Exploring the Dynamic Nature of TPACK Framework in Teaching STEM Using Robotics in Middle School Classrooms

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1. Introduction

In recent years, many kinds of technologies, such as computer systems, internet-based applications, software tools, etc., have emerged as promising aids in the teaching and learning of disciplinary content in science, technology, engineering, and mathematics (STEM).[1,2] As technology permeates every facet of human activity, from workplace to leisure, it is increasingly being incorporated in the form of educational technology to promote effective pedagogy, which has fostered the development of a new conceptual framework termed as the technological-pedagogical-content-knowledge (TPACK).[2-4] The concept of TPACK reflects the status of technological, pedagogical, and content knowledge of educators.[3] Moreover, the intersection of the three constitutive knowledge domains of TPACK, *viz.*, technology, pedagogy, and content give rise to four additional knowledge domains, *viz.*, technological pedagogical knowledge, pedagogical content knowledge, technological content knowledge, and technological pedagogical content knowledge.[4]

It is believed that the application of TPACK framework can make its three core knowledge domains complementary to each other for rendering a teaching and learning environment more effective than what a single domain can do alone.[3,5] Therefore, educators who seek to exploit TPACK for becoming effective teachers need to have content knowledge of their discipline, pedagogical knowledge to effectively transfer their ideas to learners, and the knowledge to employ appropriate educational technologies for teaching and learning. With the TPACK framework, teachers can utilize technology as an effective pedagogical tool to help themselves create and deliver alternative, more readily accessible representations of disciplinary knowledge, foster active engagement and learning in the classroom, and scaffold student comprehension of pedagogically challenging content.[5] In fact, the TPACK framework is particularly amenable to help overcome the challenge of teaching content knowledge that is abstract in nature.[3] As evidenced above, the TPACK framework allows educators to use educational technologies to improve their teaching effectiveness, enhance learners' understanding of the content knowledge, and improve the overall learning outcomes.[3-5]

Recent research[5] has used the lens of TPACK to examine the effectiveness of using robotics technology as a pedagogical tool in STEM education. The use of robotics as an educational tool has been proven to enhance student engagement in STEM disciplines.[5,6] Robotics has been shown to stimulate excitement and encourage participation of students in the classroom. Moreover, robotics technology is amenable for application in the teaching and learning of a varied range of disciplinary content, e.g., language learning, computer science, engineering, medical sciences, etc.[7-11]A robotics-based instructional framework can help learners visualize and understand abstract content knowledge in a tangible and concrete manner, offer kinesthetic learning experiences, promote active learning, intrinsically and extrinsically motivate learners, and improve the overall learning environment and outcomes.[12,13] Not surprisingly, in recent years, application of robotics in STEM education has witnessed intense interest from educators, become an area of active research, and attracted significant efforts for incorporating robotics into STEM curricula.[14] Integration of robotics for teaching science and math under the TPACK framework has the potential to advance the technological components, yield rich pedagogical strategies, render novel and effective representations of disciplinary content, and thus produce a novel instantiation of the TPACK methodology.

Application of robotics in middle school STEM education is appropriate because, in middle school, children begin to make decisions about courses that are of importance for their future careers, and young women and minorities begin to lose interest in STEM studies.[15-19] Thus, it is critical that middle school teachers effectively engage their students in STEM disciplines. With the recent proliferation of robotics in K-12 environment, implications of robotics for STEM teaching and learning ought to be examined *systematically* under the TPACK framework since teachers not only need to know how to operate robotic devices but also how to incorporate them into effectively teaching their assigned curricula. Unfortunately, enhancement of STEM teaching and learning in middle schools using educational robotics under the TPACK framework has not received sufficient attention in education research.

Note that teachers' familiarity with and development of robotics focused TPACK is expected to be dynamic in nature with various factors and contexts impacting its evolution and efficacy. For example, the particular subject matter (e.g., science or math) may affect the requirements and relative importance of and interaction between the knowledge domains of the TPACK framework. Moreover, the awareness about, knowledge of, and exposure to the TPACK concept may vary among teachers. The middle school teachers may need to account for the pre-adolescent age and still developing maturity level of their students by adapting the TPACK framework to incorporate appropriate educational theories and constructs, such as anchored instruction,[20-22] cognitive apprenticeship,[23,24] intrinsic and extrinsic motivations,[25,26] problem-/project-based learning,[27,28] situated cognition,[29] situated learning,[30] etc. However, prior research has not devoted significant effort to explore the dynamic nature of TPACK for teaching STEM in robotics-focused classrooms. Furthermore, examination of the effectiveness of the TPACK framework and teachers' self-efficacy in TPACK in middle schools have not received much consideration yet.

In this paper, we explore the dynamic nature of TPACK for teaching STEM with robotics in middle school classrooms. We collaborate with 20 teachers in eight urban, inner-city schools and observe their teaching of robotics-focused STEM lessons under the TPACK framework. Using questionnaires, we identify the ideal requirements of teachers' TPACK to effectively teach STEM lessons using robotics. We also determine the relative importance of the various domains of TPACK. Next, using questionnaires and brainstorming, we identify the factors that may affect the requirements of the technological, pedagogical, and content knowledge and their relative importance. We investigate different strategies and awareness levels of TPACK in different schools. We develop an assessment method to assess the self-efficacy of the teachers to teach robotics-focused STEM lessons under TPACK. We analyze the reasons behind the deficits in the self-efficacy scores. We explore whether the TPACK self-efficacy of the teachers is influenced by STEM subjects. We provide recommendations to improve TPACK self-efficacy of teachers for their robotics-focused STEM teaching in middle schools.

We posit that this paper, which *i)* examines the teachers' understanding of TPACK construct and their TPACK self-efficacy, *ii)* documents and analyzes the results of such an investigation, and *iii)* provides the details of methodological processes employed, can support adoption and adaptations of TPACK in K-12 STEM education. The results are novel and fundamental that may contribute to expand the conceptual horizon of TPACK, develop and maintain a balanced TPACK for teaching STEM with robotics in middle schools, and also maintain appropriate self-efficacy levels of teachers, which may enhance the overall learning outcomes of the students.

The rest of the paper is organized as follows. Section 2 introduces the robots that the teachers use in the classrooms for STEM lessons. Section 3 introduces a few middle school STEM lessons (mainly math and science) that were developed for implementation using robotics in the selected schools. Section 4 introduces the research team, the teachers, and the schools. Section 5 explains the observation procedures for robotics-focused STEM lessons in classroom environment. Section 6 reports the observation results and analyses. Section 7 proposes a set of recommendation to improve the self-efficacy of TPACK among middle school teachers for robotics-focused STEM lessons. Section 8 presents a brief discussion on connecting the study of this paper to K-12 engineering education. Section 9 draws conclusions and highlights the future directions of this research.

2. The LEGO Robot

To implement various robotics-focused STEM lessons, we created a base robot, shown in Figure 1, using the LEGO Mindstorms EV3 robotics kit.[31] The robotics kit includes *i*) a programmable brick, which serves as the control center and power station for the robot, *ii*) two large motors, which render precise and powerful action by and motion of the robot under program control, *iii*) several sensors, including color, touch, ultrasonic, wheel rotation, and gyroscope, and *iv*) two wheels, miscellaneous gears, cables, buttons, an LCD screen, and various construction parts and accessories to build the robot structure. The LEGO kit was used for its relatively affordable cost and easy programming and the base robot of Figure 1 was used for its flexibility in assembly and configuration, easy operation, and suitability of its functions in explaining the middle school science and math content.

In summer 2016, the project team (consisting of engineering and education faculty, researchers, and graduate students) held a three week long professional development (PD) workshop at the NYU Tandon School of Engineering for ten pairs of science and math teachers from eight middle schools. During the PD workshop, using the LEGO kits, teachers learned myriad robot-related tasks, such as assembly, programming, actuation, motion planning, sensor integration, operations, and troubleshooting.

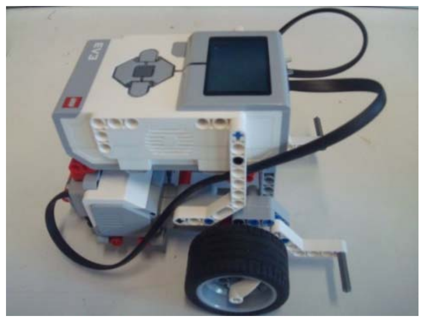

Figure1: LEGO Mindstorms EV3 base robot to be used for STEM lessons.

3. A Few Middle School STEM Lessons Developed to Implement Using Robotics

The project team and the PD workshop participants collaborated to plan and develop robotics-based lessons under the TPACK framework. Specifically, the teachers began by identifying middle school relevant science and math concepts that they deemed pedagogically challenging. For a subset of teacher identified topics, the project team and teachers collaboratively developed robotics-based teaching and learning strategies, hands-on activities, and corresponding assessment material, all of which were informed by and integrated relevant education research theories.[20-30] All lessons were planned to meet the state standards for middle school science and math, based on the Next Generation Science Standards (NGSS)[32] and the Common Core State Standards for Math (CCSSM).[33] Throughout the lesson development and implementation, the project personnel and teachers employed iterative changes to improve the lessons from the planning to implementation phase. Together, we conducted group discussions, brainstorming sessions, and co-generation meetings to adapt and modify the lessons. These summer PD activities endowed the teachers with agency to incorporate educational robotics technology in their lesson plans and redesign them based on their local environment and circumstances prior to the actual classroom implementation. While the project personnel observed the teachers' classroom implementation of robotics-focused science and math lessons to establish the fidelity of implementation, the teachers helped collect feedback from their students to further enhance the lesson content and pedagogy.

Several robotics-aided science and math lessons for different middle school grade levels have been designed. For example, the math lessons address topics such as number line, least common multiple, ratios and proportions, functions, analyzing and interpreting data, expressions and equations, statistics, etc. Similarly, the science lessons address topics such as displacement, velocity, acceleration, mass, force, gravity, friction, energy, environment, design optimization, biological adaptation, osmosis and diffusion, etc. Before implementing a lesson in the classroom setting with students, the teachers designed and constructed the base robot with needed attachments and sensors, created new or modified existing computer programs for the corresponding lessons, and developed the appropriate lesson activity sheets. During the actual class period, the teachers guided their students to build the robot and implement the lesson's activities using the robots and the students recorded the observations in activity sheets. Table 1 provides a brief overview of a representative science lesson.

Table 1: Description of a representative science lesson.

Lesson topic	Lesson description
Diffusion and osmosis[34,35]	The teacher briefly explains the basic concepts of diffusion and osmosis. The objective of the lesson is for students to learn and understand the concept of diffusion and osmosis using the movement of robots. In a classroom, a few objects are kept in a row. The room space is considered as a cell, and the objects are considered as molecules. The robot, equipped with an ultrasonic sensor, is also considered as a molecule and it is programmed so that it travels along the objects in row and counts each object. If more than a specified number of objects is counted, the robot turns around and moves past a tape, which represents the cell boundary, indicating that a molecule (robot) has migrated for the cell to achieve equilibrium. Figure 2 illustrates the classroom setup. The students perform hands-on activities, record the observation using activity sheets, and analyze the findings. The teachers explain the rationale behind the observed phenomena. The students learn the concepts of diffusion and osmosis. The outcomes of the lesson are assessed by the teacher.

4. The Research Team, the Teachers, and the Schools

Statistics of the researchers, teachers and students who participated in the robotics-focused science and math lessons are given in Table 2.

5. The Observation Procedures for Robotics-Focused STEM Lessons in Classroom Environment

Each science and math teacher randomly selected robotics-aided science or math lessons from the list of lessons introduced in Section 3 and implemented them individually in his/her classrooms. The project personnel (researchers) visited the classrooms and observed the teachers and students performing the robotics-based science or math lessons. Thus, we (the researchers) confirm that the teachers have experience of implementing at least one science or math lesson using robotics in a classroom setting in middle schools. Next, we asked the teachers to anonymously respond to a TPACK related questionnaires (see Appendix A) and a TPACK self-efficacy survey (see Appendix B). So far, a total of nine science and eight math teachers have responded to the instrument of Appendix A and eight science and eight math teachers have responded to the instrument of Appendix B.

We adopted the following working hypothesis for examination in this study.

Hypothesis: There are significant differences in the *i)* requirements of technological, pedagogical, and content knowledge perceived by teachers; *ii)* relative importance of technological, pedagogical, and content knowledge perceived by teachers; *iii)* factors affecting the requirements and relative importance of technological, pedagogical, and content knowledge perceived by teachers; and *iv)* teachers' TPACK self-efficacy levels between themselves and between teaching science and math lessons using robotics in middle schools.

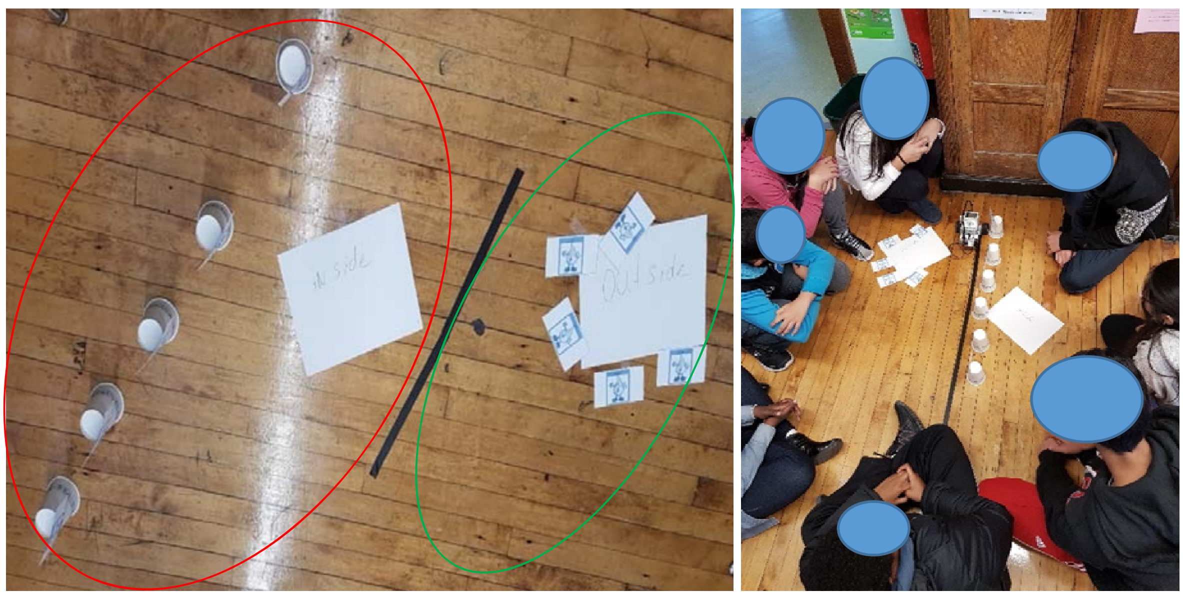

Figure 2: At the left, the cell with molecules (objects). At the right, the classroom environment where the robot moves along the row of the objects, counts the number of the objects and goes away (migrates) for equilibrium to be reached (more objects are identified than the specified number of objects).

Table 2: Statistics of the researcher, teacher, and student participants in the robotics-focused lessons.

Number of researchers	9
Number of all teachers	20
Number of science teachers	10
Number of math teachers	10
Number of male teachers	5
Number of female teachers	15
Number of different middle schools	8
Total number of students who attended science and math lessons using robotics	270
Number of male (boy) students	131
Number of female (girl) students	139
Number of students attended math lessons	166
Number of students attended science lessons	104
Student grade levels	6^{th} to 8^{th}
Usual length of a lesson	45 min.
Number of students in a class	10-25

6. Observation Results and Analyses

Based on the responses to Q3 in Appendix A, we analyzed the requirements of technological, pedagogical, and content knowledge perceived by the teachers to plan and effectively teach the math and science lessons using robotics. The results are given in Table 3. One teacher might perceive multiple requirements for a particular domain of knowledge. The digits inside parentheses in Table 3 indicate the frequencies of the perceived requirements proposed by the teachers for the technological, pedagogical, and content knowledge to plan and effectively teach the math and science lessons using robotics. We see that the requirements identified are quite diverse and there are differences and similarities between science and math lessons as perceived by the teachers. For teaching both science and math lessons using robotics, teachers identified the following as the most important requirements *i)* for technological knowledge items such as: ability to program robots, ability to troubleshoot robot program, ability to use robot, etc.; *ii)* for pedagogical knowledge items such as: skill to differentiate between students, skill to provide scaffolds, and ability to make productive teams of students, etc.; and *iii)* for content knowledge items such as: knowledge of the curriculum for specific grades.

Based on the responses to Q4 of Appendix A, we analyzed the relative importance of the technological, pedagogical, and content knowledge perceived by the teachers for planning and

Table 3: Requirements of technological, pedagogical, and content knowledge as perceived by the teachers to plan and effectively teach the math and science lessons using robotics.

Knowledge requirement	Subject	
	Mathematics	Science
Technological knowledge	Basic knowledge of how to use base robot (2); ability to download the robot software (1); ability to program the robot or having the programming skills (2); ability to load, run and troubleshoot the program (2); knowledge of using sensors effectively within the program (1)	Use of smart board (1); use of clickers (1); basic knowledge of how to use base robot (1); effective lesson delivering technology (1); base robot programming skills (3); base robot building skills (2); base robot troubleshooting skills (2); data uploading skills to and from the robot (1); ability to take good picture of robot activities (1); ability to design appropriate work activity sheets (1); ability to analyze and communicate the findings of the activity sheets (1); ability to explain using power point slides (3)
Pedagogical knowledge	How to scaffold lessons (1), skills of differentiation between students (1); delivery method (1), teaching practice (1); keeping students engaged in the robotics lesson (1); making students to be observant (1); ability to ask questions to students (1); ability to teach many students using a single piece of robot or teaching strategies under resource constraints (1)	Scaffolding of topics (2); skills of differentiation between students (4); assessment technique (1), teaching practice (1); classroom management (1); productive student grouping ability (2); ability to deliver lecture for extended time (1); ability to change in teaching style (1); skills of dealing with students' mistakes (1); skills of dealing with equipment disasters (1)
Content knowledge	Math curriculum for the specific grade (3); updates of current math curriculum (1); ability to relate math concept with robotics activities (1); basic calculation skills (1); knowledge of linear equation (1)	Knowledge of biology fundamentals (1); college level knowledge of content (1); updates of current science curriculum (1); knowing the subject matter where students usually struggle (1); knowledge of current science curriculum (1); state exam requirements in science (1); lab skills (1); knowledge of middle school standards (1); knowledge of potential and kinetic energy (1); knowledge of measurement scales (1); knowledge of energy and energy transfer (1); knowledge of gear mechanism (1)

effectively teaching the lessons using robotics. Figures 3 and 4 show the results for the math and science lessons, respectively. The results show that there are significant variations in the importance of the technological, pedagogical, and content knowledge perceived by the teachers for planning and effectively teaching math and science lessons using robotics. The technological knowledge (TK) is perceived as the most important knowledge domain for teaching both the math and science lessons using robotics. We posit that the use of robots in the lessons imposes additional responsibilities on the teachers to know robot building, programming, sensor integration, and troubleshooting, which may increase the perceived importance of knowledge about these areas for successfully teaching lessons using robotics. The content knowledge (CK) is perceived as the second most important knowledge domain for teaching both the math and science lessons using robotics. The pedagogical knowledge (PK) is perceived as the least important knowledge domain for teaching both the math and science lessons using robotics. We posit that as the robot helped the teachers teach the content matter easily, it may have affected their perception of the necessity for pedagogical knowledge. Nonetheless, we believe that effective integration of educational robotics in science and math teaching necessitates reliance on a rich array of relevant pedagogical techniques.[20-30]

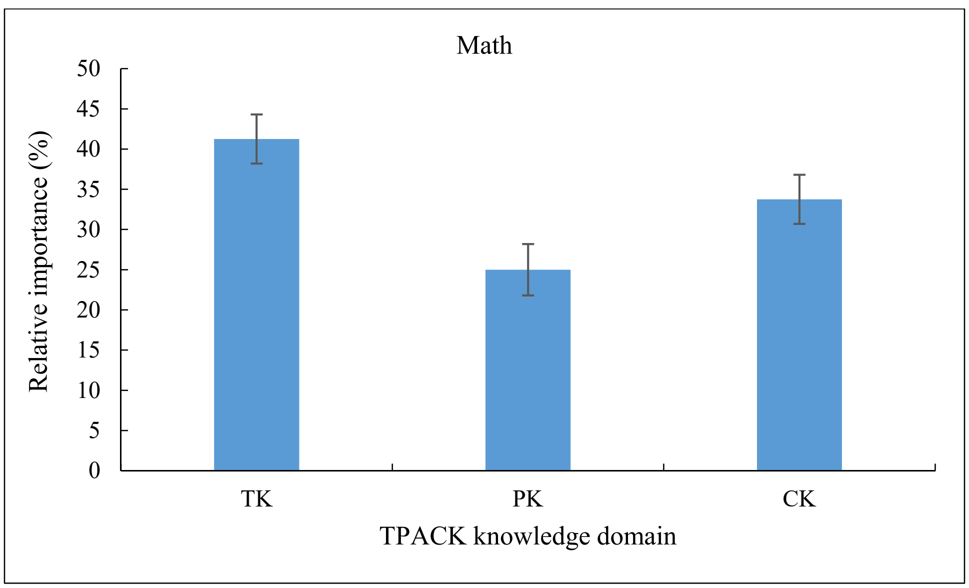

Figure 3: Mean relative importance of the technological, pedagogical and content knowledge perceived by the teachers for planning and effectively teaching the math lessons using robotics. Error bars denote the 95% confidence interval.

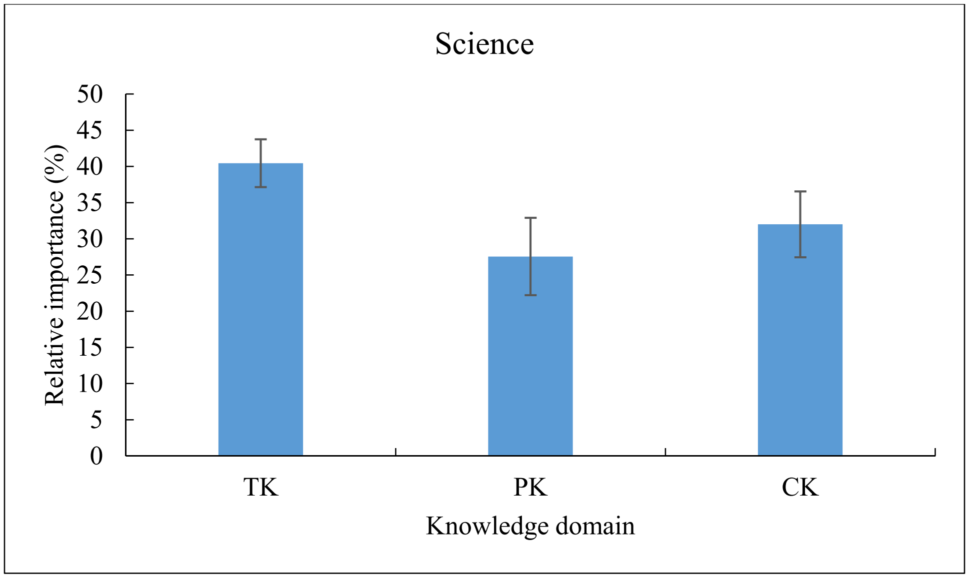

Figure 4: Mean relative importance of the technological, pedagogical and content knowledge perceived by the teachers for planning and effectively teaching the science lessons using robotics. Error bars denote the 95% confidence interval.

Using the responses to Q4 of Appendix A, we performed statistical analyses to determine any differences in respondents' perceived relative importance among the TK, CK, and PK domains for the science and math lessons. Table 4 shows the results of corresponding paired *t* tests. Moreover, the results in Figures 3 and 4 include 95% confidence interval for each bar chart. These results (i.e., Figures 3 and 4 and Table 4) illustrate that there are statistically significant differences in all cases except between the PK and CK domain for science. Moreover, using the *t* tests, we obtained $t(15)=0.3580$, $p=0.7254$ for TK between math and science lessons, $t(15)=0.8114$, $p=0.4298$ for PK between math and science lessons, and $t(15)=0.6330$, $p=0.5362$ for CK between math and science lessons. This indicates that there is no statistically significant difference between the math versus science teachers concerning their perceived relative importance for the three core knowledge domains TK, PK, and CK of the TPACK framework.

Table 4: Results of paired *t*-tests for variations in respondents' perceived relative importance among the TK, CK, and PK domains for the science and math lessons.

Subject	Domain	*n*	*t* calculated	*p* value	Significance
Math	TK v/s PK	8	5.8138	0.0006	Yes
	CK v/s PK	8	3.1305	0.0166	Yes
	TK v/s CK	8	2.8062	0.0263	Yes
Science	TK v/s PK	9	3.4920	0.0082	Yes
	CK v/s PK	9	0.9829	0.3545	No
	TK v/s CK	9	2.9645	0.0180	Yes

Based on the responses to Q5 of Appendix A, we analyzed the factors that may affect the requirements and relative importance of the technological, pedagogical, and content knowledge as perceived by the teachers for effectively teaching the math and science lessons using robotics. The results are shown in Table 5. We see that the factors affecting the knowledge requirements are diverse and there are differences and similarities between science and math lessons as perceived by teachers. The teaching period or amount of interaction time with students is the most influential factor affecting the requirements and relative importance of the technological, pedagogical, and content knowledge for effectively teaching the math and science lessons using robotics. Other influential factors are student age or grade, subject matter of the lesson, student population in class, student habit, and students' prior knowledge for math and science lessons.

Based on the responses to Q6 of Appendix A, we attempted to determine whether the teachers and/or their schools adopted any policy/strategy/program to uphold their technological, pedagogical, and content knowledge for effectively teaching the lessons using robotics. Out of the 20 teachers, 8 teachers did not respond this question. Out of the 12 teachers who responded to this questions, 10 reported that they and/or their schools adopted policies/strategies/programs to uphold their technological, pedagogical, and content knowledge for effectively teaching the lessons using robotics, and 2 teachers reported that they did not have such policy. Hence, based on the response sample, we find that 83.33% of the teachers and/or their schools adopted policies/strategies/programs regarding the implementation of the TPACK framework, which further indicates the levels of awareness of TPACK framework in the middle schools. Table 6 lists the specific policies/strategies/programs included in teachers' responses. The digits inside parentheses in Table 5 indicate the frequencies of the policies reported by the teachers. The results in Table 5 show that both the teachers individually and their schools adopted to uphold their technological, pedagogical, and content knowledge for effectively teaching the lessons using robotics. For the individual policies, we see that self-study and group study are the two major strategies to uphold TPACK by the teachers. On the other hand, from the school's perspective, arranging PD workshops, considering TPACK in yearly evaluation of the teachers, and providing encouragement to the teachers are the major strategies to uphold the TPACK framework in the schools.

Based on the responses to Q7 of Appendix A, we attempted to determine, using a 7-point Likert scale, whether the teachers were satisfied/happy with the policies/strategies/programs (i.e., whether those were adequate) adopted by themselves and/or their schools to uphold their technological, pedagogical, and content knowledge for effectively teaching the lessons using robotics. The results in Figure 5 show that the teachers are slightly satisfied with the existing policies and programs. An ANOVA test for the satisfaction levels with existing TPACK policies between the math and science teachers yields p=0.8304, i.e. p>0.05, which indicates that there are no statistically significant differences in the satisfaction levels with existing TPACK policies between the math and science teachers.

Table 5: The factors that may affect the requirements and relative importance of the technological, pedagogical, and content knowledge perceived by the teachers for effectively teaching the math and science lessons using robotics.

Factors for teaching mathematics	Factors for teaching science
Student age or grade (2); subject matter of the lesson or content knowledge (2); teaching period or amount of interaction time with students (3); student population (1); student habit (1); curriculum requirements (1); students' prior knowledge (1); base line (1); school atmosphere (1); fault in teaching technique (1); existence of high risk complex learners with multiple disabilities (1); aligning the math topics with robotics activities (1); level of students' understanding of how to work collaboratively (1); students' behavior (1); students' interest in robotics (1)	Student age or grade (2); subject matter of the lesson (2); teaching period (6); student population (2); student habit (2); students' prior knowledge (2); base line (1); necessity of programming (1); availability of technology (1); curriculum requirements (2); maturity level of students (1); level of cooperation among students (1); subject matter (1); materials to purchase and build (1)

Table 6: The specific policies/strategies/programs adopted by the teachers and/or their schools to uphold their technological, pedagogical and content knowledge for effectively teaching the lessons using robotics

Teachers' own policy/strategy/program	Policy/strategy/program of the schools
Self-study (2); group study (2); attending professional development training (1); self-practice for lab skills (1); self-collaborations with external organizations (1); self-collaborations and relationships with robotics experts (1); self-research on how to introduce robotics (introductory lessons) to the students as a technological component (1); self-brainstorming to find out the lessons aligned to the curriculum that can be taught using robotics (1); reflecting TPACK concepts when developing activity sheets (1)	Arranging professional development workshop (4); considering TPACK in yearly evaluation of the teachers (2); encouragement from school management (2); periodical assessment by school management (1); creating a TPACK atmosphere (1); providing experienced educators and mentors with less experienced teachers (1); allowing differentiation (1); two teachers in a single classroom for complementary supports (1)

Based on the responses to Q8 of Appendix A, we attempted to determine the constraints encountered by the teachers and schools when teaching robotics-based lessons under the TPACK framework. The major constraints reported by the teachers are summarized below (the digits inside parentheses indicate the frequencies of the constraints reported by the teachers).

- Time limitation of teachers in daily activities (8)
- Short class period (8)
- Huge differences in students and lesson topics (2)
- Lack of technological resources such as robots, computers, iPads (5)
- Lack of consistent efforts by the teachers and schools (2)
- Lack of support and interest from school management (2)
- Different topics need different technological knowledge (1)
- Lack of knowledge of how to select appropriate technological components (1)

- Absence of the framework from the beginning (1)
- Curriculum does not easily align to use robotics throughout the entire year (1)
- Lack of interest of the students in technological components (1)
- Difficulty in deciding how to use robotics to teach specific science content (1)
- Lack of suitable classrooms and lab facilities to implement technology-based lessons (1)

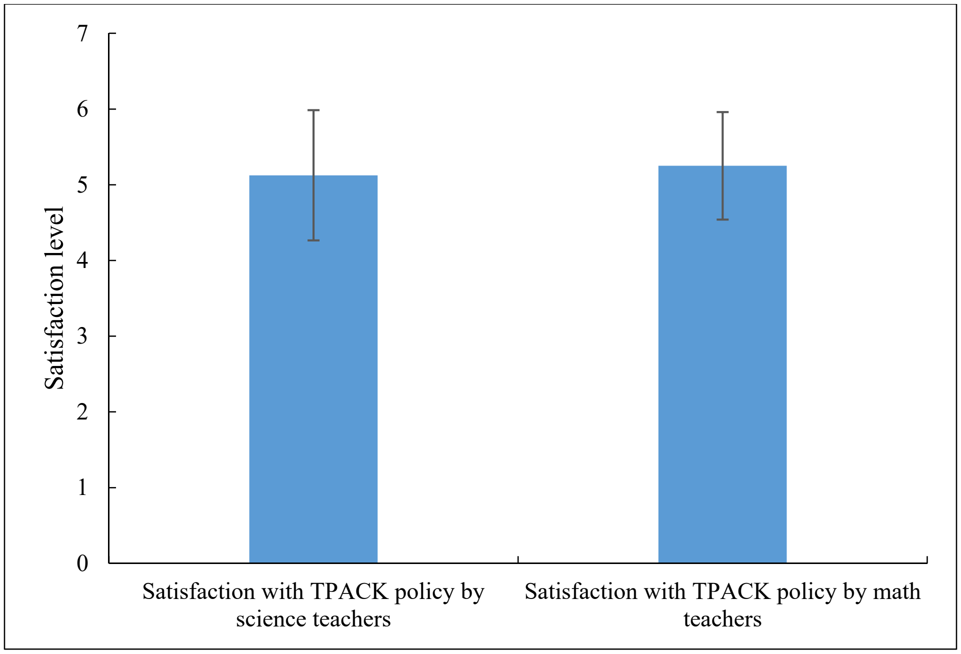

Figure 5: Level of satisfaction of the teachers with the policies/strategies/programs (i.e., whether those were adequate) adopted by themselves and/or their schools to uphold their technological, pedagogical and content knowledge for effectively teaching the lessons using robotics. Error bars denote the 95% confidence interval.

The results show that limitation of time of the teachers in their daily activities, short class duration, and lack of technological resources such as robots, computer, iPads, etc. are the major constraints for teaching robotics-based lessons under TPACK framework.

The aforementioned results from the analyses of responses to the survey in Appendix A show that there are significant differences in the requirements of technological, pedagogical, and content knowledge, and their relative importance perceived by teachers as well as the factors affecting the requirements and relative importance of technological, pedagogical and content knowledge perceived by teachers. The results thus support the working Hypothesis of this paper.

Next, we analyze the teachers' response to the TPACK self-efficacy survey of Appendix B. First, based on the responses to the TK related questions of Appendix B, we determine the mean self-efficacy scores, on a 7-point Likert scale, for the science and math teachers for different TK evaluation criteria. The results in Figure 6 show that the self-efficacy for the TK is not sufficiently high for both math and science teachers. The teachers' short experience in teaching using educational technology, such as robotics, may be the reason for their low self-efficacy in the TK domain. Second, based on the responses to the CK related questions of Appendix B, we determine the mean self-efficacy scores for the science and math teachers for different CK evaluation criteria. The results in Figure 7 show that the self-efficacy for the CK is higher than that for the TK scores for both math and science teachers. The teachers' long experience in teaching disciplinary content can be ascribed as the reasons for their comparatively better self-efficacy in the CK domain. Third, based on the responses to the PK related questions of Appendix B, we determine the mean self-efficacy scores for the science and math teachers for different PK evaluation criteria. The results in Figure 8 show that the self-efficacy of both math and science teachers is high for PK, although the scores are lower in comparison to those for their CK scores. The teachers' long experience in teaching may be the reason for their comparatively better self-efficacy in the PK domain. However, the teachers were new in using technological components such as the robots in the classrooms. Thus, the teachers were less accustomed to respond to the challenges of the technological components and they were not able to determine appropriate pedagogical strategies in this technology-rich environment. This may be the reasons for their PK scores to be not as high as those for their CK scores. Fourth, based on the responses to the TPACK related questions of Appendix B, we determine the mean self-efficacy scores for the science and math teachers for the four TPACK evaluation criteria. The results in Figure 9 show that the teachers' self-efficacy for TPACK is not sufficiently high. The teachers' prior teaching experience may yield comparatively

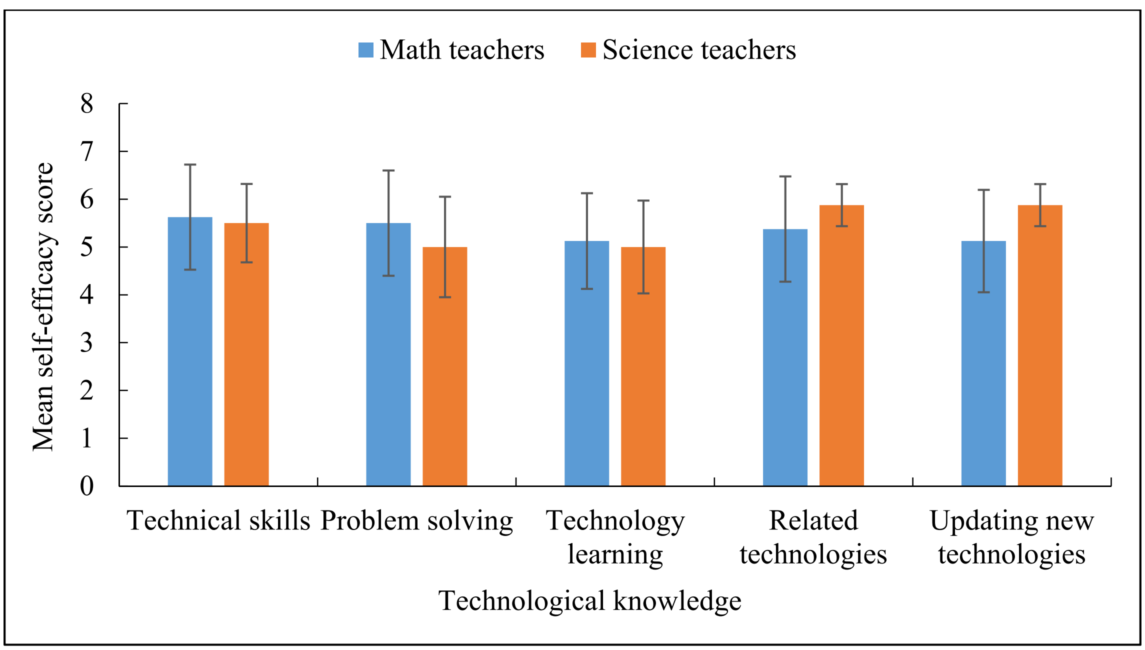

Figure 6: Mean self-efficacy scores for the science and math teachers for different TK evaluation criteria. Error bars denote the 95% confidence interval.

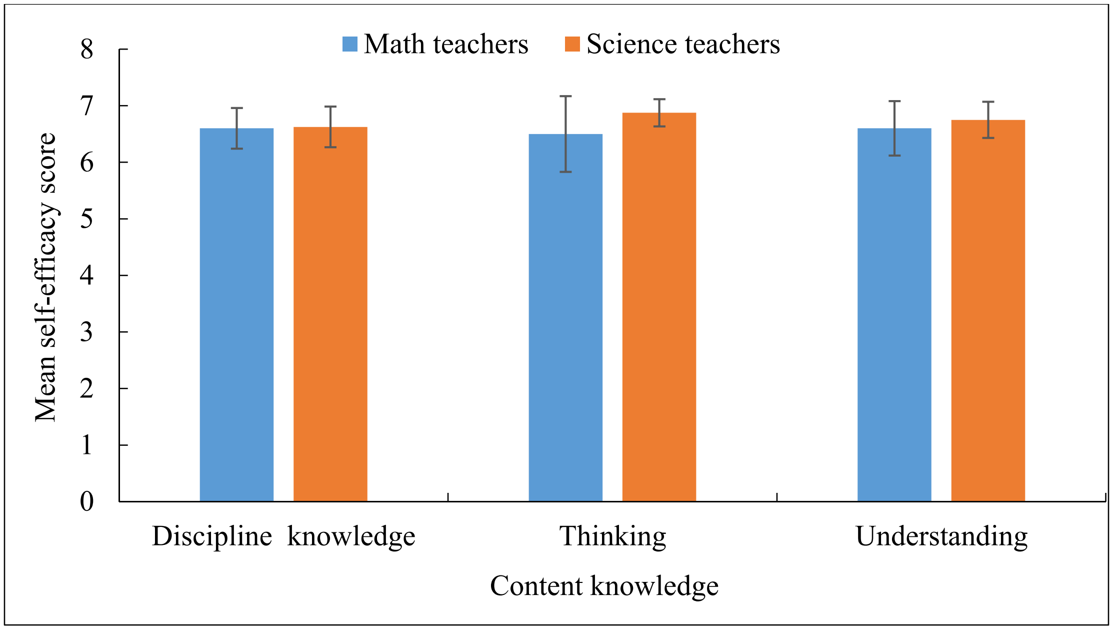

Figure 7: Mean self-efficacy scores for the science and math teachers for different CK evaluation criteria. Error bars denote the 95% confidence interval.

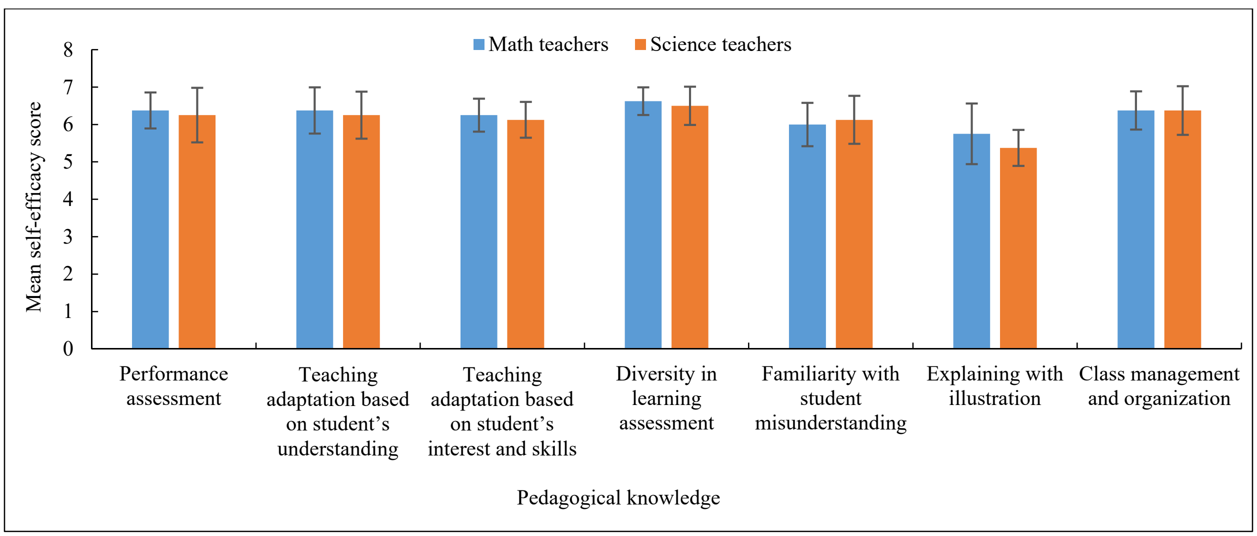

Figure 8: Mean self-efficacy scores for the science and math teachers for different PK evaluation criteria. Error bars denote the 95% confidence interval.

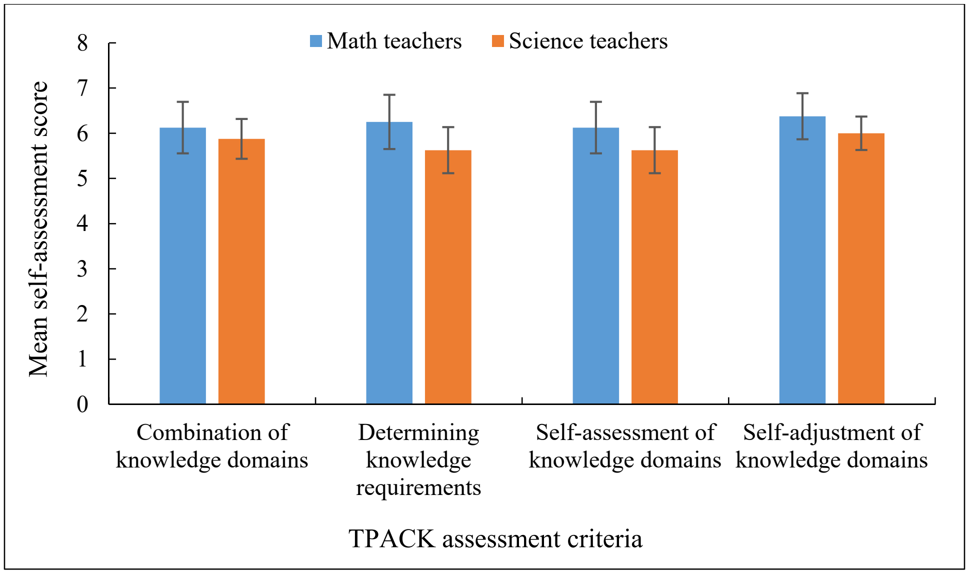

Figure 9: Mean self-efficacy scores for the science and math teachers for different TPACK evaluation criteria. Error bars denote the 95% confidence interval.

better self-efficacy in the CK domain. However, with the introduction of educational robotics technology in the classroom, teachers may not have been able to fully realize its potential and may have faced challenges in determining appropriate pedagogical strategies. This may justify their lower self- efficacy in PK components *vis-à-vis* the CK component. Moreover, as previously seen, the CK is high (Figure 7), PK is slightly low (Figure 8), and TK is the lowest (Figure 6).

Finally, to identify if there are any statistically significant differences among the seven components of the TPACK construct, statistical analyses of the self-efficacy survey responses were performed. In doing these analyses, for each teacher, his/her responses were coded using the average response for questions within each of the seven domains of the TPACK. Figure 10 provides the averages of responses by all 16 teachers, for each of the seven domains of the TPACK, where the error bars represent the 95% confidence interval. As evidenced from Figure 10, and as seen from the analyses in Table 7, for the 16 respondents, from amongst the 21 distinct pairs of TPACK domains, there are statistically significant differences for 10 pairs. According to paired *t*-tests, for science teachers, there were statistically significant differences for 8 pairs from amongst the 21 distinct pairs of TPACK domains. Finally, according to paired *t*-tests, for math teachers, there were no statistically significant differences for any pair from amongst the 21 distinct pairs of TPACK domains. The details of these paired *t*-tests by subject area are omitted. The aforementioned results from the analyses of responses to the survey in Appendix B show that there are significant differences between some TPACK domains in teachers' self-efficacy. Finally, for each of the seven TPACK domains, no statistically significant differences were found between the science and math teachers. Thus, the results support the working Hypothesis of this paper, partially.

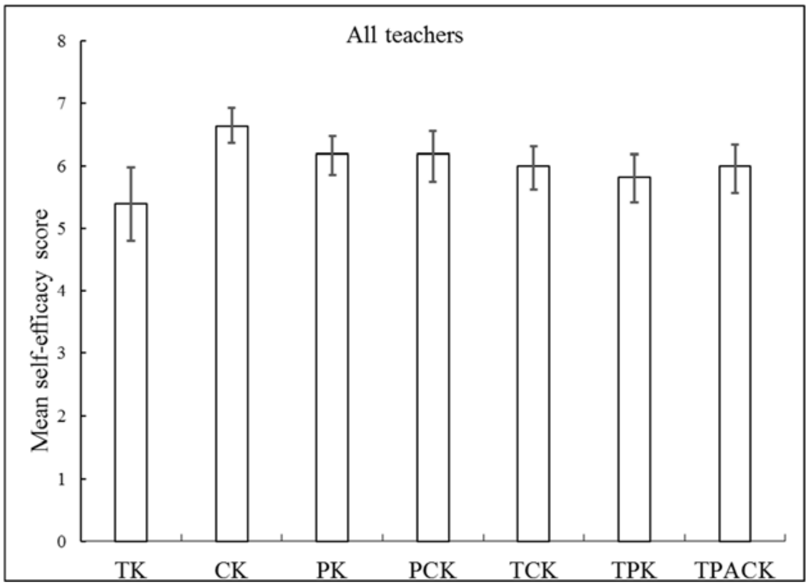

Figure 10: Mean self-efficacy scores for the cohort of 16 teachers for each TPACK domain. Error bars represent the 95% confidence interval.

Table 7: Results of paired *t*-tests for 16 respondents' self-efficacy for various domains of TPACK.

Domain	***t*(15)**	***p* value**
CK v/s TK	3.3523	0.0044
PK v/s TK	2.8207	0.0129
PCK v/s TK	2.3872	0.0306
TCK v/s TK	2.7676	0.0144
CK v/s PK	2.3569	0.0324
CK v/s TCK	2.4747	0.0258
CK v/s TPK	3.1926	0.0061
CK v/s TPACK	2.4647	0.0263
PK v/s TPK	2.5093	0.0243
PCK v/s TPK	2.3204	0.0348

7. Scope to Improve Self-Efficacy of TPACK among Middle School Teachers for Robotics-Focused STEM Lessons

Based on the results in Table 5 and the responses to Q8 of Appendix A, we see the broad scope to improve self-efficacy of TPACK among middle school teachers for robotics-focused STEM lessons, as follows.

7.1. Scope for the teachers

- The teachers should manage their time in their daily activities and schedule some time to prepare for the TPACK framework.
- The teachers should plan their lessons for a single class period.
- The teachers should receive training on managing differences and diversity in students' academic preparation and lesson topics.
- The teachers should be able to raise funds through their schools, school districts, online philanthropic sources, etc., to acquire robots, computers, iPads, etc.
- The teachers should apply consistent efforts to excel in the TPACK framework.
- The teachers should learn and practice to select appropriate technological components for varied situations.
- The teacher should investigate how to align the curriculum to use robotics, periodically, throughout the entire year.
- The teachers should engender interest in the students about technologies.
- The teachers should be familiar and experienced with the robotics kits prior to using it for planning and conducting robotics-based lessons.
- The teachers should engage in self-study and form learning communities for group study.
- The teachers should periodically participate in professional development on TPACK.
- The teachers should conduct self-practice for lab skills.
- The teachers should increase self-collaborations with external organizations, self-collaborations and relationships with robotics experts, self-research on how to introduce robotics (introductory lessons) to the students as a technological component, self-brainstorming to find out the lessons aligned to the curriculum that can be taught using robotics, and reflecting TPACK concepts when developing activity sheets.

7.2. Scope for the schools

- The schools should provide suitable classrooms and lab facilities to the teachers to implement technology-based lessons.
- The schools should grow interest and provide support to teachers who plan to teach under the TPACK framework.
- The schools should start/increase arranging PD workshops on TPACK for the teachers.
- The schools should consider TPACK in yearly evaluation of the teachers.
- The schools should encourage the teachers to adopt TPACK framework for their lessons.
- The schools should conduct periodical assessment of TPACK status in their classroom teaching.
- The schools should be serious about creating a TPACK supportive environment.

- The schools may assign experienced educators and mentors to less experienced teachers to transfer TPACK ideas among them. Two teachers in a single classroom may be arranged for complementary supports.
- The schools should allow differentiation.

8. Discussion

The TPACK self-efficacy instrument of Appendix B was used to assess the teachers' engineering and technical knowledge and skills of robotics to teach science and math lessons. For example, the instrument of Appendix B sought to assess whether the teachers: *i)* had robotics technical skills; *ii)* could solve technical problems with robots; *iii)* could learn new robotics technologies; *iv)* possessed skills of other related technologies; and *v)* kept themselves updated with new technologies and tried to pick new technologies. During the three-week summer PD workshop, teachers learned and practiced engineering skills needed to effectively use the LEGO robotics kits in science and math lessons. For example, they learned robot assembly, programming, actuation, motion planning, sensor integration, robot operations, and troubleshooting. In this manner, the teachers' self-efficacy on designing and teaching robotics-focused math and science lessons presented in this paper was connected to K-12 engineering (robotics) education. We posit that our methodological approach to examining middle school teachers' understanding of the TPACK construct and analyzing their TPACK self-efficacy can be adopted, adapted, and applied to educators who teach engineering at college level, showing its broad potential for engineering education innovation.

For the work presented in this study, under the guidance of teachers, middle school students took part in designing and building robotic devices, conducting math and science lessons, and recording their observations in activity sheets. Engaging students in the aforementioned manner allowed them to learn varied engineering knowledge and skills, e.g., engineering design, product development, laboratory experimentation, and data analysis. In addition to the content knowledge of the lessons, the students experienced and learned engineering vocabulary terms, e.g., robot, sensor, actuator, wheel, gear, measurement, shaft, power, control, programming, motion, wiring, etc. The engineering practices that students engaged in during the design, development, and implementation of robotics-based science and math lessons can be connected to engineering design projects and high-tech engineering concepts considered in prior works, e.g., embedded systems design and development performed by high school students,[36] ocean observing systems data explored by K-12 students,[37] engineering design projects for improving K-12 math understanding,[38] microelectronic systems design conducted by K-12 students,[39] etc. Therefore, in a similar spirit, the study and results of this paper are connected to K-12 engineering education.[13] Finally, we posit that this study has broad connections to and implications for K-12 engineering education. In particular, inclusion of engineering design and engineering practices in NGSS[32] necessitates the integration of engineering in teacher education and teacher PD programs.

Achieving success in such an enterprise requires a systematic examination and analysis of teachers' understanding of the TPACK construct and self-efficacy. The study of this paper constitutes one step in this direction.

9. Conclusion and Future Work

We collaborated with 20 teachers in eight urban, inner-city schools and observed their teaching of robotics-focused STEM lessons under the TPACK framework. Together we developed several lessons that integrate robotics in the teaching and learning of middle school level science and math concepts. We provided PD to the teachers on using the robots in such robotics-focused science and math lessons. We observed the lessons implemented in actual classroom settings. Using questionnaires, we identified the ideal requirements of teachers' TPACK to effectively teach STEM lessons using robotics. We also determined the relative importance of the various domains of TPACK. The results show that the ability to program the robots and troubleshoot the program and the robots is the most required technological knowledge and skill for teaching both science and math lessons using robotics. The results also show that skills of differentiation between students, skills of scaffolding the topics, and ability of making productive student groups or teams for the lessons are the most required pedagogical skills, and the knowledge of the curriculum for specific grades is the most required content knowledge for teaching both science and math lessons using robotics. The results show that the TK and PK are perceived as the most and least important knowledge domain respectively for teaching both the math and science lessons using robotics.

Using questionnaires and brainstorming, we identified the factors that may affect the requirements of the technological, pedagogical, and content knowledge and their relative importance. Results show that teaching period is the most influential factor affecting the requirements and relative importance of the technological, pedagogical, and content knowledge for effectively teaching the math and science lessons using robotics. Other influential factors are student age or grade, subject matter of the lesson, student population in class, student habit, and students' prior knowledge for math and science lessons. We investigated different strategies and awareness levels of TPACK in different schools. Results show that 83.33% of the teachers and/or their schools adopted policies/strategies/programs regarding the implementation of the TPACK framework. We developed an assessment method to assess the self-efficacy of the teachers to teach robotics-focused STEM lessons under the TPACK paradigm. The results show that the teachers possess more self-efficacy in content knowledge and least self-efficacy in technological knowledge. There is no significant variation in TPACK self-efficacy between science and math teachers. We analyzed the reasons behind the deficits in the self-efficacy and provided recommendations to improve TPACK self-efficacy of the teachers for their robotics-focused STEM teaching in middle schools.

The results are novel and fundamental that may contribute to expand the conceptual horizon of TPACK, develop and maintain a balanced TPACK for teaching STEM with robotics in middle schools, and also maintain appropriate self-efficacy levels of the teachers, which may enhance the overall learning outcomes of the students. In ongoing work, we will analyze the differences in self-efficacy of teachers based on their gender and based on the grades they teach. We also expect to increase the number of teachers participating in the TPACK surveys. We will also measure the impacts of differences in teachers' TPACK self-efficacy on students' learning outcomes.

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Appendix A **TPACK Questionnaires**

Teacher's Gender: Female/Male Name of the School:

Q 1: What subject do you usually teach using robotics kits?

(A) Science, (B) Mathematics, (C) Both Science and Mathematics

Q 2: What are the grades of your students whom you teach using robotics?

Grades of students for science lessons	Grades of students for mathematics lessons

Q 3: What technological, pedagogical and content knowledge do you ideally require to plan and effectively teach the lessons using robotics?

Knowledge requirement	Subject	
	Mathematics	Science
Technological knowledge		
Pedagogical knowledge		
Content knowledge		

Q 4: What is the relative importance of the technological, pedagogical and content knowledge for planning and effectively teaching the lessons using robotics? (e.g., if the importance of the total knowledge required to teach is 100%, then what is the percentage of importance for the technological knowledge?)

For teaching mathematics	For teaching science
A) Technological knowledge (TK): …………% (e.g., 40%) B) Pedagogical knowledge (PK): …………..% (e.g., 35%) C) Content knowledge (CK):………………..% (e.g., 25%)	A) Technological knowledge (TK): …………% (e.g., 30%) B) Pedagogical knowledge (PK): ………..…% (e.g., 40%) C) Content knowledge (CK):………………..% (e.g., 30%)

Q 5: What are the factors that may affect the requirements and relative importance of the technological, pedagogical and content knowledge for effectively teaching the lessons using robotics?

Factors for teaching mathematics	Factors for teaching science

Q 6: Do you and your school adopt any policy/strategy/program to uphold your technological, pedagogical and content knowledge for effectively teaching the lessons using robotics? (A) No, (B) Yes. If yes, please mention below:

Your own policy/strategy/program	Policy/strategy/program of your school

Q 7: Are you satisfied/happy with the policy/strategy/program (i.e., are these adequate?) adopted by you and/or your school to uphold your technological, pedagogical and content knowledge for effectively teaching the lessons using robotics?

(1) Very dissatisfied, (2) Dissatisfied, (3) Slightly dissatisfied, (4) Neutral, (5) Slightly satisfied, (6) Satisfied, (7) Very satisfied

Q 8: What are the constraints (from your side and from your school side or from other sides) when teaching robotics-based lessons under TPACK framework?

Answer:

Appendix B **Teacher's TPACK self-efficacy for robotics lessons**

Teacher's Gender: F/M Teacher's main teaching subject: mathematics/science Students' grades: School:

Statement on Knowledge	Response (please put a "X" mark where applicable)						
	Strongly disagree	Disagree	Slightly disagree	Neither agree nor disagree	Slightly agree	Agree	Strongly agree
Technological Knowledge (TK)							
1. Technical skills: I have the technical skills that I need to teach my robotics-based lessons							
2. Problem solving: I know how to solve technical problems with the robots that I use to teach my lessons							
3. Technology learning: I can easily learn robot-related new technologies relevant to my robotics-focused lessons							
4. Related technologies: In addition to robotics technologies, I know and I have skills about a lot of other technologies related to my robotics-focused lessons							
5. Updating new technologies: I keep myself updated with various new technologies and try to pick new technologies that may be incorporated in my robotics-focused lessons							
Content Knowledge (CK)							
Mathematics							
1. Discipline knowledge: I have sufficient knowledge about mathematics required for middle school grades							
2. Thinking: I can use a mathematical way of thinking							
3. Understanding: I have various ways and strategies of developing my understanding of mathematics							
Science							
1. Discipline knowledge: I have sufficient knowledge about science required for middle school grades							
2. Thinking: I can use a scientific way of thinking							
3. Understanding: I have various ways and strategies of developing my understanding of science							

Pedagogical Knowledge (PK)							
1. Performance assessment: I know how to assess student performance in a robotics-focused classroom							
2. Teaching adaptation based on student's understanding: I can adapt my teaching style based-upon what students currently understand or do not understand about the lessons using robotics							
3. Teaching adaptation based on student's interest and skills: I can adapt my teaching style to different learners depending upon their interest and skills of robotics							
4. Diversity in learning assessment: I can assess student learning in multiple ways							
5. Familiarity with student misunderstanding: I am familiar with common student misunderstanding and misconceptions about usage of robotics in lessons							
6. Explaining with illustration: I know how to explain the abstract mathematical/scientific concepts through visible illustrations using robotics tools							
7. Class management and organization: I know how to organize and maintain classes taught with robots							
Pedagogical Content Knowledge (PCK)							
1. I can select effective teaching approaches to guide students thinking and learning in mathematics/science in robotics-focused lessons							
Technological Content Knowledge (TCK)							
1. I know about technologies that I can use for understanding and pursuing science/mathematics							
Technological Pedagogical Knowledge (TPK)							
1. I can choose technologies that enhance the teaching approaches for robotics-focused lessons							
2. I can choose technologies that enhance students' learning for robotics-focused lessons							

3. I can think deeply about how robotic technologies can influence the teaching approaches I use in my classroom							
4. I can adapt usage of robotics technologies for different teaching approaches							
5. I can measure/assess the outcomes/impacts of incorporation of robotics technologies in my teaching approaches							
Technological Pedagogical and Content Knowledge (TPACK)							
1. Combination of knowledge domains: I can teach lessons that appropriately combine mathematics/science, technologies and teaching approaches							
2. Determining knowledge requirements: I can determine the requirements of technological, pedagogical and content knowledge for my robotics-focused lessons							
3. Self-assessment of knowledge domains: I can assess my technological, pedagogical and content knowledge for my robotics-focused lessons							
4. Self-adjustment of knowledge domains: I can adjust my technological, pedagogical and content knowledge for my robotics-focused lessons depending upon situations							