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Fundamental: Examining the Variations in the TPACK Framework for Teaching Robotics-aided STEM Lessons of Varying Difficulty

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Fundamental: Examining the Variations in the TPACK Framework for Teaching Robotics-aided STEM Lessons of Varying Difficulty

1. Introduction

Educators are increasingly relying on the use of educational technologies to engage students in science, technology, engineering, and math (STEM) learning [1]. However, until recently there has not been a theoretical framework that explicitly discusses the complexities of teaching and learning through the utilization of rapidly changing technologies [2], e.g., digital technologies (computers, software packages, online resources, and mobile applications), and engineering hardware and software (robotics and 3D printing), among others. Thus, education researchers have formulated and promoted a conceptual construct to examine and promote practitioners' technological, pedagogical, and content knowledge (TPACK) [2-5]. The concept of TPACK enables educators to carefully select and apply technology as an effective educational tool [4] to create active learning environments wherein pedagogically challenging disciplinary content can be rendered accessible to learners.

TPACK provides a formalism to understand the knowledge that may be required to integrate technology in the teaching and learning of certain disciplinary content. TPACK can be of particular value when content knowledge, which may be intangible in nature, presents a challenge for educators [4]. Within the TPACK framework, technology takes into consideration the technological products and the necessary knowledge and skills required for designing, building, and operating these products [6,7], whereas pedagogy deals with the principles and skills needed to administer and appraise effective teaching and learning, and the content knowledge includes basic concepts, theoretical basis, and the fundamentals aligned with classroom environment [8]. Having experienced the TPACK framework, teachers can understand and assess appropriate requirements for technological, pedagogical, and content knowledge to teach a particular lesson, which can make them well-prepared and effective, especially in a technology-enhanced educational environment. Research shows that TPACK framework can promote effective pedagogy [4,5,9]. Thus, it is clear that for teachers to make effective use of the TPACK framework, they require the knowledge of the disciplinary content as well as an understanding of technology's role in effective pedagogy.

With the accelerating adoption of robotics in K-12 STEM learning, there is a need to examine robotics-based STEM teaching and learning using the TPACK construct. This is of paramount importance since in addition to learning and becoming fluent with the design and operation of robotics devices, teachers also need to meaningfully incorporate robotics for teaching required curricula [9]. As delineated by its proponents [2-5], the TPACK framework is the net result of the interactions between technological knowledge (TK), content knowledge (CK), and pedagogical knowledge (PK). The intersection of PK and CK yields pedagogical content knowledge (PCK), referring to teachers' knowledge on how to present the content in multiple ways, differentiating for diverse learners, creating lessons that ensure learning progression by identifying students' misconceptions, and addressing students' prior knowledge [8]. The interactions of TK and CK yields TCK, "an understanding of the manner in which technology and content influence and constrain one another" [2]. TPK is the intersection of TK and PK, and similar to PCK, this refers to teachers learning how to use technology to deliver knowledge. The TPACK framework is multifaceted thereby making its implementation complex but necessary in the 21st century. Due to the rapid change in technological advances and scientific discoveries, it is vital that researchers investigate if teachers implement TPACK, how they implement it, and if there are any student learning gains.

Prior TPACK research has been quite general. In the initial years, research in TPACK with respect to STEM education was primarily directed toward formulating assessment tools and building the TPACK framework [2-4,10]. The later efforts were on validating the framework and tools [11-13]. There were also research efforts on improving the assessment tools [9]. However, in all these prior research efforts an overall assessment was made for the participants where each participant's TPACK response was an average of all the STEM lessons considered. This posed several limitations in particular situations, e.g., with regards to the development of individual teachers or individual lessons.

Specifically, teachers are expected to deliver robotics-aided STEM education to their students for many years. Some individual teachers may find it challenging to engage in robotics-aided STEM education due to their lack of required TPACK self-efficacy (see [5,9] for details about TPACK self-efficacy). Moreover, all robotics-aided STEM lessons are not the same, i.e., their difficulty levels may vary due to variations in the required TPACK. Specifically, while some lessons may be more complicated from the design or programming (technology) point of view, others may be complicated from the teaching, learning, or assessment (pedagogical) point of view, and the incorporation of robots (technology) may also impact the pedagogy. Thus, it is important to concentrate on investigating the TPACK framework for individual teacher and individual lesson, since a well-designed and focused TPACK examination can allow individual teachers to continually improve themselves as well as effectively prepare for and deliver specific lessons. This indicates the necessity of performing an investigation with a small sample size. This can also help conduct intensive research, which in turn can increase the possibility of improving the teachers' performance in classrooms. However, investigations on individual teachers for individual subjects/lessons within TPACK framework have not been considered in prior research.

In order to give an in-depth account of TPACK, this paper focuses on exploring the TPACK framework for two individual teachers teaching three robotics-aided science and math lessons with varying level of difficulty. Section 2 describes our professional development (PD) program in brief. Section 3 describes the lessons we concentrated on. Section 4 talks about the research environment and elaborates how the lessons were carried out. Section 5 presents the results of the research. Section 6 includes discussion of the study and Section 7 ends with concluding remarks and suggests directions for future work.

2. Professional Development Structure

To provide context to the study of this paper, our PD program is described here briefly. Twenty middle school teachers from eight schools in New York City participated in a three-week, full-time (five days a week for eight hours each day) robotics-focused STEM summer PD program. The PD was held at the NYU Tandon School of Engineering. The teachers were all from local schools and they commuted daily to attend the PD. The project team (facilitators of the PD program) included engineering and education faculty, researchers, and graduate students who performed a preliminary design of robotics-based lessons meeting state standards for middle school science and math, based on the Next Generation Science Standards (NGSS) [14] and the Common Core State Standards for Math (CCSSM) [15]. During the PD program, we followed a regular schedule for daily activities. Specifically, each day's schedule consisted of two four-hours long morning and afternoon sessions. Each session started with short formal lectures that introduced foundational material using presentations, videos, sample programs, etc. Each session's lecture was followed by hands-on learning activities that allowed exploration and reinforced the sessions' material. While few hands-on learning sessions engaged teachers to perform assigned activities individually, a vast majority of hands-on learning sessions engaged teachers in two-person groups. Group discussions, co-generations, etc., were also conducted. To build teacher agency, they were also engaged in creative activities such as new lesson planning, developing and assessing activity sheets for existing lessons, and developing and testing teaching and learning strategies using robotics. The project team also conducted a battery of pre-/post-surveys and collected feedbacks from the participating teachers to improve the PD program and to conduct research.

In our PD program, we used the LEGO Mindstorms EV3 robotics kit [16]. Building a robot using this robotics kit is relatively easy. The programming is simple, involving drag and drop operations of various programming blocks. For this reason, this robotics kit was used to make learning easy for teachers and students, most of whom were working with robots for the first time.

Teachers were exposed to important robotics concepts. First, they learned about building the LEGO base robots shown in Figure 1. Second, they learned programming and gradually they learned motion, actuation, sensing, etc. Third, they were taught how to implement a series of math and science lesson using LEGO robots. These lessons included energy, tug of war, ratio and proportion, center of mass, functions, number line, least common multiplier (LCM), expressions, statistics, and rover. They were encouraged to come up with their own innovative ideas as well.

After each lesson, they engaged in discussions about its suitability for classroom implementation and corresponding challenges. Several methods for assessing student learning styles, learning outcomes, and performance were discussed. In addition, the effect of teacher self-efficacy, beliefs, and performance on students' learning were explained. Most importantly, the mechanics by which teachers would implement the robotics-based lessons in actual classroom settings after the PD program was planned and reviewed.

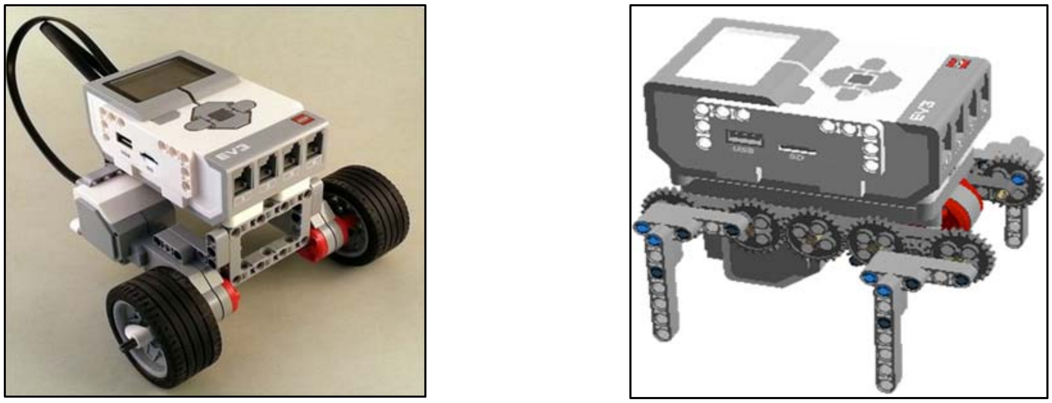


Figure 1: LEGO Mindstorms EV3 base robots.

Following the PD program, during the academic year, participating teachers taught robotics-based science and math lessons to over 300 students who had not been exposed to robotics previously. Researchers visited the school once a week during the robotics-aided lesson class to support teachers conduct lessons, observe lessons, and carry out various assessments. The research presented in this paper was conducted during the academic year in the schools, not during the summer PD program. Thus, instead of delving into the details of the PD program, we only offer its brief overview as above. Nevertheless, as delineated below, the study of this paper is an outgrowth of the PD program. First, during the PD program, teachers learned and practiced robotics-based science and math lessons. Second, during the PD program, they planned and prepared themselves on how to implement the robotics-based lessons in classroom settings of their school. Third, the PD program prepared teachers to teach the robotics-based lessons, which enabled us to perform the research study presented herein.

In prior studies, we have examined the effect of our PD program on participants' TPACK self-efficacy as well as differences in their self-efficacy across various TPACK domains [9,17]. Most prior research studies have considered overall TPACK self-efficacy assessment across multiple participants and multiple STEM lessons. Our present research differs from previous studies on TPACK in that it is not a "general" TPACK study. Specifically, our primary goal in this study was to formulate a method to improve individual teacher's performance. As a preliminary effort, out of the 20 teachers from our PD, we selected two teachers who showed enthusiasm and commitment to take part in this study. Throughout the PD program, as we interacted with and observed participants, we identified these two teachers as keenest in taking initiative and risk for improving their teaching ability. Thus, these two teachers were chosen for this preliminary study. Our future plans call for performing a study with a larger cohort of teachers to generalize our findings. The methods and results of this preliminary study with 2 teachers will guide our design, implementation, and analysis of such a larger study.

3. Lesson Description

Below we describe the lessons we considered to examine as part of this research. The description includes the content of the lessons and how the lessons were implemented in the actual classroom setting. We selected these 3 lessons for several reasons: (i) these lessons are very common in middle schools; (ii) these lessons were easy to classify according to their difficulty levels; (iii) these lessons offered a good combination of math and science topics; (iv) the project team and PD participants collectively identified these lessons to be pedagogically challenging if not taught with robotics; and (v) the classrooms and teachers participating in this study were deemed ready for these lessons. Of course, it is entirely feasible to conduct another such study with a different set of lessons meeting the aforementioned criteria.

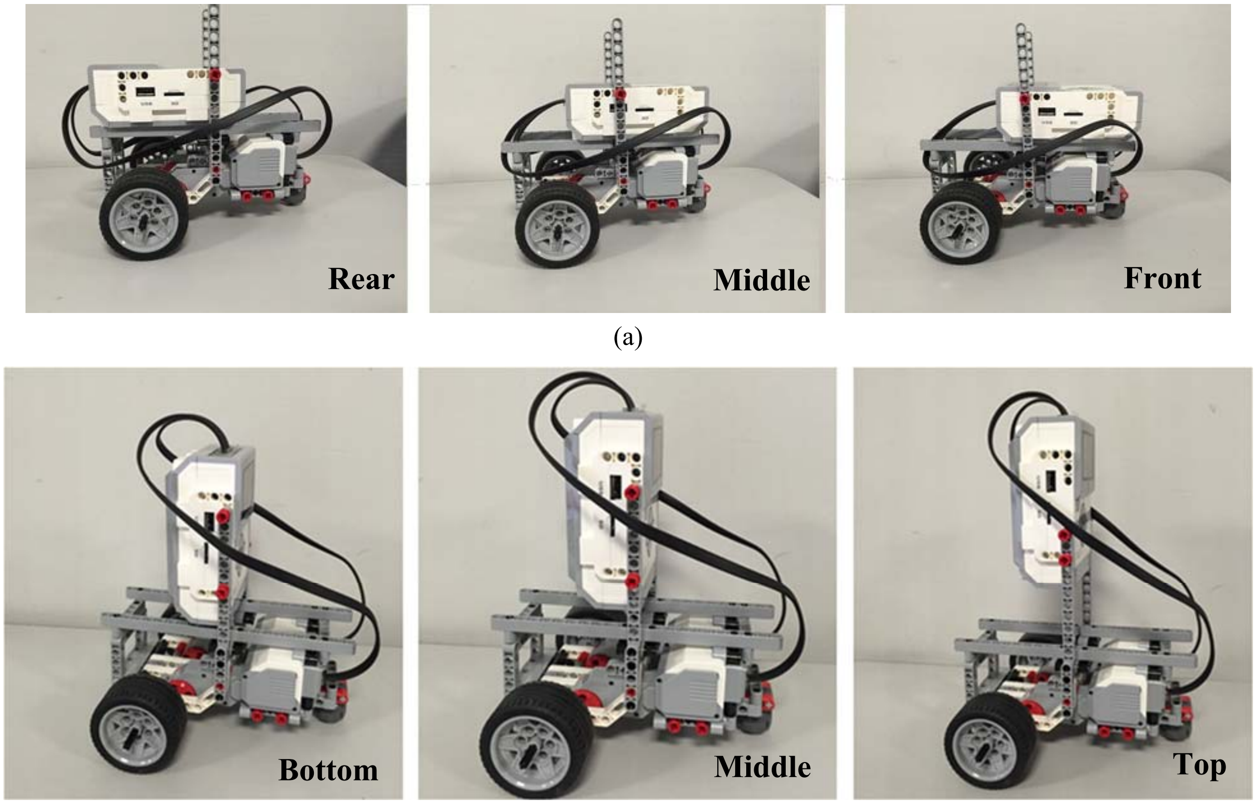
3.1. Number line: Students generally face difficulties in addition and subtraction especially involving negative numbers. Teachers noticed the lack of confidence in students solving such problems. Many students resorted to guessing. However, having students develop a solid understanding of the contents of this lesson is vital not just for building a sound foundation for further education but also in their daily life. Thus, a number line lesson with the help of robots was formulated to aid students understand this essential concept [13]. For this lesson, the mechanical design involved building a basic mobile robot. Students took a measuring tape and placed it on the floor in the classroom in a straight fashion. They marked the origin of the tape with a sticky paper and wrote –10 on it. Similarly, they attached a sticky note at 4 inches away from –10 and wrote –9. In this manner, they proceeded to the length of 80 inches on which they marked 10 with a sticky paper. In the corresponding LEGO robot program, one-unit distance was selected to correspond to 4 inches on the measuring tape. The origin (0) was at the center, i.e., at 40 inches from either end. Next, they loaded the program on the LEGO EV3 brick. This gave them the option of entering numbers into the program and they could do so by using the up and down arrow buttons of the EV3 brick. After that, they had to select a math operation (either addition or subtraction). Next, they could enter the second number in a similar fashion. Immediately after that, they placed the robot at 0 on the number line. Then, the robot would start to move and stop at the point corresponding to the answer of the math equation entered by the students. For example, input of 4 – 6 would make the robot stop at –2. Figure 2(a) shows a student implementing the lesson in the classroom.

(a) (b)

Figure 2: (a) The number line lesson and (b) LCM lesson being implemented with robots in classrooms.

3.2. LCM: The least common multiple (LCM) is another fundamental mathematical concept. In arithmetic and number theory, the least common multiple (i.e., lowest common multiple or smallest common multiple) of two integers a and b, usually denoted by LCM (a, b), is the smallest positive integer that is divisible by both a and b. Students who are taught in traditional manner find this very boring primarily because they fail to relate LCM to any practical situation. With this in mind, this lesson was designed. In several large urban, inner-city environments, students commute by mass-transit (e.g., metro, subway, light-rail, etc.) and practically all are aware of train stations. In this lesson, students applied the concept of LCM by analyzing a scenario involving two trains [18]. One train runs local and another one runs express. Two mobile LEGO robots were required for this lesson (see Figure 2(b)). Students took a meter tape and placed it on the classroom floor in a straight fashion. They marked the origin of the tape with a sticky paper and wrote 0 on it. Similarly, they attached a sticky note at 4 inches and wrote 1. In this manner, they proceeded till 80 inches where they marked 20. The LCM program was loaded on the two robots and the robots were placed at the starting position of 0. Each robot requested integer value as input by displaying 'Enter One Number' on its display screen. According to the program, if a student entered a value 3 in one robot and 5 in the other, the first robot stops at 3, 6, 9, 12, 15, and so on, and the second robot stops at 5, 10, 15, and so on. Using this example, students observed that both robots stopped at 15 in such a case.

3.3. Center of mass* (*CoM*)*: The primary objective of this lesson was to teach students about how mass and gravity act upon an object. In addition, students were also taught about movement of objects and laws of motion. In the first part of the experiment, the LEGO EV3 brick was placed horizontally on the robot structure in three different positions—front, middle, and rear—as shown in Figure 3(a). The robot was made to run on a ramp and distance travelled by the robot on the ramp was noted. In the next experiment, students changed the angle of inclination of the ramp and noted the respective observations. Then the robot was made to run downhill. In the next set of experiments, the brick was placed vertically at different heights—top, middle, and bottom—as shown in Figure 3(b). Based on the observations of this experiment, students understood that rigid bodies with wide bases and low centers of gravity are more stable and less likely to tip over as in case of high speed racing cars. Alternatively, rigid bodies with a narrow base and a high center of gravity, e.g., sport-utility vehicles (SUVs), are less stable and more likely to tip over when driven at high speed or making a sharp turn. Thus, racing cars are designed with wide bases and low heights. Figure 4 shows students implementing the lesson in the classroom.



(a)

(b)

Figure 3: The LEGO EV3 brick is placed on the robot structure (a) horizontally in the rear, middle, and front positions and (b) vertically in the bottom, middle, and top positions.

Figure 4: The center of mass lesson being implemented using robotics in a classroom.

The three illustrative lessons considered in this study address concepts regularly taught by middle school teachers who do not have opportunities to teach them using robotics. In such cases, lacking the involvement of robotics, these teachers adopt varied approaches to explain abstract concepts of these lessons to their students. Below, we provide several illustrative examples of alternative methods that we have previously observed in middle school science and math classrooms. First, to illustrate number line, teachers use the example of a hopping frog. They begin by drawing a number line on the board and then present a scenario where a frog jumps from one number to another number in positive or negative direction. Next, teachers explain the number line concept associated with addition and subtraction operations. Second, for explaining the LCM, teachers give an example of a racing competition where two runners have an opportunity to meet each other. In addition, teachers give the example of two passengers on two different trains meeting at the same station. Third, for the CoM lesson, teachers give the example of a ferry ride where all the passengers are in the front, back, or near the center of the ferry. The effect of such changes on the movement and stability of the ferry are also discussed.

Note, however, that the aforementioned approaches to illustrate abstract science and math concepts vary among teachers and school. Moreover, the above three example for explaining the math and science concepts without robotics have limitations. Specifically, these explanations are stories, they may or may not engage students, and they do not offer students to do something with their own hands to experientially learn something. Thus, in such a scenario, the underlying math or science concepts may or may not be understood properly and may give rise to misconceptions. In contrast, the robotics platform provides hands-on kinesthetic learning opportunities where students perform activities with their own hands, analyze data, share results, etc., all of which can enhance learning engagement and performance of students.

4. Research Description

In a classroom environment, we carried out several experiments and observations while teachers explained the lessons to students; students then implemented those lessons.

4.1. Classification of lessons: As stated above, difficulty levels of lessons vary, and this variation depends on several factors. We hypothesize that the variation in difficulty levels of lessons affects the TPACK self-efficacy. The perception of difficulty of lesson is subjective. We brainstormed with the teachers to categorize the selected math and science lessons into three categories based on their difficulty levels: (i) easy, (ii) difficult, and (iii) very difficult. Based on the input from two teachers and two facilitators we came to the conclusion that the number line lesson is easy, the lesson on LCM is difficult, and the CoM lesson is very difficult.

4.2. TPACK prerequisites: Using questionnaires, we identified the ideal requirements (prerequisites) of teachers' TPACK domains to effectively teach the selected lessons using robotics. We formulated the questionnaires by modifying a survey from [9] to meet the requirements of our research. We also determined the relative importance of the various domains of TPACK for each lesson. Some of the questions on the survey included: ‘What technological, pedagogical and content knowledge do you ideally require to plan and effectively teach this particular lesson using robotics?’ and ‘What is the relative importance (percentage) of the technological, pedagogical and content knowledge for planning and effectively teaching this particular lesson using robotics?’ Question like ‘… knowledge … to plan and effectively teach … using robotics?’ best answer what teachers perceive as the requirements for a particular domain of knowledge for a particular lesson. This offers opportunities to identify the different skills required for each lesson and teachers can work on the skills as part of their preparation before the class begins. This also gives opportunities to see how the requirements vary from one lesson to another, i.e., how diverse or similar these requirements can be.

4.3. TPACK self-efficacy: We also conducted a survey to assess the TPACK self-efficacy levels of the teachers for the robotics-aided lessons. We developed a survey by adapting the protocol of [5,9,19] to suit our study. In this survey, teachers rated themselves on a scale of 1 to 7 on questions that fell under four major categories, *viz.*, TK, CK, PK, and their intersections (PCK, TCK, TPK, and TPACK). For example, under TK, teachers responded to five items concerning the technical skills and problem-solving skills they have for the particular robotics-focused lesson; the easiness with which they can learn robot-related new technologies; technical skills other than robotics relevant to the lesson; and how up to date they are with technologies. Under CK, they similarly responded to six items about their discipline knowledge, thinking, and understanding of the lesson being taught. Under PK, the seven subcategories included performance assessment; teaching adaptation based on student’s understanding; teaching adaptation based on student’s interest and skills; diversity in learning assessment; familiarity with student misunderstanding; explaining with illustration; class management and organization; etc. For the intersection of knowledge domains, they responded to 11 items, including, effective science and math teaching; using robotics for science and math learning; adapting robotics to enhance teaching and learning; etc. We combined together the values of each of the subsections of TK—5 items, CK—6 items, PK—7 items, and intersecting domains (PCK—1 items, TCK—1 item, TPK—5 items, and TPACK—4 items) to obtain our results in Table 1.

4.4. Impact of robotics-based lesson on learning: We divided the students in the class into two groups, each handled by one teacher. Additionally, we explored the impact of robotics-aided education on student learning. To do so, we further divided the students in each teachers’ group into two groups. Each teacher taught three lessons to one group with the use of robotics and to the other group without using robotics. The latter group of students were taught the lessons in a traditional manner where the teacher used white board to explain the lessons. The students in this latter group did not design or program the robot. Like a traditional classroom environment, the students practiced some example problems in their notebook. For example, while teaching the lesson on number line in the traditional manner, to explain addition and subtraction, the teachers drew a number line on the white board and gave the example of a frog jumping from one point on the number line to the other. For teaching the LCM lesson, teachers verbally went over the lessons on factors and multiples. Next, they explained what common multiple meant and taught students to find the LCM of two numbers. Then they solved simple LCM problems on the white board and verbally explained the example of local and express trains to motivate the concept of LCM. This was followed by assigning LCM problems for students to solve in their notebooks. For the lesson on CoM, teachers explained how the distribution of weight on a truck will affect its balance while carrying the load uphill. We examined the performance of students using a content quiz based on the lessons. The questions for this quiz were created after consulting with the teachers. For our research, the performance of the students in each group was critical. The quiz questionnaires for the three lessons are given in Appendices A-C.

5. Results of the Experiments and Observations

Table 1 gives the TPACK self-efficacy scores of two teachers for the number line (easy), LCM (difficult), and CoM (very difficult) lessons, and the corresponding performance score of the four groups of students. Table 1 shows that there is direct relation between teachers' TPACK self-efficacy and student performance in quizzes for both sets of students for each lesson. Results indicate that the higher the teachers' TPACK self-efficacy score were, the more favorable the students' performance. In fact, when TPACK self-efficacy scores between the teachers differed greatly the more this was reflected in the normalized difference in scores of the quiz (student performance). Our classroom observations indicate that in the robotics-aided lessons teachers differentiated by engaging students with diverse learning styles differently, used different pedagogical approaches to enhance learning outcomes and classroom management, and addressed students' misconceptions. Teacher 2 carried out the aforementioned observations more successfully. We posit that this is because this teacher had more teaching experience and technical skills than Teacher 1. Although both teachers were motivated to improve their performance, and their self-efficacy was satisfactory; results confirmed that Teacher 2 had better TPACK self-efficacy.

Although we focused on two teachers for the purposes of this paper, we had 12 sets of data because we concentrated on three lessons with four groups of students. We treat these results as preliminary, which nonetheless are informative because the relationship between teacher self-efficacy and student performance for lessons of varying difficulties, although necessary, has not been examined in prior literature. These findings can guide in the design and performance of a full-scale study with larger number of teachers to produce generalized findings for supporting concrete instructional decisions.

Table 1: Self-efficacy of teachers and performance of students for the number line, LCM, and CoM lessons.

	TPACK self-efficacy score (weighted mean computation uses number of category items as weights)					Quiz results for lessons taught with robotics		Quiz results for lessons taught without robotics	
	TK mean	CK mean	PK mean	TK,CK,PK intersection weighted	Overall weighted mean	Mean	Std. dev.	Mean	Std. dev.
Number line lesson									
Teacher 1	3.4	5.17	5.71	4.55	4.76	8.4	4.03	4.5	1.29
Teacher 2	5.6	5.17	6.0	5.91	5.72	10.6	2.8	8.75	1.7
LCM lesson									
Teacher 1	4.2	4.83	4.57	4.82	4.66	8.6	1.9	5.6	4.09
Teacher 2	5.0	5.33	4.79	5.00	5.02	9.8	.83	6.5	1.64
CoM lesson									
Teacher 1	3.3	4.33	5.43	4.55	4.50	5.0	1.67	3.0	1.0
Teacher 2	4.6	4.83	5.86	4.73	5.00	5.5	0.54	3.6	1.21

Next, in Figure 5, for each of the three lessons we provide bar charts of differences in teachers' TPACK self-efficacy scores and normalized differences in students' test scores. From Figure 5, it is seen that for Lesson 1 there is a large difference in teachers' TPACK self-efficacy scores as well as a large normalized difference in students' test scores. However, for Lessons 2 and 3, the differences in teachers' TPACK self-efficacy scores are smaller as are the normalized differences in students' test scores. This shows that after Lesson 1, teachers' TPACK self-efficacy scores narrowed in Lessons 2 and 3 and correspondingly normalized difference in students' test scores also narrowed.

Table 2 gives the TPACK prerequisite values of the number line (easy), LCM (difficult), CoM (very difficult) lessons, and the corresponding score of the four groups of students. Technological, pedagogical, and content knowledge requirements vary from 20—50%, 20—40%, and 30—40%, respectively, of the total knowledge requirement for each teacher for lessons of various difficulty levels. It is evident from the TPACK prerequisite table that no conclusion can be drawn with respect to the quiz results because the prerequisite values vary and there is no concrete relation between these variations and quiz scores. So, we can say that our hypothesis is correct, i.e., the TPACK prerequisites vary from lesson to lesson and should not be treated as constant for an individual lesson or teacher. These values are individual perceptions and can be used for individual improvement. As previously, in this case, we had 12 sets of data because we concentrated on three lessons with four groups of students.

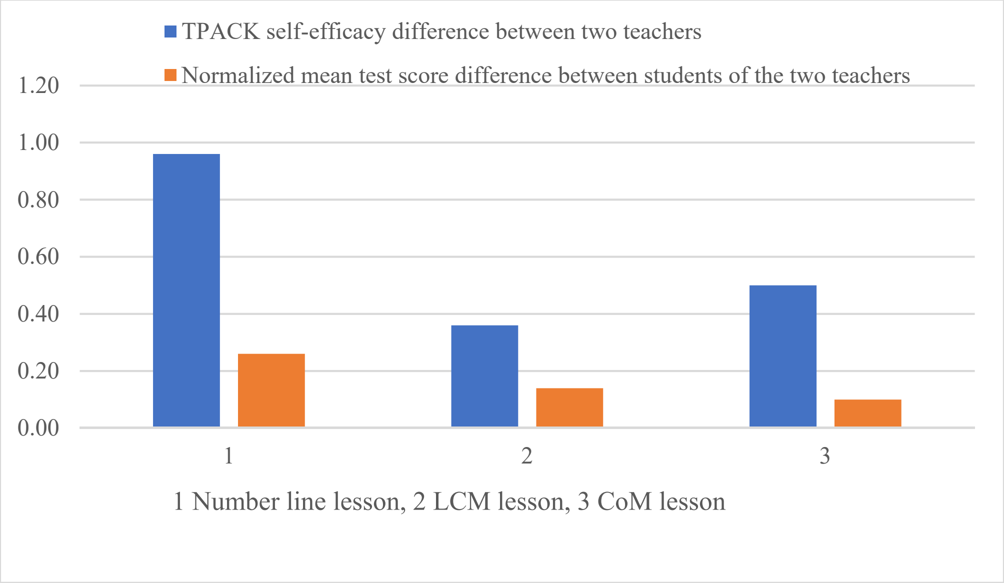


Figure 5: Bar graph showing the TPACK self-efficacy difference vs. student performance (normalized quiz score) difference.

From Table 1, we see that the quiz scores are better for the robotics-aided student group for all the lessons implemented and for both the teachers in the study. If, for the students of both the teachers, we compare the students who learned the lessons without robotics with the students who learned the lessons with robotics, we see that the robotics-focused student groups averaged 9.5 out of 20, 9.18 out of 11, 5.25 out of 8, while the non-robotics groups averaged 6.63 out of 20, 6.09 out of 11, 3.36 out of 8. These results indicate that the robot-aided lessons improved students' learning outcomes when compared to traditional lessons. For example, Table 3 illustrates students' overall improvement averages when exposed to robot-aided lessons ranged from 43—56%. Not only is there an increase in average values but also the lowest and the highest values show an increase. This increase in average values is depicted in the bar chart of Figure 6, from which we also note that for the most difficult lesson (CoM) students' improvement average was the highest at 56%. Next, we performed a *t*-test analysis of the data (learning outcomes in terms of quiz scores). The results of *t*-tests for quiz results between the groups learning the lessons without robotics and with robotics are shown in Table 4 for the three different lessons. For two out of three cases, the results obtained are significant at 95% significance level. To build additional support for robotics-based STEM lessons, one may compare students' performance with robotics-based lessons *versus* alternative, hands-on lessons that do not utilize robotics. However, this is beyond the scope of current paper and will be considered in a future study.

Table 2: TPACK prerequisite score of teachers and performance of students for the number line, LCM, and CoM lessons.

	TPACK prerequisite score			Quiz results for lessons taught with robotics		Quiz results for lessons taught without robotics	
	TK mean	CK mean	PK mean	Mean	Std. dev.	Mean	Std. dev.
Number line lesson							
Teacher 1	40	30	30	8.4	4.03	4.5	1.29
Teacher 2	20	40	40	10.6	2.8	8.75	1.7
LCM lesson							
Teacher 1	45	35	20	8.6	1.9	5.6	4.09
Teacher 2	35	35	30	9.8	.83	6.5	1.64
CoM lesson							
Teacher 1	50	30	20	5	1.6	3	1
Teacher 2	30	35	35	5.5	.54	3.6	1.21

Table 3: Quiz scores for lessons of various difficulty levels for robotics-aided vs. non robotics-aided student groups.

Lessons	Quiz score of students learning without robotics			Quiz score of students learning with robotics			
	Mean	Lowest	Highest	Mean	Lowest	Highest	% improvement in average
Number line (easy)	6.625	3	11	9.5	4	14	43
LCM (difficult)	6.09	2	10	9.18	6	11	50
CoM (very difficult)	3.36	3	5	5.25	3	7	56

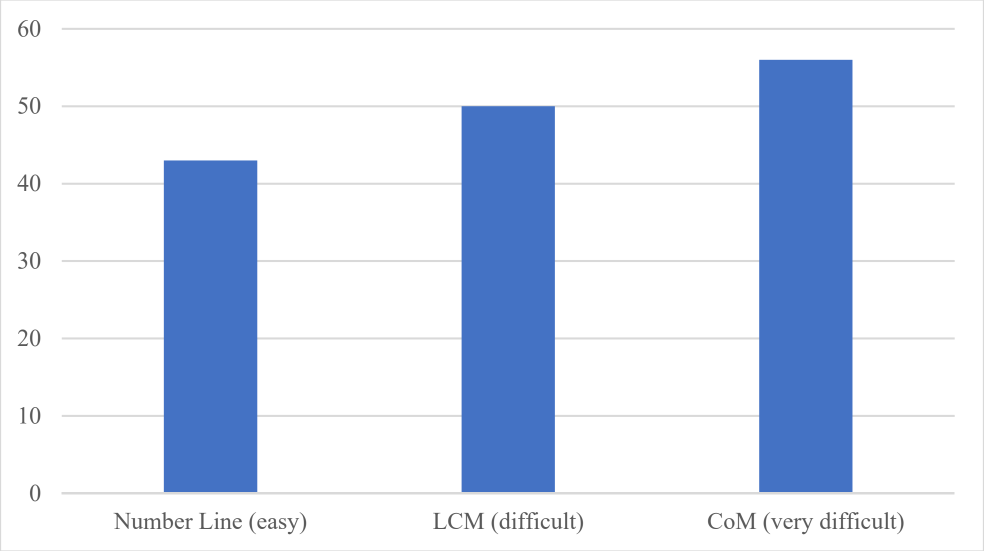


Figure 6: Percentage improvement in average quiz scores with robotics-aided lessons.

Table 4: Results of *t*-tests for quiz scores of robotics vs. non-robotics student groups.

Lesson	Domain	*p* value	Significance
Number line (easy)	Learning with robotics vs. without robotics	0.065766	No @ 95%
LCM (difficult)	Learning with robotics vs. without robotics	0.005698	Yes @ 95%
CoM (very difficult)	Learning with robotics vs. without robotics	0.000879	Yes @ 95%

During our classroom observations, we noted that students were more engaged, enthusiastic, and motivated to learn when they were taught robotics-aided lessons. For example, students were interacting with each other when they were building and programming their robots and asked numerous questions about the concepts. Alternatively, students who were taught the lessons in the non robotics-aided classroom paid less attention to the teachers' explanations of the concepts, did not interact, and exhibited behaviors of boredom.

6. Discussion

Through our experiments/classroom observations, we have observed encouraging preliminary results. Both TPACK self-efficacy and TPACK prerequisite values vary from lesson to lesson for individual teachers. We found that when a teacher's TPACK self-efficacy value is higher then her students' learning outcomes are also higher. We posit that the reason for this may be because teachers continually self-reflect on their own TPACK and their students' learning. That is, teachers' self-efficacy values reflect the confidence they have in their ability and motivation level, which in turn translates into the delivery of lessons and their students' learning outcome. The TPACK prerequisites did not show a clear trend. However, these values are individual perceptions. These values can be used for individual improvement. Specifically, teachers are expected to deliver robotics-aided STEM education to their students continuously for many years. This evaluation will help in the individual improvement of the teachers.

From quiz results, we determine that there is at least 40% improvement in student learning outcomes if robotics is used as a learning tool. This is because students were attracted to and enjoyed working with robots. Using robots and exposing students to real-life phenomenon improved their performance in tests and increased their STEM interest. We conclude that when robots are used in teaching, students understand lessons better and consequently pay more attention, which improves their performance on tests. Moreover, robots provide opportunities for kinesthetic learning, which has an effect on eliciting intrinsic motivation. Prior TPACK research results are quite general and possess limitations in particular situations (e.g., with regards to the development of an individual teacher or individual lessons). Based on the obtained results, individual teachers may be able to work on strengthening their TPACK for a particular lesson with a specific difficulty level to further enhance their robotics-aided lessons and to enhance student learning.

Unlike previous research on TPACK, this study does not examine TPACK in a general manner across multiplicity of teachers and lessons. Moreover, this work does not examine teachers' TPACK in the context of a PD program. Instead, we concentrated on two middle school teachers implementing robotics-based science and math lessons in an actual classroom environment during the academic year. Our goal was to gain an understanding of teachers' TPACK self-efficacy and its impact on their students learning outcome. Even though we focused on only two teachers we obtained 12 sets of data (for each the of TPACK prerequisite and TPACK self-efficacy). By limiting our attention to only two teachers, we had the benefit of devoting our resources to conduct an in-depth study, which can inform future research, including further development of curriculum and PD program. Moreover, having conducted this study, we now have a tested methodology that can be employed to conduct research with additional teachers and additional lessons.

From our classroom observations, we noticed that students were more engaged when they were taught using robots. We speculate that when students build robots and write programs for learning the fundamental science and math concepts, they have a greater understanding of those concepts. This is evidenced from the quiz performance of students who performed robotics-based learning activities. Alternative strategies for engaging students using hands-on learning may include using a push-cart for the number line lesson, stacking blocks of different thickness for LCM lesson, and constructing and analyzing tall or short structures for CoM lesson. However, such methods may fail to interest and excite today's students whose lives are enriched by and benefit from modern technologies [20]. Moreover, the aforementioned techniques may have limitations *vis-à-vis* opportunities for differentiation for students of varied interests or skills. Use of robotics-based science and math lesson also allows students to gain familiarity with advance technological tools, including robotics, programming software, etc. For all of these reasons, we recommend engaging students in STEM learning with robotics.

The results of this paper show that both teachers' TPACK self-efficacy and use of robotics are important factors in improving student performance. Since our sample size is small, we are not able to distinguish which factor between TPACK self-efficacy and use of robotics has greater effect on improving student performance. In each of six cases where students learned the lessons using robotics, quiz results showed that they exhibited higher learning outcomes *vis-à-vis* students who learned the lessons without robotics. Since the teachers originally received introduction to teaching science and math using robotics under our PD program, the PD effected student learning at least indirectly. These preliminary findings provide impetus for a larger study with greater number of teachers for further validation. The analysis results of this study are additionally important because in prior literature such analysis with lessons of varying difficulty has not been considered.

7. Conclusions and Future Work

We collaborated with and observed two teachers as they implemented three STEM lessons using robotics in middle school classrooms. We jointly categorized the lessons according to their difficulty levels. Through a PD program, teachers had been trained on developing and teaching robotics-based STEM lessons. We developed a method to assess teachers' TPACK self-efficacy levels. We also developed a method to understand the performance level of the participating students. Preliminary results show that teachers' TPACK self-efficacy levels and use of robotics impact student performance and learning outcomes. We believe that this type of focused study on TPACK is first of its kind. Further studies that investigate TPACK self-efficacy of teachers using robotics-aided lessons and its effects on student learning are needed to inform STEM teaching and learning. Having established the presented methodology, we can carry on the research with additional teachers and additional robotics-based STEM lessons. Such a study can further validate the preliminary results of this paper and help identify results that are generalizable. The robot platform used in this study was LEGO EV3 because our PD program utilized the same robot. Other robotics and technology platforms can have different impact on teachers' TPACK self-efficacy and students' learning outcomes and may be additional directions for future research. In future research, to gain an understanding of contributions of robotics in improving lesson outcomes, we will compare student performance for robotics-based lessons *versus* alternative, hands-on lessons that do not utilize robotics

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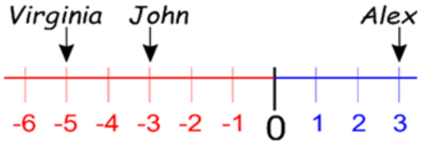
Appendix A: Number line quiz

Direction: Answer all questions

1. What do you mean by the number line?
2. How do you think the lesson on number line can help you in your life?
3. The temperature at noon on a winter day was 10^0 F. At midnight, the temperature had dropped by 15^0 F. What was the temperature at midnight?
4. Time in Moscow is 3 hours ahead of London and time in Portugal is 1 hour behind London. If time in Portugal is 4a.m., what is the time in London?
5. Amy bikes at 4 miles/hour. Carol bikes 2 miles/hour faster than Amy and Janet’s speed is 3miles/hour faster than Carol’s. What is Janet’s speed?
6. Let a = 5, b = –3, c = 4, and d = –2. Which of the following is the greatest? i) a × b, ii) b × c, iii) d × a, or iv) d × c.
7. From the number line below what is Virginia – Alex? What is Alex – John?



8. What is –9–8?
9. What is 0–8?
10. What is –7+5?
11. What is 1+3?
12. What is 9–8?
13. What is –9 – (8)?
14. What is (–9) –8?
15. What is – (–)9–8?
16. What is –9–2?
17. What is –9–(–8)?
18. What is 4–4?
19. What is –4×3–2×5?
20. What is 6×4+5(–5)?

Appendix B: Least common multiplier (LCM) quiz

Direction: Answer all questions

1. How do you think the lesson on LCM will help you in your life?
2. LCM of 6 and 8 is ___
3. 12 is the LCM of _________ (write two numbers)
4. The bell at a school rings at 10 min intervals. The bell at a university rings at 15 min intervals. Suppose both the bells rang at 10 am. When will they ring again at the same time?
5. 30 is the LCM of: A) 5 and 6, B) 4 and 5, or C) 6 and 8? Please tick the correct answer.
6. LCM of 27 and 36 is 108. Dividing 109 by 27 we get remainder of 1. Then what is the remainder when dividing 110 by 36?
7. There are 16 stations in a railway system. The station names are A, B, …, O, P. A local train starts at the station A and stops at every other station (A, C, E, …). An express train also starts at the station A and stops at every two stations (A, D, G, …). At which station do both the trains stop?
8. LCM of 3 and 4 is ___
9. LCM of 1 and 2 is ___
10. LCM of 5 and 4 is ___
11. 10 is the LCM of 2 and 5 and LCM of 1 and 10. A) True or B) False

Appendix C: Center of mass (CoM) quiz

Direction: Answer all questions

1. If diameter of a circle is 6 inch, the radius of the circle is _________ inch
2. If diameter of circle is 7 inch, the circumference of the circle is __________inch
3. If mass of a body is 60 kg and the gravity of earth is 10 m/s^2, the weight of the body is_____?
4. If the body in question 3 is taken to the moon where gravity is one-sixth that of earth, what is the weight of the body on moon _____?
5. Consider that the gear ratio between the drive motor and driven wheel of a robot can be changed. In such a case, which of the following robot moves fastest? Please tick the correct answer. A) a robot with gear ratio 1:3, B) a robot with gear ratio 3:1, or C) a robot with gear ratio 1:4.
6. Consider a force of 10 units is applied on a body from East and a force of 5 units is applied on the same body from West. Please tick the correct answer. A) the body stays still, B) the body moves towards East, C) the body moves towards West.
7. Consider a force of 10 units is applied on a body from East and a force of 10 units is applied on the same body from West. Please tick the correct answer. A) the body stays still, B) the body moves towards East, C) the body moves towards West.
8. The first robot has a mass of 10 units and the second robot has a mass of 5 units. Acceleration is same for both the robots. Please tick the correct answer. A) the same force is applied on both the robots, B) the force applied on the first robot is twice of that applied on the second robot, C) the force applied on the first robot is half of that applied on the second robot.