotics program may promote inquiry. This is an examination of a general belief, quite different from this study, which measures students' gains in scientific inquiry skills from one robotics summer camp. Although we agree that robotics programs may promote problem solving and scientific inquiry, we found that these are not easily achievable goals. At the end of the robotics summer camp, students' gain in scientific inquiry skills was not evident in the measure that we used. It may require more careful design and implementation of the robotics program as well as better quantitative measures to document any significant gains in students' scientific inquiry skills.

IMPLICATIONS AND FUTURE RESEARCH

This study was intended to not only provide empirical evidence for the educational use of robotics, but also to inform the design and implementation of robotics programs. The findings of the study suggest the following implications or principles for developing and implementing robotics programs; they may also serve as potential topics for future research.

Principle 1: Just-in-time resources such as lessons, tutorials, and examples should be embedded in robotics programs to support scientific inquiry and acquisition of content knowledge. In this study, the resources we offered enabled students to acquire content knowledge. They provided the concepts and principles that students needed to build and program the robots. However, the resources would have been more relevant and interesting if they were presented in a just-in-time manner. For example, the tutorial on gears might have been more relevant if available earlier in the program. Robotic toy examples would have been more beneficial if they had been provided to serve as sample problem solutions throughout the program. The finding of the study is consistent with the literature. Many researchers emphasize the importance of providing resources such as case examples, information resources, and various scaffolding tools to support student-centered learning (e.g., Hannafin, Land, & Oliver, 1999; Jonassen, 1999; Kolodner et al., 2003). Future studies are needed to develop and research various types of resources that are important in robotics programs.

Principle 2: Students should be encouraged to explain their design by citing related scientific concepts and principles during debriefings. Researchers in the field of problem-based learning advocated the role of whole-class or small-group debriefings in providing students with an opportunity to synthesize and reflect on their learning (Barrows & Tamblyn, 1980; Nelson, 1999). In our study, we found it important for facilitators to explicitly ask students to use scientific concepts to explain the design of their robots and the strategies that worked or did not work for them. Explicit discussions of the scientific concepts during whole-group debriefing might have contributed to students' gains in physics content knowledge, even for students who were not completely engaged in the design challenges.

Principle 3: A robotics program should provide opportunities for students to explore the learning environment but at the same time encourage them to follow the process of scientific inquiry to complete design challenges. In this study, we found that some students needed unstructured time to explore LEGO robotics pieces and to play with various robot designs. Future research may be needed to examine how to maintain the balance between free play and problem solving structured by the scientific inquiry process.

Principle 4: Students who have different levels of expertise with content knowledge and problem solving skills may need different activities in robotics programs. In our study, we found that structured robot building tasks worked well for a low performing student who had limited content knowledge and problem solving skills. Future studies may be needed to identify a variety of activities that may benefit students with different levels of ability.

Principle 5: Long-term programs are needed to help students develop scientific inquiry skills over time. Students did not make significant progress in their scientific inquiry skills in this two-week program. We believe that part of the reasons might be that the intervention was not long enough. It might take years for students to acquire the skills. Longitudinal studies may be needed to investigate how learners develop scientific inquiry skills over time and what support they need to develop the skills.

Principle 6: A robotics program should prepare facilitators with knowledge and skills to facilitate scientific inquiry. In this study, we found that facilitators seldom mentioned scientific inquiry in their daily journal; we believe that their lack of scientific inquiry skills might have affected students' learning. Future studies may be needed to research and develop effective strategies to train facilitators on scientific inquiry skills.

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