



University-Designed Middle School Science Experiences Aligned with NGSS

Mrs. Zahraa Stuart, Stony Brook University

Zahraa Stuart received Bachelor of Engineering in electrical engineering from Stony Brook University in 2016. In 2017, she joined the PhD program in Electrical engineering statistical signal processing. Zahraa design, develop and instruct engineering teaching laboratories for both high school and middle school students and teaches since 2016.

Dr. Angela M Kelly, Stony Brook University

Angela M. Kelly is an Associate Professor of Physics and the Associate Director of the Science Education Program at Stony Brook University, New York. She attended La Salle University, Philadelphia, Pennsylvania, where she received her B.A. degree in chemistry, and completed her M.A. and Ph.D. degrees in science education (2000 and 2006, respectively) and her Ed.M. degree in curriculum and teaching (2007) at Teachers College, Columbia University, New York. She is the recipient of the SUNY Chancellor's Award for Excellence in Teaching (2016); the Provost's Faculty Recognition Award for Excellence in Scholarship and Research from Lehman College, City University of New York (2010); and the Outstanding Teaching Award from Teachers College, Columbia University (2006). Her research has been rooted in a commitment to equity in precollege and university science and engineering.

Dr. Monica Bugallo, Stony Brook University

Monica Bugallo is the Associate Dean for Diversity and Outreach of the College of Engineering and Applied Sciences and a Professor of Electrical and Computer Engineering at Stony Brook University. She received her B.S., M.S., and Ph. D. degrees in computer science and engineering from University of A Coruna, Spain. She joined the Department of Electrical and Computer Engineering at Stony Brook University in 2002 where she is currently a Professor. Her research interests are in the field of statistical signal processing, with emphasis on the theory of Monte Carlo methods and its application to different disciplines including biomedicine, sensor networks, and finance. In addition, she has focused on STEM education and has initiated several successful programs with the purpose of engaging students at all academic stages in the excitement of engineering and research, with particular focus on underrepresented groups. She has authored and coauthored two book chapters and more than 150 journal papers and refereed conference articles.

Bugallo is a senior member of the IEEE, serves on several of its technical committees and was the past chair of the IEEE Signal Processing Society Education Committee. She has been part of the technical committee and has organized various professional conferences and workshops. She has received several prestigious research and education awards including the award for Best Paper in the IEEE Signal Processing Magazine 2007 as coauthor of a paper entitled "Particle Filtering," the IEEE Outstanding Young Engineer Award (2009), for development and application of computational methods for sequential signal processing, the IEEE Athanasios Papoulis Award (2011), for innovative educational outreach that has inspired high school students and college level women to study engineering, the Stony Brook University Hispanic Heritage Month (HHM) Latino Faculty Recognition Award (2009), the Chair of Excellence by the Universidad Carlos III de Madrid-Banco de Santander (Spain) (2012) and the Ada Byron Award from the Galician Computer Engineering Society.

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Abstract

The adoption of the Next Generation Science Standards (NGSS) by many U.S. states involves the inclusion of engineering practices in science instruction to equip and prepare K-12 students with sufficient engineering literacy. Engineering and science education faculty members at a research university designed a one-week, 20-hour engineering camp aligned with NGSS and middle school science curricula to measure the efficacy of such programs in developing middle school students' engineering interest and knowledge. Four different projects were designed: 1) a 3D-printed spirograph, 2) a night light, 3) an optical intrusion detection with memory, and 4) a traffic light. Students who participated in the camp ($N=56$) built and optimized their own take-home electronic devices. Pre- and post-surveys were collected to analyze the students' engineering self-efficacy, knowledge, and engineering skills. Results suggested that students' self-efficacy and beliefs in succeeding in engineering majors and careers increased after their experiences in the camp; they also improved their engineering knowledge and skills ($p<.001$). The program was aligned with New York State P-12 learning standards and may be replicated and scaled by informal science educators and classroom teachers to improve students' interest in pursuing engineering majors and careers.

Introduction

With the pace at which science, technology, engineering, and mathematics (STEM) is advancing globally, the shortage of engineering talent in the workforce may place the U.S. at a technological disadvantage with social and economic ramifications [1][2]. For this reason, STEM outreach programs have proliferated in the U.S. in the past decade, alongside an ongoing effort to grow formal STEM educational innovations in K-12 schools. The goal of many of these outreach programs is to increase students' interest in STEM and their capacity to solve future technological challenges and to participate in a competitive, global economy [3][4].

Research has shown that capturing and reinforcing student's interest in STEM at the middle school level increases the chance of students majoring in STEM fields by 200% [5]. However, less than 34% of eighth graders have shown proficiency in mathematics and science [6][7], and students have reported that STEM is often too challenging and/or boring [5]. School science teachers have often not experienced formal training in engineering [8][9], so they may not prioritize making active connections between science and engineering in their classrooms. This suggests the need for informal STEM learning for students, especially at the middle school level. Out-of-school activities have been shown to positively influence the success of students, especially those who have difficulty learning in school [10].

STEM informal learning experiences have included many forms, with most striving to engage students in unique hands-on learning experiences that positively influence their STEM interest [4][11][12][16]. *Project Lead the Way* [13], the *Infinity Project* [14], and *The National Girls Collaborative Project* [15] are three popular programs nationwide. While most of these programs focus on increasing students' interest in STEM related careers, there has been a lack of integration between formal and informal learning. Closing the gap between formal and informal learning may facilitate an increase in student motivation for STEM learning, conceptual reasoning, and science and engineering skills [17]. Consequently, the purpose of the *Design and Build Summer Camp* was to create and implement effective

hands-on engineering activities for middle school students. The program was aligned with the *Next Generation Science Standards* and the *New York State Science Learning Standards* in an effort to bridge the gap between informal and formal learning.

Unlike other programs, the *Design and Build Summer Camp* was created by engineering and science education faculty and incorporated activities from every part of the STEM spectrum: science, technology, engineering, and mathematics. The activities were piloted for middle and high school students and were also used for professional development for K-12 STEM teachers prior to the summer camp [18] [19]. The activities were deemed appropriate by the science teachers for both formal classroom learning and informal camps and out-of-school experiences [11][20][21]. The camp focused on integrating the classroom science curriculum with real-world applications.

The present study explored the effectiveness of the camp in meeting the goals of advancing middle school students' STEM interest and skills, particularly in engineering. The overarching research question was the following: How did middle school students' engineering self-efficacy and spatial reasoning skills change after participating in the *Design and Build Summer Camp*?

Methods

Context and program design. Engineering (mostly from Electrical and Computer Engineering) and science education faculty collaborated to design a one-week *Design and Build Summer Camp* for middle school students entering seventh, eighth, or ninth grades. Two identical camp sessions ran throughout the summer and admitted 30 and 26 students to the sessions, respectively ($N=56$). In the first session, both male and female students were admitted, while only female students participated in the second session. Both sessions were equivalent in content and format and a total of four different activities were implemented. At the end of each week students took home all four of their designed gadgets. The camp took place in a fully equipped lab that contained computers, 3D printers, soldering stations, and safety tools. University faculty and doctoral students instructed the sessions, along with teacher assistants (TAs) who were recruited from the graduate and undergraduate student population. The student to instructor ratio was 8:1. All eligible students were admitted to the program regardless of their science performance.

The camp was scheduled from 9am-1pm on weekdays, for a total of 20 hours of instruction. Day-to-day scheduling was consistent. The day started off with an icebreaker to get students warmed up for the day, followed by a presentation about the activity. All instructional presentations included educational games to encourage students' participation. The students then designed and assembled the activity under study through hands-on experiences. Next, students continued optimizing and testing their designs. The day ended with final remarks and questions about the activity under study. On the last day of camp, different STEM majors and careers were discussed with students and questions regarding students' STEM career interest were addressed. Also, family members and friends were invited to a showcase where students demonstrated their four designed engineering gadgets and presented lessons learned. Finally, certificates were awarded to participants who attended the complete program. Figure 1 shows the participants engaging in an educational activity.



Figure 1. Middle school students attending the engineering summer camp.

The *Design and Build Summer Camp* consisted of four different activities which incorporated mathematics, programming, and hands-on engineering practices. The activities were all aligned with the *Next Generation Science Standards* [22] and to *New York State P-12 Science Learning Standards Performance Expectations* [23], as indicated by the objectives described below:

- MS-PS3-6. Make observations to provide evidence that energy can be transferred by electric currents.
- MS-ETS1-1. Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
- MS-ETS1-2. Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-4. Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

The *Design and Build Summer Camp* curriculum adhered to effective attributes of STEM informal learning by exposing students to application of classroom science and mathematics in four different hands-on engineering activities. In doing so, the program incorporated several aspects of effective informal learning environments, including academic enrichment, opportunities to apply mathematics and science, teaching by trained instructors, enjoyable learning experiences, camaraderie with peers, and promotion of engineering skills and career awareness [24,25]. The activities were designed to solve real world problems that students experience in their daily lives. The camp provided informal mentoring to students whereby eight students had a designated engineering Teacher Assistant (TA) that had a fun identity. For example, instructors and TAs were addressed by nicknames such as: Galaxy, Willy Wonka, Mr. Babbage, and Skittles. Students were also encouraged to engage in teamwork during the design process that required critical thinking. For example, in the design of the Optical Intrusion Detection with Memory, a security alarm system, students were given the freedom to design their own alarm system sound and timing. By understanding how electronics work and applying that knowledge, students were able to design different alarms with different sounds and time mechanisms.

Camp activities. Camp activities occurred during the course of the week, with most completed in one day (4 hours). The specifics of each activity are described below:

1. ***Spirograph*** (mathematics & engineering). A 3D-printed spirograph is a geometric toy that produces a variety of kaleidoscopic mathematical curves by putting your pen into one of many holes in a set of interlocking gears. The pen pushes the gears around an outer ring. This gadget may be designed in different shapes and sizes and requires a basic understanding of middle school mathematical phenomena. Students used an online spirograph tool to experience how different shapes and sizes affected the geometrical representation of the curves produced. Then in groups of two, students teamed up to produce a two-part spirograph using Tinker cad and a 3D printer.
2. ***Night Light*** (engineering, technology, applied science). A night light is an electronic device utilized at night by providing sufficient light to allow us to see. The students used a red, green, and blue (RGB) light emitting diode (LED) and controlled the current flow passing the LED using both manual and automated features. A simple breadboard was used to insert components and complete a full circuit. In the manual experiment, students were asked to design the light intensity and light pattern of the LED. In the automated experiment, students were introduced to programming and were given a programmed chip that automatically changed the intensity and color of the LED. Finally, students painted their own acrylic panels to place above the designed light [20].
3. ***Optical Intrusion Detection with Memory*** (engineering, technology, applied science). A detection system is an electronic device utilized for security purposes. Students assembled a printed circuit board (PCB) with some basic electronics including a photo-transistor, buzzer, and an integrated circuit timer. Students had the choice of optimizing their design and choosing the desired time and frequency of their alarms by selecting the values of their resistors and capacitors. Also, students assembled an add-on memory part made of transistors to memorize any alarm activation state [21].
4. ***Traffic Light Board Game*** (engineering, technology, applied science). A traffic light is an electronic device utilized to control the flow of vehicle traffic. These signaling devices are positioned at road intersections, pedestrian crossings, and other locations worldwide to maintain safety standards for driving vehicles and avoid accidents. Students assembled a PCB with some basic electronics such as LEDs, registers, and pushbuttons. Students then used an Arduino uno to code the lights to function in a four-intersection traffic light manner and used the push-buttons as sensors to traffic induction. Last, students installed a code to their gadget to make it function both as a traffic light and as a cyclone board game made for two players.



Figure 2. Students soldering the traffic light.

The cost of the activities ranged between \$2/student to \$8/student, which makes them easily adaptable for middle school classrooms. The activity manuals are designed to be easily utilized by science teachers with no engineering background.

Safety precautions. Students were introduced to the lab safety precautions including a short soldering one-on-one training. Students were asked to remove all jewelry prior to soldering and washed their hands after they were done. Students with synthetic nails were not allowed to solder because synthetic nails are flammable. Students were always expected to wear goggles during engineering activities.

Survey instrument. Students were given pre- and post-surveys to assess their engineering self-efficacy, engineering knowledge, and spatial reasoning skills. The surveys were created and validated by engineering and science education faculty. They were administered at the start of camp before instruction, and on the last day of camp. The *Engineering Self-Efficacy Survey* questions included questions related to confidence, career interest, career awareness, and how school science relates to engineering preparedness. Each question was scored using a 5-point Likert scale, where 1=strongly disagree, 2=disagree, 3=neutral, 4=agree, and 5=strongly agree. The reliability for the survey was adequate ($\alpha = 0.795$).

Questions on the first survey included the following:

1. I am confident I understand what engineering is.
2. I understand the differences between different engineering disciplines.
3. I am interested in engineering and science careers.
4. I believe I can be successful in a career in engineering or science.
5. I understand how engineering careers/majors are related to concepts I learned in my science and math classes in school.
6. I believe I would excel in an engineering major.
7. I will take physics in high school.

The second questionnaire, the *Engineering Knowledge and Spatial Reasoning Survey*, included multiple choice and open-ended questions including the following:

1. Which cube cannot be made based on the unfolded cube?

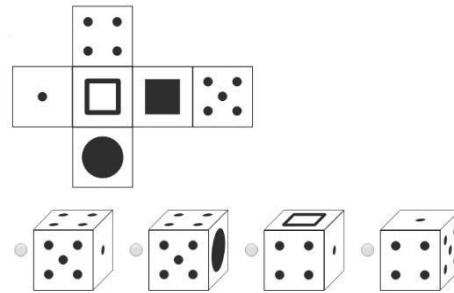


Figure 3. Spatial reasoning question 1.

2. Spirograph mathematics: Match holes (1-8) with generated design (A-G)

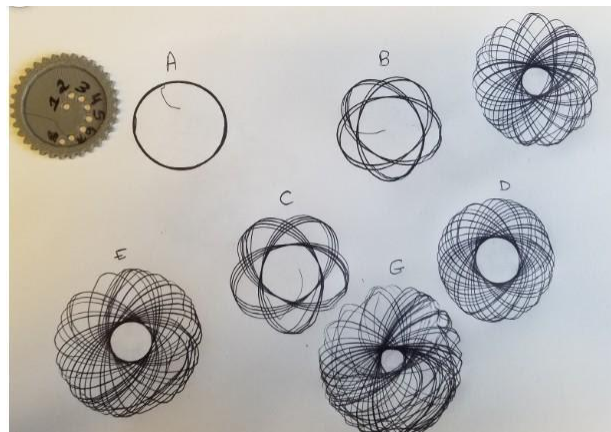


Figure 4. Spatial reasoning question 2.

3. Give an example of an electronics device.
4. Batteries have chemical energy inside of them. In an electrical system, what type of energy is the chemical energy converted to?
5. Define conservation of energy and give an example.
6. What type of engineers design cell phones?
7. Give one example of something a programmer does at work. Give one example of how coding is used in an everyday product.

Results

To measure the effectiveness of the *Design and Build Summer Camp*, paired-samples t-tests were conducted to compare mean composite survey scores before and after the camp. A priori power analysis indicated a sample size of 19 was required to detect a large effect with 95% power. For the *Engineering Self-Efficacy Survey*, students significantly improved their self-assessed confidence, engineering career interest and awareness, and recognition of the relationship between science and engineering principles ($t=6.479$, $df=50$, $p<.001$) from pre-survey ($M=3.549$, $SD=1.189$) to post-survey ($M=4.431$, $SD=1.005$), with a large effect size (Cohen's $d=0.80$). For the *Engineering Knowledge and Spatial Reasoning Survey*, students significantly improved their engineering knowledge and spatial reasoning ($t=9.348$, $df=50$, $p<$

.001) from pre-survey ($M=0.686$, $SD=0.583$) to post-survey ($M=1.529$, $SD=0.578$), with a large effect size (Cohen's $d=1.45$).

Discussion

Results from this study indicated that the *Design and Build Engineering Camp* was effective in improving the self-efficacy, engineering knowledge, spatial skills, and engineering career awareness of middle school students. The camp was innovative in that it combined foundational principles in mathematics, electrical engineering, and computer science. Although NGSS has suggested the incorporation of integrated STEM learning throughout grades K-12, many school districts have not implemented the standards [18]. Similarly, schools often do not have the resources to advise students on pre-college preparation for engineering post-secondary study, nor may they advise on the diversity of engineering careers [19]. Consequently, informal learning environments show particular promise in promoting STEM interest and career awareness in the middle school years, a time when many students are formulating academic and career aspirations.

The potential of the *Design and Build Engineering Camp* has implications for both formal and informal learning environments. Informal settings may fill a void in access to engineering education while school districts are redesigning science curricula to align with NGSS. School districts might look towards the innovative curricula created by university engineers and educators to model engineering design activities that might be adapted for formal learning contexts. Future research will explore the effectiveness of leveraging curricula developed in informal settings to initiate transformed science instruction in K-12 schools.

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