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The Potential of a First LEGO League Robotics Program in Teaching 21st Century Skills: An Exploratory Study

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Abstract: *Business and political leaders in the US call for schools to teach 21st century skills. In the meantime, researchers call for more research to develop curriculum that teach 21st century skills. In this study, the authors examine the experience of a First LEGO League (FLL) robotics team to explore the potential of FLL for teaching 21st century skills. We found that the program provided opportunities for learning many 21st century skills such as systems thinking, decision making, problem solving, teamwork, conflict resolution, flexibility, perseverance, and self-management. We also found that instructional strategies such as modeling, coaching, scaffolding, examples and case studies were important in providing successful experience to children. For children to retain and transfer these 21st century skills, articulation and reflection are critical.*

Keywords: robotics, 21st century skills, engineering design, non-routine problem solving, project-based learning

1. Motivation for the Study

Business and political leaders in the United States (US) call for schools to teach 21st century skills because of the decline of jobs that involve routine tasks and the growth of jobs that require complex communication and non-routine problem-solving competencies (Partnership for 21st Century Skills, 2013). In a National Research Council (2012) report, "21st century competencies" refer to a blend of knowledge and skills, including "content knowledge in a domain and knowledge of how, why, and when to apply this knowledge to answer questions and solve problems." (p. 6). The 21st century competencies are knowledge that can be transferred to other situations.

In the meantime, there is an increased interest in teaching engineering design problem solving in American K-12 schools. The Next Generation Science Standards (NGSS) (Achieve, 2013) raise engineering design to the same level as scientific inquiry. Both engineering design and scientific inquiry will be taught in all grades from kindergarten to 12th grade. There is significant overlap between the new science standards and 21st century skills, especially in the cognitive domains. For example, 21st century skills such as critical thinking, nonroutine problem solving, constructing and evaluating evidence-based arguments, systems thinking, and complex communication are strongly supported by NGSS (Achieve, 2013).

Researchers call for more research and development on educational programs and curriculum that teach 21st century skills and engineer design problem solving (National Research Council, 2012). The First LEGO League (FLL) (U.S. First, 2013a) is a worldwide robotics program for children 9 to 16 year old (9 to 14 in the US). It challenges participants to design, build, and program a robot to complete a robotics challenge. A survey of 188 FLL teams (Melchior, Cutter, & Cohen, 2004) shows that students, parents, and coaches believe that participants acquired life and workplace-related skills such as teamwork, time and project management, problem solving, and communications skills. It seems that FLL robotics would be a good candidate for teaching 21st century skills and engineering design. However, from anecdotal evidence such as the authors' personal experience in coaching FLL and discussions in FLL online forum, we know that coaches vary in their ability and experience that reflect upon participants' experience in FLL also. In spite of rapid growth of robotics programs such as FLL, there is lack of research-based knowledge on the best practice of coaching FLL and other robotics programs. In this article, the authors examine the experience of a FLL robotics team to explore the potential of FLL for teaching 21st century skills and engineering design. We will identify the support and guidance provided or should be provided for the children to acquire the skills. The findings may inform the design and coaching of similar programs so that they can better meet the challenge of teaching 21st century skills and engineering design.

2. Literature Review

2.1. 21st Century Skills and Engineering Design

In the National Research Council (2012) report, 21st century competencies are categorized into the following three domains: cognitive, interpersonal, and intrapersonal. Cognitive competencies refer to cognitive processes and strategies, knowledge, and creativity such as critical thinking, problem solving, decision making, system thinking, information literacy, oral and written communication, and innovation. Interpersonal competencies include teamwork and collaboration in addition to leadership. Intrapersonal competencies include intellectual openness, work ethics/conscientiousness, and positive core self-evaluation. A person with positive core self-evaluation thinks positively of oneself and has confidence in one's abilities.

Researchers synthesized the literature and identified some instructional design principles for teaching 21st century competencies in the cognitive competencies (National Research Council, 2012). The principles include the following: using multiple and varied representations of concepts and tasks, encouraging elaboration, questioning, and self-explanation, engaging learners in challenging tasks with supportive guidance and feedback, teaching with examples and cases, priming student motivation, and using formative assessment. Because there is limited research on how to teach intrapersonal and interpersonal competencies, researchers believe that these instructional design principles may work for these other two categories of competencies.

Engineering design is a new and separate component from scientific inquiry in the Next Generation Science Standards (Achieve, 2013). It describes an iterative design process. The following three core components of engineering design provide guidance to designers, but they are not steps in a "lock-step" process:

1. Defining and delimiting engineering problems involves stating the problem to

be solved as clearly as possible in terms of criteria for success, and constraints or limits.

2. Designing solutions to engineering problems begins with generating a number of different possible solutions, and then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.

3. Optimizing the design solution involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important (Achieve, 2013, p. 2).

2.2. First LEGO League (FLL) and Related Research

Like many other robotics competitions such as BEST and Vex, First LEGO League (FLL) (U.S. First, 2013a) is designed to introduce children to engineering, programming, and employment and life skills through building and programming robots. In FLL, participants work in teams to compete on a 4' x 8' playing field where their LEGO-based robot must autonomously complete as many of the specified challenges as possible within a set time of two and a half minutes (see Figure 1).

Each year FLL releases a new thematic challenge that includes three parts that includes the research project, the robot game, and Core Values. In 2012, the challenge was called Senior Solutions (U.S. First, 2013b). The research project requires the FLL teams to identify the problems brought about by aging and develop a solution to solve the problem. The robot game challenges the teams complete missions such as delivering or retrieving objects, and turning or pushing levers. The Core Values distinguish FLL from other similar programs in that it emphasizes the values of teamwork and teach children how to work with each other and compete with other teams.

Figure 1. FLL 2012 Challenge "Senior Solutions" table setup.

Research on robotics education programs is limited. Most of the studies use self-report data to show that students and teachers believe that robotics activities improve children's interest in physics and improve their knowledge and skills in programming, problem solving, teamwork, time and project management, hardware, electronics, and communications skills (Nourbakhsh et al., 2005; Petre & Price, 2004; Robinson, 2005; Sklar, Johnson, & Lund, 2000). These studies also found that robotics activities improve students' self-identification with science, engineering, and technology. Only a few studies went beyond collecting self-report data and the results are mixed. For example, Barker and Ansorge (2007) reported positive results of robotics activities in improving achievement in science, engineering, and technology from the pre-test to the post-test. Whereas another study (Wagner, 1998) found in comparison to the use of manipulative, the robotics intervention did not significantly improve science achievement or general problem solving, but did improve programming problem solving. Williams, Ma, Prejean, Ford, & Lai (2007) found that a robotics summer camp enhanced students' physics content knowledge, but failed to improve their skills in conducting scientific inquiry.

A few studies have identified issues and strategies involved in designing robotics education programs. In a robotics program implemented in an elementary school (Rogers & Portsmore, 2004), researchers found it important to provide extensive technical support to teachers. Williams et al. (2007) provide the following recommendations to embed resources in the robotics activities such as short lessons, tutorials, and example solutions in order to support scientific inquiry and acquisition of content knowledge.

3. Research Methods

The purpose of this study was to explore children's experience in this program in order to (a) identify opportunities for children to learn 21st century skills and engineering design in the FLL context, and (b) to determine the guidance and support needed for them to acquire these skills. Qualitative inquiry methods were chosen to guide data gathering and analysis because of the exploratory nature of the research (Creswell, 2004).

The following research questions guided the study:

1. What opportunities do children have to learn 21st century skills and engineering design?

2. What guidance and support have been or should be provided to help children acquire 21st century skills and engineering design?

3.1. Participants

The participants included six children. The children were members of a FLL team. They are all girls. Their ages were 8 to 10 at the time of the study. Four of the children were from three different elementary schools and the other two were homeschooled. Four children were Caucasians and two were Asian. This was their first-year experience with FLL.

3.2. Data Sources

The data sources included coaches' field notes and focus group interviews with the children.

Coaches field notes. The two coaches, who were also researchers for this study, kept 23 daily field notes of observations and reflections of the FLL experience. An entry of the field notes typically describes the sequence of activities and events for a certain day, the reactions and feelings of the children and coaches, and anything interesting in that day's FLL experience.

Focus group interviews with children. A focus group interview was conducted by one of the researchers/coaches. The coach asked the children what they liked and disliked FLL, what they have learned, and what parents and coaches should do to improve the program. The focus group interview lasted about 30 minutes.

3.3. Data Analysis

The authors imported interview transcripts and the field notes into NVivo 7, a software package that helps manage and analyze qualitative data. Miles and Huberman's (1994) data analysis procedures guided data analysis. First, in the data reduction step, we coded the transcripts and field notes into conceptual chunks and grouped them into categories. To categorize the support provided by the coaches to the children, cognitive apprenticeship (Collins, Brown, & Holum, 1991), an instructional model that consisted of strategies such as modeling, coaching, scaffolding, articulation and reflection, was used. Next, in the data display step, we ran queries to make sense of the relationship among the categories. The authors also created tables to compare the codes/themes with 21st century skills and engineering design components. Finally, we wrote up conclusions and verified them. To enhance the trustworthiness and rigor of this study, the authors adopted techniques such as triangulation, peer debriefing, discrepant evidence or negative case analysis, thick descriptions, and member checking (Lincoln & Guba, 1985).

4. Summary of Data

The robotics program is very challenging, which provided many "teachable moments" for children to learn 21st century skills and engineering design. The authors have identified the challenges that children experienced in the program and the possible skills that they may learn. For each challenge, we also identified the support that has been and should be provided. We categorized the challenges that children have experienced into three domains: cognitive, interpersonal, and intrapersonal.

4.1. Challenges in the Cognitive Domain

Table 1 shows a list of challenges that children encountered in the cognitive domain. It also describes the corresponding 21st century skills that the challenges might provide opportunity to teach and the support has been or should be provided to the children.

4.1.1. Challenge 1. Starting with a problem. One of the biggest challenges that the children encountered was their lack of strategies and methodologies on how to approach unstructured problems. At the beginning of the program, when looking at the missions, children did not know where to start. The coaches and members from another team who had two-year FLL experience analyzed the missions from the perspectives of the points that can be earned, distance of the mission from the base, and the difficulty level, and then developed strategies on how to group the missions. The girls had little input at the meeting. Because the team had little experience, the coaches guided the girls to choose missions that are close to the base and relatively easy to complete.

This situation may provide an opportunity for children to learn how to analyze a problem and how to consider multiple factors to make decisions on what missions to complete. They might also learn how to strategize when devising a plan for solving design problems. Although modeling from the other experienced team and coaches were helpful, more discussions with the children about strategies might help the children with articulation and reflection, which might make the learning more explicit.

Table 1. Challenges in the cognitive domain

	Key 21st century skills	Support Provided	Other Support Needed
Challenge 1. Starting with a problem	Analysis, systems thinking, decision making	Modeling, scaffolding	Articulation and reflection
Challenge 2. Building robots and attachments	Creativity, problem solving	Examples, scaffolding	Articulation and Reflection
	Executive function	Coaching	Modeling, scaffolding, coaching, articulation, and reflection
Challenge 3. Programming	Problem solving, information technology literacy	Examples, modeling, coaching	Articulation and reflection
Challenge 4. Knowledge	Problem solving	Modeling and coaching	Coaching, articulation and reflection
Challenge 5. Inconsistency	Systems thinking	Experiments	Articulation and Reflection
Challenge 6. Chain reactions	Systems thinking	Modeling	Articulation and Reflection

4.1.2. Challenge 2: Building robots and attachments. The children had difficulty building the robots and the attachment. Examples and scaffolding did help them move on. The coaches provided images on various attachments such as bumpers, plows, delivery boxes, and discussed their designs and uses. These examples seemed to have helped some children create their own designs. For example, from an example design, Melissa was able to create a robot arm, which served as the main attachment for most of the missions for the team. Scaffolding helped children understand the key concepts in design. For example, Melissa used a LEGO piece that has a 130-degree angle to hold squared LEGO "quilts," but she was not successful. A coach suggested that Melissa look for a piece that had a 90-degree angle to hold the "quilts" because the "quilts" were square. This suggestion helped Melissa to successfully build the attachment.

Another challenge related to building was the children's lack of planning. Once Melissa finished creating the attachment to deliver the "quilts," a coach asked her how she would attach it to the robot. She said that she had not thought about that yet. In another example, failure to think ahead made children's design completely useless. For example, Nancy and Lisa borrowed an existing robot arm design from a book to hold some LEGO objects. When they were building the arms, they focused on building without thinking about how the arms could be attached to the robot and how they could hold the objects. The arms turned out to be too long and unbalanced. They had to give up this design after spending a lot of time building it. These experiences may provide opportunities for children to see the importance of planning.

In summary, the challenge to build and create robots and attachments provided the children with opportunities to solve design problems, be creative, and practice planning. Examples and scaffolding helped the children gain knowledge and expertise with design. Adequate support had been provided to guide the children with planning. Modeling and coaching might show children how to plan, and articulation and reflection might help them reflect on the effectiveness of planning.

4.1.3. Challenge 3. Programming to complete the missions. The participants experienced many challenges when programming to complete the missions. One type of challenge related to controlling the robot. For example, for one mission Nancy and Lisa programmed the robot to move forward, make a 90-degree turn, and then go forward to deliver some objects. The children found that once the robot made a 90-degree turn, it was no longer going straight. From videos of previous competitions, the children learned that having the robot move forward or backward to push the nearby wall of the playing field would help the robot straighten up. This strategy helped them solve the problem. Another type of challenge related to troubleshooting programming problems. Nicole was confused as to which programming blocks correspond to which robot behaviors. One of the coaches showed Nicole how to add sounds in the program. The sounds could alert her to notice which parts of the code have been run. The coach also showed Nicole how to add comments to the code to help her and others understand what she has programmed.

In summary, the challenge related to programming offered opportunities for children to solve problems by using strategies acquired from examples, modeling, and coaching from the coaches. Articulation and reflection could help children make the strategies their own.

4.1.4. Challenge 4. Using mathematics and physical science knowledge. Children were challenged to use mathematics and physical science knowledge in completing the challenges. For example, the children tended to depend on trial and error instead of calculation to estimate the rotations needed for a robot to move a certain distance. The coaches taught the children how to calculate the number of rotations that the robot wheels should move by dividing the distance the robot needed to travel with the circumference of the wheel. In another instance, Megan and Nicole could not use the robot to push a LEGO object to the base although they set the robot speed to the maximum of 100. Megan thought that if she stopped the robot when it got closer to the object and then program the motor to turn at the maximum power, it would reach higher speed before pushing the object. A coach let her try and they noticed that the object was actually pushed for less distance. The coach explained to Megan that it takes some distance for a person or a vehicle to speed up. Megan then understood why her solution did not work.

The activities provided opportunities for children to learn and apply math and science knowledge in completing the missions. In the examples, modeling and coaching were helpful for children to learn the new skills. However, to convince children to use calculation instead of trial and error, more coaching, articulation, and reflection are needed.

4.1.5. Challenge 5: Dealing with inconsistency. One of the issues with the robot was its inconsistency in performance. For example, for many missions the children found that the robot performed inconsistently when the robot was on different playing fields or when it was used on different days. This may provide opportunities to discuss various factors that may impact the robot's performance such as the mat set up, power level of the robot, the battery level, and the lighting of the playing table. When children were programming for a mission, they typically stopped once the missions worked one time. The coaches encouraged them to try the solution many times and on different playing fields to test its consistency. The children were able to appreciate the importance of testing a program many times because they saw the inconsistency during tests, but they were not always aware of the factors that were at play.

These experiences provided opportunities for children to learn that there are multiple variables that affected a robot's performance and they needed to identify these variables to optimize the solutions. Experiments, articulation, and reflection could be helpful for them to identify and discuss the variables.

4.1.6. Challenge 6. Dealing with chain reaction. Another challenge for the children was to experience the chain reaction of changes. One small change might cause a series of problems. When Nicole and Megan were refining one of the missions, they made a couple of small changes and the robot could no longer complete the mission. The children did not understand what happened. A coach demonstrated to the children that when the robot moves an inch more than the previous program, it no longer pushed the object by using its center point, which turned the robot a little so that it can no longer move straight for the next step. The children saw the causal relationships of the steps and were able to fix the problem. When the robot was programmed to complete two missions in one outing, the chain reaction tended to be more of an issue because there were more steps involved in one run of the robot.

These situations afforded children the opportunities to identify the causal relationships between various steps in a system and learn to troubleshoot when the system did not work. However, although the coaches helped the children solve the problem, children may not have gained a deep understanding and appreciation of the chain reactions. More explicit analysis and discussions with the children may be needed

Table 2. Challenges in the interpersonal domain

	21st century skills	Support Provided	Other Support Needed
Challenge 1: Sharing products with others	Trust, cooperation, teamwork	Articulation and Reflection	Articulation and Reflection
Challenge 2: Reaching agreement	Negotiation	Articulation and Reflection	Articulation and Reflection
Challenge 3: Sharing work	Trust, cooperation, teamwork, communication	None provided for this incident	Articulation and reflection
Challenge 4: Personality conflict	Conflict resolution	Articulation and Reflection	Articulation and reflection

to help the children articulate and reflect on the chain reaction and the factors.

4.2. Challenges in Interpersonal Domain

Teamwork is the aspect that children talked a lot about when asked what they have learned from the afterschool program. See Table 2 for an overview of the challenges in the interpersonal domain.

4.2.1. Challenge 1: Sharing creations with others. Children had many challenges related to teamwork. One of the challenges is that children tended to have ownership over what they have created and hesitated to share with others. For example, Melissa created an attachment for one of the missions. Nancy and Lisa wrote a program for this mission, so the coach asked Melissa to give the attachment to Nancy and Lisa to try out the mission. Melissa was very unhappy because she built the attachment so she wanted to write a program to try the mission. After a discussion about teamwork and how the team needs to share the tasks and the attachments that are built, Melissa gave the attachment to Nancy and Lisa reluctantly. As the team used the same attachment for multiple missions, Melissa said that she was proud and happy that other team members used her attachment for multiple missions.

From experiences like this, children may learn to trust their teammates and share creations with them. In this situation, although the discussions with Melissa was helpful to her, more discussions with the whole team might help the team better articulate and reflect on what it means to be a team.

4.2.2. Challenge 2: Reaching agreement. Sometimes children had difficulty reaching agreement. For example, after voting for several times, the children still could not agree on a name for the team. Nancy came up with the name "a new generation." The coaches asked her why she chose this name, but she could not provide any reasons. She said that she just liked it and did not want to change it to anything else. One of the coaches gave them a talk about developing names that express the meaning and the spirit of the team. After some brainstorming, the girls eventually came up with a more meaningful team name.

This experience provided a good lesson about reaching agreement. Children may learn that when they disagree with each other, they need to provide their reasons, be open-minded, and compromise when necessary. More explicit debriefing would help children better articulate and reflect on these values.

4.2.3. Challenge 3: Sharing work. Another challenge that the children experienced was the lack of ability to work on a task together. Children worked in pairs to complete tasks such as building or programming. Nicole and Megan were able to share responsibilities when working together. One of them would focus on programming and the other would take control of the robot to do the testing. They would discuss how many rotations the robot should move and how it would turn when one of them wrote the program on the computer. They would also switch roles once in a while. The other children were easily distracted if they did not have direct control of the task at hand, whether it is programming or building. In some practice sessions, when some children were absent, the rest of the children were happy because they each had a robot to work with.

These situations provided opportunities for children to learn how to cooperate and communicate with each other when sharing work. The coaches could have discussed strategies on how the children could share the workload when working together, how to brainstorm, and give feedback to each other.

4.2.4. Challenge 4: Personality conflict. Personality conflict is another challenge that the children had to face. Nancy has a strong personality. She liked to have control and it was difficult for her partners to work with her. At one time, she was paired with another girl who has the same personality as her. The two girls enjoyed each other because they were alike, but they also had many conflicts because of their similar personalities. One of the coaches talked to them about core values and how team members should be respectful of each other. However, when these two students worked together, they still tended to annoy each other.

This afterschool program challenged the children to learn to deal with personality conflicts. They needed to learn how to respect each other and how to compromise. Discussions with the individual children are helpful, but more activities are needed to help the children articulate and reflect on the learning of core values.

4.3. Challenges in the Intrapersonal Domains

The robotics practices and competitions posed intrapersonal challenges for children to display competencies such as flexibility, perseverance, and self-management. The following paragraphs describe these challenges and identified in Table 3.

Table 3. Challenges in the intrapersonal domain

	21st century skills	Support Provided	Other Support Needed
Challenge 1: Trying new task	Intellectual interest and curiosity, flexibility	Modeling and coaching	Articulation and reflection
Challenge 2: Working under pressure	Perseverance	Articulation and Reflection	Articulation and Reflection
Challenge 3: Be persistent	Perseverance, grit	Modeling and coaching	Articulation and reflection
Challenge 4: Open to ideas	Flexibility, adaptability, continuous learning	Modeling, articulation and reflection	Articulation and reflection
Challenge 5: Take initiative	Self-management, initiative	Little support	Modeling, coaching, articulation, and reflection

4.3.1. Challenge 1: Trying new task. Unstructured problem solving, building, and programming were out of the children's comfort zone. Once they felt more comfortable in one area, they hesitated to try tasks in other areas. For example, after Melissa built some attachments, she gained confidence in building. But, when she was asked to try a programming task, she was reluctant to try. The coach sat down with her and helped her with the task. The positive experience reduced some of her fear of programming. However, Melissa and other children still tended to attribute outcomes of their work to their innate ability instead of effort.

The robotics afterschool program provided opportunities for children to tackle problems and complete tasks that are outside of their comfort zone. Modeling and coaching were helpful in encouraging children to try new tasks and build confidence in areas in which they had limited experience before. More articulation and reflection could help children understand that regardless if they are not good at some tasks due to limited experience, if they try the tasks with enough help they can learn to do it well.

4.3.2. Challenge 2: Working under pressure. FLL competition requires the children to complete as many missions as possible within two and a half minutes. Within this short period of time, the children need to position the robot correctly and run the first program, change the attachments and position the robot correctly when it is back to base, switch to the correct program, and run the robot again. This may repeat several times depending on the number of missions that they can complete within the competition time. They need to remember all the programs that they will run, all the starting positions for each mission, and all the attachments they will need for each mission. At the competition, two children go to the table to compete. They need to work with each other to complete the missions, so it is important for each to have a role and work together with one another. This is very challenging for some children. In the first competition that the children participated, one of the pairs almost missed all the missions. Because it was the first competition for the day, there were a lot of people watching them and there was a lot of noise. They were very stressed during this time. They got better later in other competitions after they practiced the procedures more with their partners. During the interview at the end of the season, the children talked about the importance of letting go of the stress and concentrating on the tasks. They also talked about how they should not be distracted or annoyed by the other children who were stressed or who were practicing their routines with the robot.

The FLL program gave children opportunities to experience how to work under pressure. By practicing the competition routines and getting exposed to the stressful competitions, the children became stronger when they had to work under pressure. More discussions with children on this issue might help them better articulate and reflect on the strategies of working under pressure.

4.3.3. Challenge 3: Be persistent. FLL is very challenging for the children. Children lack the experience for building, and the robot is not always consistent in its performance. It can be very frustrating for the children. Nancy describes her frustration with one of the missions, “you are like OMG, how in the world do you do this? And then you like I just changed….it kept running into the flag, and then it took a lot of the time, there is something wrong with the wheel.” However, the excitement of problem solving also encouraged them to push through the difficulties with persistence. Lisa talks about the excitement of solving a problem. She said, “It is like…” Wait. I cannot figure this out. Wait. Here is the answer. Woo Hoo...” Guidance from the coaches seemed to have helped them to persist longer. For example, when Melissa was about to give up building the attachment for one of the missions, one of the coaches showed her two LEGO pieces that might be useful. She immediately had an idea of what to do and she persisted in completing the design of the attachment. In another instance, Nancy and Ann were very discouraged and negative toward each other when practicing for the regional competition. One of the coaches said that they might need to better position themselves so that they would not get into each other’s way. She also pointed out to them that they were delayed because they were not familiar with the attachments for the first three missions. After they changed their positions and once the coach refreshed their memory on how to add the attachments, their performance improved greatly and their attitude got much better. A little guidance and success helped them persist to continue to work on their task.

The robotics after-school program was very challenging, which provided many opportunities for children to learn to be persistent. Modeling and coaching were effective in giving children guidance so that they did not give up easily. More explicit discussions with the team might help the children articulate and reflect on the importance of persistence and strategies to become more persistent.

4.3.4. Challenge 4: Open to ideas. Unlike the typical problems that children solve in the school, non-routine design problems do not have one best answer. In addition, the design process is iterative. A solution that is optimal in one iteration of the project may no longer seem optimal in the next. In the end of the season interviews, children described how they decided not to include one of the missions in the qualifying competition, but then changed their mind later and included it in the regional competition. They decided not to include it in the qualifying competition because it took too much time to run the program and the mission required the change of attachments. In addition, the point value was not high enough to make the mission worthwhile to complete. However, after the qualifying competition, the children reprogrammed this mission so that when it was completed, the robot moved forward to complete another mission close to it. Completing two missions in one run allowed the team to earn more points in a short period of time. Therefore, for the regional competition, the team changed strategy and included this mission and the other one that could be completed in the same run. During the focus group interview, the children used this example to talk about how they needed to be open-minded and willing to make changes to their strategies. Another example children talked about was that during the final practice before the regional competition, one child wanted to change the attachments. The coach told her that it might be too late because the competition was right around the corner. The child quickly showed the coach how she could add something to an attachment so that this attachment could be used for another mission. With this change, the number of attachments that children had to switch was reduced, which made it less stressful for the children during the robot competition. The coach reflected on this experience and discussed it with the children about the importance of being open-minded. One of the children said that “No idea is a bad idea.” The children agreed that even when they might not think somebody’s idea is good, they would still allow it to be tried first.

The FLL experience exposed children to situations in which design decisions made earlier may be changed later. These situations might teach them to be open to ideas and changes. One of the coaches modeled how to reflect and articulate in these situations. More discussions throughout the program may better facilitate the articulation and reflection of this issue.

4.3.5. Challenge 5. Self direction. Because of their lack of knowledge and skills in robotics and their limited experience in solving unstructured problems, the children tended to lose focus or interest when they were not given a specific task or when they were stuck in solving problems. In the beginning phase of the project, children needed a lot of guidance. Every time when the coaches were not readily available to help the children, they tended to quickly lose focus or become discouraged.

The experiences challenged children to take the initiative and become more self-directed. The coaches might need to model how to break down tasks so that they are more manageable. When children need guidance, instead of giving them a task, brainstorming with the children to identify tasks might help them learn how to be more self-directed. Articulation and reflection on self-management might be also helpful.

5. Research Results

Question 1. What opportunities do children have to learn 21st century skills and engineering design?

Table 1 shows that the robotics afterschool program provided opportunities for children to learn skills in cognitive processes and strategies, knowledge, and creativity, which are the three clusters of 21st century skills in the cognitive domain. Children may learn the following skills related to the cluster of cognitive processes and strategies: analysis, systems thinking, decision making, executive function, and problem solving. They may learn to use math and physics knowledge, which is related to the cluster of knowledge in the 21st century skills. They may learn to design robots and attachments, which is related to the cluster of creativity. The afterschool program also provided opportunities to learn engineering design. Challenge 1 in Table 1 is related to the first component of engineering design: defining and delimiting engineering problems. The rest of the challenges involve the other two components of engineering design: designing solutions and optimizing the design solution.

The robotics afterschool program provides opportunities for children to learn skills in teamwork and collaboration, which is a cluster of 21st century skills in the interpersonal domain (see Table 2). Specifically, children may learn the following skills: trust, cooperation, teamwork, negotiation, communication, and conflict resolution. These skills are important in all phases of engineering design.

The robotics afterschool program provides opportunities for children to learn skills in intellectual openness, work ethics/conscientiousness, and positive core self-evaluation, which are the three clusters of 21st century skills in the interpersonal domain (see Table 3). Children may learn the following skills: intellectual interest and curiosity, flexibility, perseverance, adaptability, self-management, and initiative. These skills are important in all phases of engineering design.

Question 2. What guidance and support have been or should be provided to help children acquire 21st century skills and engineering design?

For challenges in the cognitive domain (see Table 1), the authors found that coaches provided the following types of support to children: modeling, coaching, scaffolding, and experiments. For challenges in the interpersonal domain (see Table 2), articulation and reflection were the main guidance provided. For challenges in the intrapersonal domain (see Table 3), the coaches used the following facilitation strategies: modeling, coaching, articulation, and reflection. In many of the situations, the support was effective, but more articulations and reflections were needed.

6. Discussions and Implications

The findings of this study provide suggestions for coaches of robotics programs and educators interested in teaching 21st century skills. The first suggestion is that programs like FLL should be supported and children should be encouraged to participate even if these children may not go into science and engineering fields. This study shows that the FLL afterschool program provides many teachable moments for learning 21st century skills such as problem solving, decision-making, systems thinking, creativity, intellectual openness, persistence, and teamwork. FLL is designed to attract children to science and engineering, but the skills that children can potentially learn from FLL are important for all professions and daily life. Because children do not typically obtain these skills from school, programs like FLL are good options.

The second suggestion is that for children to acquire 21st century skills, robotics programs like FLL requires thoughtful design with the use of sound instructional strategies. Although FLL involves solving unstructured and non-routine problems, the teaching itself does not need to be unstructured. In order for children to learn the 21st century skills from these programs, a lot of support is needed. There have been debates among FLL coaches on the amount of support that should be provided to children (U.S. First, 2013c). Some coaches believe in providing minimal support so that children can discover the knowledge and strategies on their own. Some other coaches believe that children need a lot of examples and guidance to be successful. This study shows that children who have limited experience in robotics and non-routine problem solving would quickly lose interest and focus if support is not readily available. The finding is consistent with an analysis of education research in the past half-century that shows minimally guided instructions fail to help children achieve expected learning outcomes (Kirschner, Sweller, & Clark, 2006). An National Research Council (2012) report on the 21st century skills also emphasize the importance of supportive guidance and feedback, providing examples and cases, and using formative assessment as effective strategies for teaching 21st century skills.

Another suggestion is to choose appropriate instructional strategies to guide children. In this study, modeling, coaching, scaffolding, examples, and experiments seemed to have helped the children succeed in completing the missions, get exposed to or use various cognitive processes and strategies, and resolve various issues related to teamwork, intellectual openness, and persistence. This may provide suggestions for other coaches and educators interested in programs such as FLL. To help children succeed and gain confidence in FLL, the coaches may need to model, coach, or provide scaffolding such as hints and suggestions on how to use processes and strategies to solve problems, how to build and program, how to work with each other, and how to manage themselves and their emotions. They may also use examples and case studies of existing robot designs and programming to provide knowledge that the children may need to solve the problems.

However, for children to really retain and transfer the strategies and the 21st century skills that the afterschool program challenge them to learn, activities are needed for children to articulate and reflect on their learning. Articulation and reflection are critical components of cognitive apprenticeship (Collins, Brown, & Holum, 1991). In this afterschool program, the coaches seem to have used some cognitive apprenticeship strategies such as modeling, coaching, and scaffolding, but limited effort has been made to encourage articulation and reflection. Articulation refers to asking children to describe their knowledge, reasoning, and problem solving process. Reflection involves comparing one's problem solving with that of an expert (Collins, Brown, & Holum, 1991). Dewey (1933) and Schön (1983) argue that reflection occurs when one's routine approach fails, which encourages one to seek other solutions and restructure one's existing knowledge and problem solving process. Articulation and reflection are key steps for knowledge construction. In FLL programs, articulation and reflection of the design and problem solving process in a group environment may allow the children to make the tacit knowledge in problem solving become explicit so that they may use the knowledge in other context and share with their peers. Articulation and reflection on intrapersonal and interpersonal skills may encourage children to take more personal responsibilities for being persistent, be open to ideas, and for developing strategies to solve problems.

This study also provides implication for researchers. Although researchers generally consider articulation and reflection as beneficial instructional strategies, little formal research has been done to identify the effect of the strategies and best practices in specific educational contexts. Some studies of articulation and reflection have been conducted in the field of mathematics education (Brandenburg, 2002; Derrick 2005) but studies on articulation and reflection are difficult to find in learning environments that support unstructured or non-routine problem solving.

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