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Student Learning of STEM Concepts Using a Challenge-based Robotics Curriculum

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Student Learning of STEM Concepts Using a Challenge-based Robotics Curriculum (RTP, Strand 4)

Abstract

This paper examines pre- and post-student learning of science, programming, and engineering concepts using a tightly integrated robotics curriculum that challenges student teams to design, build, program, test, and redesign robots as part of a series of increasingly sophisticated design challenges. Data from over 750 middle school and high school youth from both in-school and out-of-school environments during the third year of implementation of a national scale-up project indicate that student post-test scores for the science and programming concept areas increased, but only to just above 50 percent of the total possible scores. Although a large majority of students found the curriculum highly enjoyable and felt they had learned, and teachers agreed, the degree of learning was not reflected in the assessment scores. Furthermore, although educators felt that the curriculum had helped their students learn engineering design through hands-on activities, student results did not show increases in learning of the Engineering Design Process. This suggests that more explicit instruction in science and programming content and the engineering design process may be required for deeper learning.

Introduction

Robotics is a timely, relevant and exciting field that incorporates a very broad spectrum of engineering, science, and information technology disciplines. Robotics curricula have been widely used in both formal classroom instruction and out-of-school contexts and at many grade levels to engage students in learning of several fundamental physical science concepts, computer programming, and engineering design. Some also use robotics as an educational strategy to increase students' excitement and motivation for pursuing STEM careers. With increased national attention to and advances in STEM learning research, the National Research Council's Framework for K-12 Science Education[1] and the Next Generation Science Standards[2] call upon curriculum developers and teachers to increase the prominence of engineering within the context of science education.

A growing body of research suggests that problem-based learning, engineering curricula, and "design-based science" are effective means of increasing students' conceptual understanding of science, their long-term retention of learning, and their abstraction or transfer of learning. Several studies conducted at the middle school level indicate that design-based activities result in significant gains in student understanding of science concepts[3, 4] and science skills.[5] Studies conducted in high school science classrooms using design-based curriculum provide evidence that these activities can result in significant gains in student understanding of science concepts.[6, 7] Several studies[8, 9, 10] have also documented the impact of educational robotics on student learning of STEM concepts in informal learning environments.

This paper examines pre- and post-student learning of science, programming, and engineering concepts using an underwater robotics curriculum known as *WaterBotics*® in which student teams design, build, program, test, and redesign increasingly complex robots as part of a series of mission-based design challenges. Building robots that can maneuver in multiple dimensions, grab objects and navigate obstacles underwater supports students' development of physical science and engineering core ideas, practices, and cross-cutting concepts as emphasized in the Next Generation Science Standards.[11] In addition, students learn and employ computer programming to control behavior of their robots.

WaterBotics fosters an active, discovery-based learning environment that integrates many scientific, engineering, and information technology principles, as well as such 21st Century skills as working in groups and communicating results. While these elements may be common to a number of robotics programs, there are unique features of *WaterBotics* that distinguish it from other robotics curricula:

(1) The curriculum's approach to embedding science lessons within each design mission is an intentional and distinctive feature of the curriculum design. The goal is to attain measurable student learning gains in common physical science concepts.
(2) The underwater environment of *WaterBotics* adds both high interest and additional engagement with physical science concepts such as buoyancy and stability. Designing, building and controlling a robot to function underwater presents a level of complexity that is not found in many land-based robotics program.
(3) The curriculum makes specific links to the interdependence of science ideas and the constraints imposed on design. For example, students make connections between optimizing the force and motion relationships in the gearing choices in robot design.
(4) The curriculum is mission-driven with "achievements" that teams can earn, rather than competition-driven, making it attractive to youth who may not yet have established STEM identities, interest and self-confidence. Each of the design tasks is framed by a personally interesting or contemporary social purpose, and groups are encouraged to periodically share their prototypes and learn from successful and failed designs.
(5) Use of LEGO® components makes rapid prototyping easy, while use of a small inflatable kiddie pool is feasible in typical classroom and out-of-school time settings.

Despite its differences from other robotics curricula, there are implications for K-12 engineering curriculum design that may possibly be learned from the *WaterBotics* experience and applied to other curriculum development efforts in order to strengthen student learning and career interest and inform the STEM research community.

Background

This study was conducted as part of a National Science Foundation Innovative Technology Experiences for Students and Teachers (ITEST) scale-up project that built on a previous research effort to develop and pilot the underwater robotics curriculum, *WaterBotics*. The scale-up effort involved expanding the program from one environment (formal classroom settings) to an additional environment (informal, out-of-school settings primarily targeting girls) and spreading the program to five new geographic regions. The overarching goal of the program is to provide middle and high school students with hands-on experiences in science, engineering design, and computer programming that will lead to greater understanding of STEM concepts and increased awareness of and interest in engineering and STEM careers. *WaterBotics* was further refined, studied, and evaluated in this context as part of the national scale-up grant, Build IT Underwater Robotics Scale-Up for STEM Learning and Workforce Development (BISU) Project.

A previous study[12] examined the impact of the program on student interest/engagement and on content learning in science and engineering in both formal and informal environments during the second year of implementation. The study's original hypothesis was that the informal sites would have greater levels of interest and engagement while students in traditional classroom settings would score higher in learning. Results from the second year of implementation indicated that students from informal sites did better on STEM interest and engagement, as hypothesized, but also did better in content learning than students in formal classrooms. However, grade level and gender were confounding factors in any simple comparison of the two types of sites.

The BISU Project had its third year of implementation in 2012-2013, with the formal (in-school) implementations during the 2012-2013 academic year and the informal (summer camp) implementations during the summer of 2013. During this time, five hub sites in different U.S. geographic regions facilitated training of teachers/educators and implementations with youth. In addition, a hybrid training (one day face-to-face followed by weekly webinars) for classroom teachers was conducted by the lead organization. As part of the research study, we examined the student learning and enjoyment outcomes from over 750 middle and high school youth from both formal, classroom settings and informal, out-of-school environments during the third year of implementation of the national scale-up project. The study questions included:

- Are student outcomes similar regardless of the teaching environment (formal vs. informal)? If there are differences, what are they and what accounts for them?
- To what extent was the curriculum taught as designed (fidelity of implementation) and to what extent is greater fidelity associated with better student outcomes?

Learning assessments for the topics of gears, buoyancy, programming and the engineering design process were administered to students as well as surveys designed to measure student engagement that include enjoyment, interest, and learning. Student factors such as learning environment, gender, and grade level that affect student learning outcomes were also examined.

In the following pages, the two environments are referred to as formal and informal meaning school-based classroom settings and out-of-school settings, respectively. The terms "teachers" and “students” are used for the formal environment and “educators” and “campers” are used for the informal environment.

Instructional Design Principles

The underwater environment presents novel challenges that can facilitate unique learning experiences for students engaged in robotics programs. In *WaterBotics*, teams of middle and high school students engage in problem-based learning as they collaborate to design, build, test, and redesign underwater robots made of LEGO® components and other materials. The robots are developed through an iterative engineering design process. As described more fully in other publications,[13, 14] student teams complete a series of design challenges or “missions” that increase in complexity and require more sophisticated solutions. Ultimately, students produce a fully functional underwater robot capable of maneuvering in a three foot deep pool. Students also learn computer programming as they design and program custom controllers for their robots.

The *WaterBotics* instructional materials are based on three guiding principles:

(1) *Engineering design is an essential component of youth educational development for success in the 21st century and provides advantages for science learning.* The National Research Council’s Science Framework[15] makes a compelling case that developing the capacities of youth to understand the designed world, the engineering design process, and the practices of engineers are essential features of science literacy that are critical contributors to students’ ability to successfully navigate life, become informed citizens and participate in the 21st century workforce.[16,17,18]

Studies on the impact of design-based activities on student learning of science content have demonstrated a decrease in the achievement gap between some demographic groups and significant gains in student understanding of science concepts.[19, 20, 21, 22] One middle school study showed that students can develop more complex understandings of energy transfer and transformation during [engineering] design than they can produce during non-design-based transfer activities.[23] Mehalik, Doppelt and Schunn found that infusing “design-based” learning activities into a middle school unit on electronics led to superior performance in terms of knowledge gain, engagement, and retention when compared with a guided inquiry approach.[24] In addition, Bamberger and Cahill argue that “object-based learning” is essential to engineering design and that manipulation and exploration of objects enables the deconstruction of how things function and helps students identify relationships and patterns within a real-world paradigm.[25] While a variety of design-based approaches have been identified including Learning by Design,™ [26, 27] Informed Design,[28] Design-Based Science,[29] and using design challenges to inspire and engage students,[30, 31] Apedo and Schunn[32] point to the “challenge for curriculum designers and teachers of design-based science learning curricula […] to scaffold the scientific inquiry process for learners in a way that seamlessly integrates design and science, maintaining the integrity of the design process” (p. 17).

(2) *Robotics learning represents a powerful learning opportunity for diverse youth*. There has been tremendous growth in educational robotics programs in K-12 and informal education settings in recent years, illustrated, in part, by the participation and publicity surrounding programs like U.S. FIRST Robotics and FIRST LEGO® League. Robotics offers an exciting and engaging context for students to learn science and engineering concepts and skills,[33, 34, 35, 36, 37, 38, 39] as well as an educational strategy to increase students' excitement and motivation for STEM areas.[40, 41, 42, 43, 44, 45] It also offers students an opportunity to practice 21st century skills such as teamwork, problem-solving, and creativity and innovation.[46, 47, 48, 49, 50] Robotics has been demonstrated as an effective vehicle to teach STEM concepts at many levels. The theoretical foundation for using robotics in education has been put forth by Jonassen,[51] who described cognitive tools or "mindtools" that can enhance the learning process. Others have posited that robotics enables students to creatively explore computer programming, mechanical design and construction, problem solving, and collaboration,[52, 53] as well as the ability to present open-ended problems that require integrative thinking.[54] Robotics enables students to own their learning as they make choices and explore many paths in order to solve design challenges. Through the use of robotics technology, students learn various facets of problem solving while simultaneously mastering numerous scientific and engineering concepts.

(3) *Science content learning is scaffolded through mastery of a series of increasingly complex design challenges. WaterBotics* is based upon the educational theory of social constructivism, which situates learning in dynamic, iterative, and authentic contexts.[55] In a constructivist-based environment, learners build upon their prior knowledge but draw upon the learning of others within the community as well as new knowledge gained through experiential practice (physical and mental manipulation of objects) and independent or guided research to integrate new knowledge and arrive at deeper understandings.[56,57,58,59,60] Students using *WaterBotics* test and re-design their robots through this collaborative, iterative process. The design missions are intentionally scaffolded to increase in complexity, building students' understanding and confidence. The curriculum is divided into a series of four missions that gradually lead to the production of a fully functional robot. In each mission, students plan, design, build, test and iteratively improve a robot that possesses a specific subset of the capabilities of the final robot, always building on their knowledge and experience gained from the prior missions.

Participants

In the third year of implementation, 87 teacher/educators (29 teachers and 58 educators) engaged in project-sponsored professional development. Educators who participated in pairs were expected to implement together, reducing the number of expected implementations to 63. Forty-one (18 teachers and 23 educators) actually started an implementation, along with 6 teachers and 4 educators trained in previous years and 2 trainers who led summer camps, bringing the total that started to 53. Thirty-eight of these (16 teachers and 22 educators) completed at least one full implementation (defined as having completed at least 3 of the 4 challenges in the curriculum) and 34 provided complete data sets.[i] Twenty-seven of the 38 teacher/educators who completed at least one implementation also completed a separate post-implementation survey.

A background survey hosted in the project's content management system (CMS) was administered to all students/campers before embarking on the curriculum activities. A total of 1,512 participants completed this survey. In addition, assessments were embedded in each challenge, including quiz-like questions and open-ended logs accessed through the CMS. The students/campers also completed a separate activity called a pile sort, designed to assess their understanding of the engineering field, and a survey at the end of the implementation.

The number of participants who completed the embedded assessments, the pile sort activity and the post-implementation survey was considerably less than the number who completed the background survey, either because their class or camp did not complete at least three challenges (the minimum necessary to have data on all the concepts being assessed) or because full sets of data were not provided for those who did complete the full implementation. Students in formal classrooms made up 55 percent of the 776 participants who completed all the surveys and assessments, while campers made up 45 percent. Table 1 shows the number who completed the different surveys and assessments.

Table 1: Participant Data Set

	Formal	Informal	Total
Number of students/campers completing background survey	969	539	1508
Number of students/campers completing 3 sets of embedded assessments	451	430	881
Number of students/campers completing pile-sort activity	413	344	757
Number of students/camper completing post-project survey	429	347	776

Instruments to Measure Student Outcomes

Table 2 includes a summary of the desired outcomes as developed at the start of the project, with the instruments used to measure each outcome. All of the student/camper assessments were embedded in the project CMS. This included the concept assessments, log questions that asked about teamwork, questions on the Engineering Design Process (on the pre- and post-surveys), and a pile sort that was designed to assess changes in understanding of what engineers do. The teacher/educator post-implementation survey was completed at the end of an implementation.

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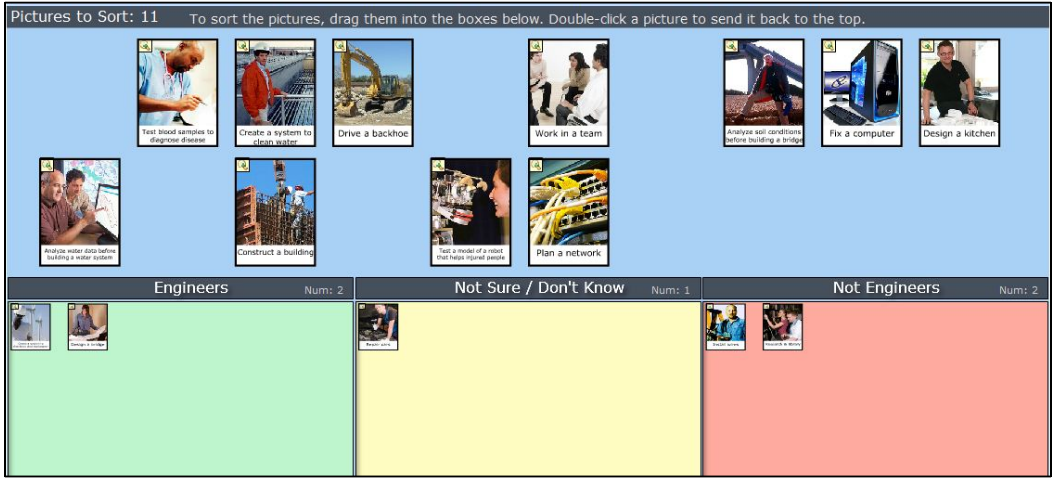
[i] This total included two teachers who participated in the hybrid course and conducted camps and whose data is therefore included in the informal analysis, and two trainers who also conducted summer camps.

Table 2: Outcomes and Instruments

	Outcomes	Instruments
Engagement/ Content	Students/campers enjoy the project	Student/camper post-survey; teacher/educator post implementation-survey
	Students learn from the project	Student/camper post-survey; teacher/educator post implementation-survey
	Students/campers show understanding of the concepts of gears/gear ratios and buoyancy/stability	Pre /post-assessments
	Students/campers show understanding of basic programming concepts	Pre /post-assessments
Engineers and Engineering	Students/campers show interest in, or engagement with, the science and engineering in the curriculum	Student/camper post-surveys
	Students/campers show increased interest in science and engineering as subjects to engage with in the future	Student/camper pre/post-surveys
	Students/campers show increased interest in science and engineering careers	Student/camper pre/post-surveys
	Students/campers show understanding of the iterative engineering design process	Student/camper pre/post-surveys
	Students/campers show an understanding of the importance of teamwork	Student/camper post-survey, logs
	Students/campers show better understanding of the kinds of work engineers do	Pile sort
	Students/campers show better understanding of the kinds of people engineers are (i.e., reduce stereotypes)	Pile sort

As shown in Figure 1, the pile sort is an interactive online activity that involves students accessing a virtual set of cards with pictures of people performing various activities, and then sorting them into three piles: Engineers, Not Engineers, and Not Sure/Don't Know. The goal of the pile-sort activity is to evaluate if the participants' understanding of who engineers are and what engineers do expands from beginning to end of the project.

Figure 1: Pile Sort Activity


Pictures to Sort: 11

To sort the pictures, drag them into the boxes below. Double-click a picture to send it back to the top.

Findings

This section discusses student outcomes, first in relation to contextual components, where applicable, and then the extent to which the structural and instructional components of fidelity may have had an impact on those outcomes.

Ratings for Engagement

The students/campers were asked to rate their experience with *WaterBotics* in terms of how much they had enjoyed it, using a grading scheme from A to F that included + and - (A+, A, A- etc.). In Years 1 and 2, a higher percentage of campers than students had given an A for enjoyment and this was also the case in Year 3, with 83 percent of campers giving the program an A compared to 72 percent of classroom students. A Mann-Whitney U test showed that the difference in ratings by the two groups was statistically significant ($p < .01$). As part of their post-implementation survey, the teacher/educators were also asked to rate the project in terms of how much they felt it had engaged their students, using a scale of 1 to 5, with 5 the highest. The ratings from teachers and educators were higher than the student ratings--with more informal educators (87 percent) giving a higher rating than classroom teachers (75 percent)—but since there were only have survey results from 27 of the 34 teacher/educators who implemented the curriculum with the above dataset, the results need to be read with caution.

Ratings for Learning

The student/campers were also asked to rate the curriculum in terms of how much they felt they had learned. More campers (79 percent) gave As (A+, A, A-) for learning than classroom students (70 percent). A Mann-Whitney U test showed that the difference in ratings by the two groups was statistically significant ($p < .01$). The teacher and educator ratings for learning were lower than their ratings for engagement. Sixty-seven percent of teachers gave the highest rating for how well the project helped their students learn how gears work and also for how well it helped their students learn the principles of buoyancy, compared to 67 percent and 60 percent of informal educators, respectively.

Concept Assessments

As noted previously, the curriculum was divided into four design challenges or “missions.” Each challenge covered the concepts related to gears/gear ratios, buoyancy, and/or programming. Three challenges were considered critical for completion while the fourth was strongly recommended. Each challenge had its own pre- and post-assessment, designed to evaluate student learning of the concepts used in that particular challenge. However, since completing three challenges was considered sufficient for learning the concepts, the data that follows is based on the students who completed both pre- and post- assessments for the first three challenges only.

Prior Knowledge

On the background survey, the participants were asked which of the concepts covered in *WaterBotics* they had studied in school. Just over 25 percent of students and campers said they had studied buoyancy and fewer had studied gears. More campers (43 percent) than students (25 percent) reported that they had been exposed to programming and robotics, which might have been expected since the campers were a self-selected group attending a robotics camp, but few in either group had taken pre-engineering or engineering courses. Although there was small difference in the pre-test scores between the two sets of participants, the difference was not statistically significant. In other words, both groups began with the same baseline knowledge of the assessed concepts. In general this was low, as shown in Table 3.

Table 3: Mean Pre-test Scores by Concept

	Formal (n=429)		Informal (n=347)	
	Pre-test mean	SD	Pre-test mean	SD
Gears (highest = 4)	1.53	1.30	1.64	1.29
Buoyancy (highest = 9)	4.48	1.87	4.59	1.83
Programming (highest = 14)	6.44	2.24	6.60	2.51

Change from Pre-test to Post-test

As shown in Table 4, campers also had slightly higher post-test scores for each concept, but the difference was not statistically significant. The increase was greatest for gears, while buoyancy improved the least—as had been the case in all the previous years. Further, as also was the case in previous years, the mean post-test scores were only just above 50 percent of the total possible scores in each content area. This suggests that although students felt they had learned, and teachers agreed, the learning was not reflected in the assessment scores.

Table 4: Change from Pre-test to Post-test Means by Concept

Formal (n=429)	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Gears (highest = 4)	1.53	2.09	37%	52%	4
Buoyancy (highest = 9)	4.48	4.69	5%	52%	9
Programming (highest = 14)	6.44	7.10	10%	51%	14

Informal (n=347)	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Gears (highest = 4)	1.64	2.17	33%	54%	4
Buoyancy (highest = 9)	4.59	4.92	7%	55%	9
Programming (highest = 14)	6.60	7.24	10%	52%	14

Engineering Teamwork

One goal of the curriculum was to help the students/campers understand the importance of teamwork in engineering. As was the case in previous years, the grades for teamwork were considerably lower than the grades for enjoyment or learning. Fifty-one percent of campers gave an A grade for teamwork compared to 45 percent of students. Although the grades were slightly higher in the informal environment, a Mann-Whitney U test showed that the difference was not statistically significant. The classroom teachers were also unsure how much the curriculum had helped their students work well in groups, but the informal educators were much more convinced that it had, with 79 percent of informal educators giving teamwork the highest rating compared to 50 percent of teachers.

Engineering Design Process (EDP)

In the *WaterBotics* curriculum, the engineering design process is introduced as a series of steps that engineers typically take as they devise solutions to problems. The steps include identifying the problem, researching, brainstorming, designing, building, testing, evaluating, and redesigning. An included handout about the EDP discusses its iterative nature. The question was scored based on how many of the steps the students included in their answers to a question that asked them to describe the EDP, from 0 to 8. A large majority of the participants wrote on the background survey that they did not know or were not sure what the EDP was, and the number who actually answered the question was small (only 13 percent). On the post-survey, most of the students and campers listed two or three of the eight steps, but there was a wide range among them. Although campers did slightly better than the students, listing an average of 2.63 EDP steps compared to 2.36 steps, the difference was not statistically significant. As had been the case in prior years, the terms the students and campers were most likely to use were “design,” “test,” and “redesign,” but this year “build” topped the list for both groups, while the campers were more likely to use “test” and the classroom students were more likely to use “redesign.”

More informal educators (86 percent) were sure that the curriculum had helped their students learn the EDP than teachers (65 percent). However, it is clear from the student/camper results that the learning was based on practice and not formalized. Without that formalization, the participants were not able to demonstrate how much they had learned.

Understanding of Who Engineers Are

The goal of the computer-based pile sort activity was to evaluate the participants’ understanding of who engineers are and what engineers do in order to see if their conceptualizations had expanded from the beginning to the end of the project. There were 16 cards, 9 with pictures of engineers at work and 7 with pictures of other types of workers, each with a caption that described what that particular person did (for example, “Create a system to clean water”). The participants were directed to sort the cards into three piles: engineers, not engineers, and not sure. For the analysis, one point was awarded for each card sorted into the correct pile.

As shown in Table 5, the baseline scores for the campers were slightly higher than the baseline scores for the students but the difference was not statistically significant. A total of 413 students and 344 campers completed the post-implementation pile-sort activity. The following comparison is based on the paired results. As was the case in previous years, the participants had the most difficulty with the non-engineer cards and their difficulties increased on the post-test. We hypothesize that this is because they began to see engineers everywhere.

Table 5: Change from Pre-test to Post-test Means for Pile Sort

Formal (n= 413)	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Engineer cards	6.13	6.77	10%	75%	9
Non-engineer cards	2.54	2.27	-11%	32%	7

Informal (n= 344)	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Engineer cards	6.17	6.94	12%	77%	9
Non-engineer cards	2.23	1.71	-23%	24%	7

On the pre-test in previous years, almost all the participants (>90 percent) were able to identify the three cards that showed electrical, civil, and environmental engineers, while the card least likely to be identified correctly was captioned “Research in library.” This was the case again this year. The campers showed the greatest increase for the “Research in library” card, but this card was only identified as something engineers would do by less than half the campers.

The non-engineer cards that showed the greatest decrease in correct placement—in other words, those who were incorrectly classified as engineers--were pathologists (“Test blood samples to diagnose disease”) for both students and campers, interior designers (“Design a kitchen”) for students, and backhoe drivers (“Drive machines”) for campers. The cards for pathologist and interior designer used the verb “test” and “design,” which are part of the EDP, suggesting that the participants relied on these word cues rather than looking at the picture or understanding the context.

Correlation of Pile Sort Scores with Other Assessments

The concept post-test scores were correlated with the engineer and non-engineer card scores for the campers but only with the engineer cards for the students, with the exception of a correlation with buoyancy as shown in Table 6. This may have been because those teacher/educators who focused on the learning activities also focused on the activities that taught about a variety of engineering careers, but it may also have been because these were simply the better students.

Table 6: Correlation of Post-assessment and Pile Sort Scores

	Formal		Informal	
	Engineer cards	Non-engineer cards	Engineer cards	Non-engineer cards
Gears	r=.14, p < .01	No	r=.25, p < .01	r=.14, p < .01
Buoyancy	r=.26, p < .01	r=.16, p < .01	r=.19, p < .01	r=.16, p < .01
Programming	r=.27, p < .01	No	r=.34, p < .01	r=.24, p < .01

Attitudes toward Science and Engineering

The camps were advertised as STEM experiences so it is not surprising that on the background survey 71 percent of the campers listed STEM subjects as the subjects they most liked. In contrast, only 58 percent of students in classroom settings did so. In addition, more campers than students agreed or strongly agreed that they liked science and engineering, that they would like to take more courses in these subjects, that they might like to major in them, and that they might like to be scientists or engineers. However, even among campers, less than half said that they saw these as their future professions.

In order to see if their interest in, or engagement with, science and engineering as subjects of study or as future careers had increased after participating in *WaterBotics*, the students and campers were asked on the post-survey if they agreed with a series of statements about their interest in these subjects. The choices were “Yes,” “No,” and “Not sure.” Despite the fact that the campers were already more interested in engineering, they showed greater positive changes in interest by the end of the project than did the students. The difference was especially noticeable in desire to do more afterschool science or engineering projects. Table 7 below shows the number and percent that selected “Yes,” with the highest percentage for each item highlighted in green:

Table 7: Changes in Interest in Science and Engineering, Post-project

	Formal (n=429)	Informal (n=347)
This project changed my mind about how interesting **science** is.	45%	58%
This project made me want to take more classes in **science** if they are available.	30%	54%
This project changed my mind about how interesting **engineering** is.	60%	65%
This project made me want to take more classes in **engineering** if they are available.	42%	56%
This project made me consider **engineering** as a career path.	39%	47%
This project made me want to do more after school **science or engineering projects** if they are available.	30%	55%

Of those who, on the background survey, had disagreed or strongly disagreed that they liked engineering, almost half of both groups (47 percent of the students and 45 percent of the campers) reported that the project had changed their minds about how interesting engineering is. For those who on the background survey had disagreed or strongly disagreed that they would like to be engineers, about 23 percent of campers and 15 percent of students reported that the project had made them consider engineering as a career path. When the teachers/educators were asked whether they felt the curriculum had helped their students learn about engineering careers, a higher percentage in the informal environment (67 percent) than in formal classrooms (50 percent) felt that had been the case. It is likely that this is because the camps tended to spend more time on career awareness activities.

Factors Affecting Learning Outcomes

Although there was not a statistically significant difference in outcomes related to learning the concepts of gears, buoyancy, and programming for classrooms compared to camps, there was some variation among participants by gender and grade level. We therefore examined fidelity of implementation and the contributions of different participant and teacher/educator factors to the post-test scores for each concept area and for understanding of engineers.

Differences by Gender

Project leaders expected that the informal hub sites, which were part of the National Girls Collaborative Project, would have more girls than boys in their camps and this was the case, with 71 percent of participants being girls compared to 42 percent of participants being girls in the formal, classroom environment. However, overall the girls were younger, with more than half of the girls in middle school, compared to 34 percent of the boys being in middle school.

Boys performed significantly better than girls on the gears and buoyancy concept assessments at baseline but although they maintained the lead in the post-test scores, the difference in the post-test scores between boys and girls was statistically significant only for gears ($p < .01$). Gender was a significant factor in explaining the gears post-test scores even after the difference in pre-test scores is taken into consideration. For programming, in contrast, while girls began with lower scores than boys on the pre-tests, they surpassed them on the post-tests. Gender was a statistically significant variable explaining the variability in the programming post-test scores.

Table 8 summarizes the changes by gender. Those changes that are statistically significant ($p < .01$) are highlighted in green.

Table 8: Science and Programming Pre- and Post-test Scores by Gender

Girls (n=422)	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Gears	1.38	1.89	37%	47%	4
Buoyancy	4.27	4.72	11%	52%	9
Programming	6.38	7.27	14%	52%	14

Boys (n=348)	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Gears	1.80	2.39	33%	60%	4
Buoyancy	4.84	4.87	1%	54%	9
Programming	6.63	7.01	6%	50%	14

The increase in the number of correct engineering cards from pre- to post- project was statistically significant for both girls and boys as shown by the green highlights in Table 9 below. However, in the post-test girls outperformed boys in listing the steps in the EDP and in identifying the engineering cards correctly. The difference between girls and boys was statistically significant for engineering card post- test score ($p < .05$) and EDP score ($p < .01$). The post-implementation survey asked the teacher/educators in mixed gender situations if they had seen any gender differences while teaching the curriculum and most said they had not.

Table 9: Engineer Card Sort and EDP Scores by Gender

Girls	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Engineer cards (n=419)	6.04	6.99	16%	78%	9
Non-engineer cards (n=419)	2.15	1.86	-13%	31%	6
EDP (n=422)	-	2.69	-	34%	8

Boys	Pre-test mean	Post-test mean	Pre-to-post change as %	Post-test mean as % of total possible score	Maximum score
Engineer cards (n=336)	6.29	6.69	6%	74%	9
Non-engineer cards (n=336)	2.71	2.21	-18%	37%	6
EDP (n=348)	-	2.23		28%	8

Differences by Grade Level

Students in formal classrooms were divided equally between middle and high school (50 percent in each), while many more campers were in high school than in middle school (61 percent compared to 39 percent). As might be expected, grade level was correlated with all three concept assessment scores and with the engineer card scores. In other words, students in the higher grades performed better than those in the lower grades. However, Table 10 shows that although the correlations were statistically significant, the correlation coefficients are very small, suggesting that the correlations were weak.

Table 10: Correlations between Pre- and Post-test Scores and Grade

(n=774)	Pre-test scores	Post-test scores
Gears	r=.26, p < .01	r=.23, p < .01
Buoyancy	r=.20, p < .01	r=.15, p < .01
Programming	r=.16, p < .01	r=.23, p < .01

(n=774)	Pre-test scores	Post-test scores
Engineer	r=.24, p < .01	r=.17, p < .01
Not-engineer	r=.10, p < .01	No
EDP	-	r=.10, p < .05

Fidelity of Implementation

Fidelity studies assume that a curriculum implementation needs to meet certain pre-determined criteria such as instructor behaviors and engagement conditions, if the program is to have the desired outcome. These criteria are based on research and previous experience with the current or past projects. For this project, those outcomes are based on measures of student/camper learning and engagement. The structure of *WaterBotics* implementation is complex and has evolved over the course of the project with different training, implementation models, and curriculum versions being used by project partners. Lowes and Tirthali[61] constructed an instrument to measure the fidelity of implementation of the *WaterBotics* implementation that included structural, instructional, and contextual components. Each was analyzed separately in order to determine whether it should be included in a final regression model. Details of their full analysis are not provided in this paper. Instead we present here the aspects of fidelity that the analysis indicated contributed to student learning outcomes.

The emphasis on fidelity assumes that there will be greater success, in terms of both learning and engagement, for participants whose programs adhere to the structural and procedural fidelity components emphasized in the curriculum. A sequential multiple regression analysis was conducted for the three content areas with the variables relevant to that content area, for the pile sort, the EDP, and the grades given for engagement/enjoyment.

Some of the factors included as fidelity components did not have enough variation to be used in the analysis, were not correlated with the student/camper outcomes, or could not be measured and so were not used in the multiple regression analysis. The factors from the fidelity model that were considered are shown in Table 11 along with the contribution of each variable to student post-test scores in each of the concept areas listed.

Table 11: Summary of Contributions to Variance

	Gears	Buoyancy	Programming	Engineers
All variables together	31%	28%	35%	30%
Participant-related variables				
Student/camper pre-test scores (as a proxy for prior knowledge)	18%	22%	24%	26%
Student/camper gender	2%	--	1%*	2%
Student/camper grade level	1%	--	5%	--
Teacher/educator and instructional variables				
Teacher/educator pre-test scores (as proxy for background knowledge)	--	--	3%	--
Training model (face-to-face or hybrid; length)	2%	3%	4%	--
Time spent on the curriculum	2%	--	2%	--
Using the concept-specific supplementary materials (including videos, simulations, and sample programs)	--	--	--	--
Having the student/camper play the role of programmer (programming only)	n/a	n/a	3%	--

*$p < 0.05$

For the content topic of gears, the full model explains 31 percent of the variance in the participants’ gears post-test scores and is statistically significant ($p < 0.01$). However, the percent contribution of each variable is very different. When a similar model is built for the topic of buoyancy, the model explains 28 percent of the variance in the buoyancy post- test scores. The student/camper buoyancy pre-test scores, grade, and training model were the only variables that were statistically significant ($p < 0.01$). As had been the case in previous years, the buoyancy pre-test scores were the most influential variable, explaining 22 percent of the unique variance in the post-test scores. The programming model included an additional variable -- the number of times the programming role was played by a student/camper. The full model explains 35 percent of the variance in the participants’ programming post-test scores and is statistically significant ($p < 0.01$).

A similar model was considered for understanding engineering careers using the pile sort assessment. The model explains 30 percent of the variance in the engineer card scores. The engineer card sort pre-assessment scores and gender were the only statistically significant variables ($p < 0.01$). The engineer card sort pre-assessment score explains 26 percent of unique variance in the post-assessment scores while gender explains 2 percent, with the probability of girls doing better than boys. The number of engineering activities was not predictive when added to the full model. A similar model built to explain variance in the EDP scores had a very low R^2, making it of no practical significance.

All the variables taken together explained approximately 30 percent of the post-test scores for each concept area and for understanding of engineers. However, participant pre-test scores—in other words, prior knowledge--were the most predictive variable. Training model was predictive for all concept areas but not for the engineering assessment, while time spent on the curriculum, gender, and grade level were predictive for gears and programming but not for buoyancy or the engineering assessment. Playing the programmer role was predictive for the programming assessment, as were teacher/educator pre-test scores for programming. Use of the supplementary resources (videos, simulations) and number of engineering activities was not predictive in any area. Finally, none of the variables were predictive of engagement.

Discussion of Results

Although students/campers felt they had learned, and teachers/educators agreed, the learning was not reflected in the assessment scores. While learning about gears, buoyancy, and programming may not have been the main purpose in the summer camps, one would have expected it to be a major part of the classroom implementations. For example, despite the fact that the participants had an intuitive understanding of the concept of buoyancy and were able to master it sufficiently to complete the hands-on activities, they were not able to transfer this understanding effectively outside the context of the project they were working on and/or were not able to use it in a paper-based (or in this case, digital) assessment.

It is natural to speculate whether the learning gains were small because the instruments themselves were not sensitive enough to measure the intended learning outcomes. The assessment instruments used for this study were developed jointly by the researchers and curriculum developers affiliated with the initial *WaterBotics* ITEST grant and piloted with thousands of students in New Jersey. The assessment questions were designed to measure specific content and practices covered by the *WaterBotics* curriculum. The assessments are considered to be locally developed and validated instruments. However, future work may be needed to ensure that the content being assessed is explicitly taught to students who experience the *WaterBotics* program, whether in classroom or out-of-school settings.

In research on previous projects using earlier versions of the curriculum,[62] teacher content knowledge and confidence in teaching the content area were shown to be significant factors in explaining the variance in student post-test scores. That was not the case in this analysis, which indicated that teacher/educator knowledge of the topic was not correlated with student post-test scores for any topic except programming. This may be due to the expanded instructions, descriptions and images, and educator resources available in the revised curriculum, especially in the informal educator version which has more step-by-step guided instructions and explanations.

Neither the campers nor the students did well in listing the steps in the EDP on the post-assessment and the differences between the two groups were not statistically significant. Most of the teachers/educators felt that the curriculum had helped their students learn the EDP, but it is clear from the student results that this learning also was based on practice and not formalized. It is important to question whether the identification and definition of steps in the EDP is a sufficient measure of students' ability to engage in and apply the EDP. It may be that listing the steps of the EDP does not capture what students have learned in practical terms or about how to use the EDP to iterate engineering design solutions. Furthermore, it could be argued that self-awareness of how the EDP steps improve design is more important than naming the steps and, in fact, makes the recall of the EDP terms more likely. Additional ways to assess students' understanding of the EDP may be warranted.

Overall, the curriculum has worked best in the informal environments. Engagement was higher at the informal sites, they did more with engineers and engineering, and participants did better on the assessments. This may be attributed to the amount of time spent on the curriculum during intensive summer camp experiences whereas there is a great range of class time devoted to the curriculum in the formal environment.

Recommendations for Consideration

During the third year of implementation of this project, most of the teachers/educators implemented most of the instructional practices deemed important for success. As we have seen in this study and in earlier program implementations, student/camper pre-test scores were the most predictive variable for student/camper post-test scores and grade level was correlated with pre- and post-test scores for all assessments. These are factors that the project cannot control. However, the results of the item by item analysis and the regression model lead to a number of recommendations to strengthen student learning, career interest, and teacher professional development:

Recommendation #1: Reconsider how to teach the learning goals

Although there was improvement from pre-test to post-test for all three assessments (gears, buoyancy, and programming), the final average was only about 50 percent and the teacher pre-test scores were relatively low as well. This suggests that although the participants learned these concepts through their hands-on activities, there needs to be more explicit attention to instruction about the interdependency between particular science concepts and engineering design choices if these types of formalized assessments are to be used to judge outcomes.

Recommendation #2: Reconsider how to teach the EDP

Neither group did well in listing the steps to the EDP. Although the use of the language of engineering could not be observed, it seems possible this was not sufficiently emphasized in the classrooms and camps. If the EDP is considered important, then it must be included more explicitly in the teacher/educator training and revised in the curriculum.

Recommendation #3: Emphasize the minimum amount of time to cover the curriculum

Time spent was correlated with higher assessment scores, so if higher scores are the desired outcome, the amount of time should not be reduced and the need for a certain number of hours should be emphasized. It should be noted that only those teacher/educators who completed at least three challenges were considered in this report, but that those who completed fewer challenges would not have gone through the entire scaffolded sequence.

Recommendation #4: Consider building on the informal curriculum's approaches to engagement and learning about engineering careers

Although camper and student scores for learning were similar, the campers' ratings for engagement were considerably higher than the students' ratings, as were their self-ratings for how much they had learned and their ratings for how well their groups had worked together. In addition, campers were much more likely to express increased interest in science and engineering, both as subjects of study and as careers. This may have in part been because of the self-selected nature of some of the camps, but among those who had not been interested in engineering at the start, more campers than students reported that they would now consider engineering as a career. Although it was not a significant factor in the final model, the number of engineering activities conducted was correlated with both the engineering pile sort and the EDP scores. This suggests that formal classrooms may need more engaging activities and that more activities about engineering careers should be built into the curriculum.

Recommendation #5: Strengthen the teaching about engineering careers

The number of engineering activities was correlated with the engineering pile sort scores, with more activities associated with higher scores. However, while the students and campers expanded their conceptions of engineering careers, they also tended to overgeneralize, by the end of the project thinking that almost any career might include engineering. This may have been in part because the card sort assessment encouraged this, but it may also be that the participants need to be given a way to determine how an engineering career differs from other types of careers.

Recommendation #6: Emphasize that participants need to do an activity to learn it, particularly programming

While campers and students may want to find a role in their group that is comfortable for them and teachers/educators may find that having the participants choose their roles leads to less contention within groups, it is clear that if a student/camper does not do the programming, he or she is unlikely to learn that skill. Campers were almost twice as likely as students to play that role, while taking on that role at several points was correlated with programming post-test scores. Group organization involves trade-offs that the teachers/educators may have to make but the need to share roles may need to be emphasized. This is especially true for mixed-gender and boys-only groups, where the role of programmer was played by fewer students than in all-girl groups.

Recommendation #7: Reconsider the training model

Training model was predictive for all concept areas, in favor of the shorter training. This suggests that full five-day trainings may not be necessary, especially if online follow-up is structured to take the teachers/educators through the curriculum in a systematic way and provide additional instructional strategies for specific situations.

Conclusions and Future Directions

The student impact study discussed in this paper present learning and enjoyment outcomes in both formal classroom and informal learning settings. Results for the science and programming concept areas indicate that although students felt they had learned, and teachers agreed, the degree of learning was not reflected in the assessment scores. Although there was improvement from pre-test to post-test, the final average was only just above 50 percent of the total possible score. Although the participants learned the relevant concepts superficially through their hands-on activities, several potential improvements to *WaterBotics* that would make it more effective for both educators and youth include:

- Provide more explicit, formal teaching of STEM content for deeper learning; instruction that goes beyond the activities themselves
- Include more explicit instruction in the engineering design process both in training and revised in the curriculum so that students understand the rationale behind engineering practices and can demonstrate how much they have learned
- Develop a cost effective training model to flexibly blend face-to-face and online educator professional development

Additionally, to address the connections between the science and engineering content and practices as identified in the Next Generation Science Standards, curriculum developers also have the opportunity to make enhancements that would address the research findings and better align the curriculum with the standards:

- Despite existing curricular connections to important physical science concepts, the science lessons need to be more deeply integrated into the design tasks and aligned more closely with the NGSS disciplinary core ideas and crosscutting concepts. Science content that must be learned in order to proceed with design choices (as opposed to trial and error) should be identified and incorporated. Increased targeted references to connect science principles and engineering design choices are desired.

- Student engagement in the engineering design process needs to be aligned more closely with the NGSS and educators should explicitly teach the EDP as part of the curriculum's instructional content.

Our research to examine the differential impacts of the *WaterBotics* program on different student groups and in differing implementation scenarios have led to valuable understandings about strategies to foster learning in STEM areas and student interest and engagement in STEM careers. The recommendations resulting from this student impact study are relevant and applicable to the design of future engineering curricula especially those that will bring curricula into closer alignment with the Next Generation Science Standards.

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