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Fundamental: Determining Prerequisites for Middle School Students to Participate in Robotics-based STEM Lessons: A Computational Thinking Approach

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Fundamental—Determining Prerequisites for Middle School Students to Participate in Robotics-based STEM Lessons: A Computational Thinking Approach

1. Introduction

Increasing interest in the utilization of robotics in K-12 STEM education has drawn significant research interest and curricula development activities [1-3]. Prior studies have illustrated that the robotics framework offers a multitude of benefits for learners, e.g., transforming abstract content into concrete representations that are readily visualized; offering hands-on activities to support kinesthetic learning; promoting active learning; improving engagement in and excitement for learning [2,4]; engendering intrinsic and extrinsic motivation [5]; and enhancing the overall learning environment and achievement. Moreover, applications of robotics in K-12 STEM learning offer productive opportunities to examine, refine, and validate varied educational research paradigms, such as: cognitive apprenticeship [6], situated cognition [7], and collaborative and inquiry-based learning [8], among others. Considering these benefits of robotics-based K-12 STEM education, robotics-based lessons are being implemented in many K-12 schools on pilot basis [9-12]. Nonetheless, despite its tremendous potential, robotics remains to be widely incorporated in K-12 STEM curricula.

Based on our prior experiences, we have come to realize that a plethora of activities need to be performed beforehand to incorporate robotics-based lessons into K-12 STEM curricula. For example, to select, develop, and implement effective robotics-based lessons we suggest: (i) identifying appropriate illustrative scenarios, informed by situated cognition [7,9], for teaching STEM topics using robotics kits so that the robot plays a central role in the teaching and learning [10-12]; (ii) carefully examining the developed lessons, robotic behaviors, and adopted scenarios to ensure that (a) they do not generate misconceptions among learners, (b) they are safe and do not harm students in any manner, and (c) they do not require excessive time for implementation, etc.; (iii) developing robotics-based lessons with necessary materials such as lesson descriptions, activity sheets, etc. [10-12]; and (iv) considering the potential effect of robotics-based lessons on student performance evaluation and annual evaluation of teacher performance [10,12]. Next, regarding teachers, we recommend: (i) providing necessary professional development (PD) so that they successfully teach robotics-based lessons [9,11] and (ii) considering instructional supports such as classroom allocation, class time allocation, troubleshooting supports of robotics kits, etc., [11,12]. Finally, concerning the material resources, we recommend that the robotics kits should consist of appropriate hardware and software to illustrate the identified scenarios [9-12].

In addition to the aforementioned items, another important issue is the prerequisite knowledge, skills, and abilities that learners need to possess in order to successfully participate in robotics-based STEM lessons. As part of the STEM curricula, middle school students are taught general math and science background. The existing curricula usually do not account for the possibility that students may need to participate in robotics-based lessons at some stage of their middle school education. That is, the existing curricula do not include opportunities for students to effectively partake in robotics-based lessons. We posit that if we incorporate robotics-based lessons in middle schools, it might create a change in students' activities, students might be unprepared to learn using robots, and they might hesitate in using robots to support their learning. Hence, it is vital that we systematically investigate the prerequisite knowledge, skills, and abilities that learners need to possess to successfully participate in robotics-based STEM lessons. Having determined such prerequisite knowledge, we can identify and address misconceptions held by students and teachers about the role of robotics in STEM lessons; students' feelings of stress and anxiety due to lack of knowledge in robotics; students' level of interest or disinterest in robotics-based lessons; and appropriate lesson planning and pedagogical approaches of teachers. The knowledge about whether students meet prerequisites is critical for teachers to predict the readiness and capabilities of their students and the potential circumstances they may encounter in the classroom. Hence, it is important to examine the prerequisites for middle school students to participate in robotics-based math and science lessons. Unfortunately, such investigations remain to be pursued.

Emphasis on the abilities of learners to engage in and perform computational thinking, a concept popularized by Jeannette Wing [13], appears to be important to incorporate robotics into K-12 STEM curricula. The notion of computational thinking is broad and it has recently emerged as an important construct in K-12 education [13,14]. Cognitive process and abilities using which humans discover concepts, rules, and procedures to solve problems is termed as *computational thinking* [15]. Guided by metacognition, learning such concepts and rules enhances one's ability to reason and solve problems [15]. In order to use robotics in STEM lessons, students need to have some level of computational thinking as a prerequisite. Otherwise, they may not be able to fully grasp the benefits of using robotics in their STEM learning. Nonetheless, the prerequisites of computational thinking may not fully encapsulate the varied knowledge, skills, and abilities necessary for meaningful learning through robotics. The use of robotics can also be a good tool to foster and assess learners' computational thinking. However, the level of computational thinking required as a prerequisite to participate in robotics-based K-12 STEM lessons has yet to be investigated. How the use of robotics in STEM lessons can foster computational thinking of K-12 students is also not quite clear. We posit that such information on computational thinking centered on robotics can be employed to use robotics as a pedagogical tool in the K-12 STEM curricula and add to the current research literature.

Hence, the purpose of this study was to determine the prerequisites for middle school students to participate in robotics-based STEM lessons. In collaboration with several middle school teachers, we gathered data from several classrooms and examined it to address the following research questions. R.Q.1: What are the prerequisites needed for middle school students to succeed in robotics-based STEM lessons and what are the different categories and themes of prerequisites? R.Q.2: How can the themes of prerequisites be compared to each other in terms of importance and whether or not computational thinking constitutes a theme of prerequisites with significant level of importance for participation of students in robotics-based STEM lessons? R.Q.3: What is the current status of students regarding fulfillment of these prerequisites? The results of this study have the potential to inform the needs for additional instruction and scaffolds that should precede the robotics-based lessons for students to be successful. Otherwise, we run the risk of doing hands-on but not minds-on robotics-based STEM teaching and learning. We posit that such an approach may impart the benefits of robotics-based science and math lessons to students in a thoughtful way while also enhancing their overall skills and abilities including computational thinking abilities. All of which will support incorporation of robotics-based STEM lessons into regular K-12 curricula.

2. Literature Review

We began our study by conducting a literature review to identify the key definitions, concepts, principles, characteristics, elements, scope, importance, possibilities, challenges, frameworks, and assessment methods for computational thinking, especially in the context of K-12 education, [13-25]. Ribeiro *et al.* discussed the importance of computational thinking and explained how to include techniques to teach this kind of ability in elementary, middle, and high schools [15]. Pane and Wiedenbeck investigated the expansion of the benefits of computational thinking to diverse populations and investigated how researchers and designers of end-user development environments can support computational problem-solving and information manipulation by diverse user populations [21].

Barr and Stephenson initiated an effort to introduce computational thinking in K-12 environment through computer science education [16]. They suggested that successful integration of computational thinking into K-12 curricula requires improvement in education policy and additional resources for teachers [16]. Braaten and Perez explored teachers' computational thinking dispositions by embedding STEM and computer science in algebra [17]. Dasgupta *et al.* examined computational thinking practices in a kindergarten classroom through the analysis of student work [18]. Ehsan and Cardella investigated what computational thinking might look like in settings that approximate children's everyday experiences such as play-like activities [19]. Sengupta *et al.* proposed integrating computational thinking with K-12 science education using agent-based computation [22]. Werner *et al.* suggested a method to assess computational thinking in middle school through game programming [23]. Weese and Feldhausen proposed another method to assess computational thinking of K-12 students based on self-efficacy in solving problems with microcontrollers and computer programming [24]. Yasar *et al.* investigated the essence of computational thinking and tools to promote it in K-12 education [25]. Most importantly, the Next Generation Science Standards (NGSS) have also recommended incorporation of computational thinking in K-12 science education [20]. However, prior efforts have not considered exploration of computational thinking within the context of robotics-based K-12 STEM education.

From the aforementioned literature review, below we discuss the details of two relevant articles and their fundamental lessons about computational thinking. We specifically focus on Wing [13] who offered a fundamental understanding of computational thinking, and Grover and Pea [14] who addressed computational thinking in connection with the K-12 environment. Moreover, Grover and Pea [14] briefly discussed the potential of robotics to assess and improve computational thinking in K-12 students.

We begin by providing a brief description and our understanding of computational thinking as informed by Wing [13]. Computational thinking is a universally applicable attitude and a fundamental analytical skill that can be acquired and practiced by anyone, i.e., it is not the sole province of computer scientists. Generally computational thinking deals with something that is computable. It can be reflected through system design; the human thought process in problem solving; understanding the difficulty level of a given problem; understanding the quality of a proposed solution to a given problem; systematically assessing and selecting from among alternative solution strategies; understanding the fundamentals of mathematics, engineering, and computational models; analysis of findings obtained through hands-on activities; understanding human behavior; etc. Computational thinking is recursive and parallel thinking. Moreover, it is the ability of a person to judge a solution not only for being correct and effective, but also for its accessibility and aesthetics. Computational thinking affords appropriate representation and modeling of a problem to make it tractable. It enables a person to solve a problem, demonstrate confidence in the solution, and anticipate and predict the potential consequence of the solution. In addition to one's ability to solve a problem or make a decision, computational thinking has a bearing on the speed of the solution and the decision-making process. It may entail thinking in terms of preventing and protecting an artifact (e.g., a robot) from damage and attempting recovery through corrective actions. Computational thinking is the concept behind the computation, it is not the act of programming or using the rules. It is the fundamental of computing and not the computing skill itself. It is the thought process a human undertakes and not the working process or principle of a computing machine or a computer. It is the ideas or philosophy behind the computing and not the artifacts related to or used for computing.

Furthermore, as proposed by Grover and Pea [14], computational thinking is the abstraction in computing and is the cognition behind computation. Grover and Pea summarized a variety of effective pedagogies and tools to promote computational thinking among K-12 students and also explained how computational thinking can be included in K-12 curricula. Moreover, they explained how computational thinking is different from or similar to other types of thinking that adults or children can develop, and how computational thinking is shared with mathematical, science, engineering, and design thinking. Grover and Pea also highlight robotics kits as one of the ideal environments and tools that can help assess and foster computational thinking.

3. Development of Research Setting

In order to determine the prerequisites for middle school students who participated in robotics-based STEM lessons and to address the adopted research questions, as described below, we first developed the required infrastructure (human, technology, curricula, and processes), which constitutes as our research setting.

3.1. Overview of Teacher PD Program: To facilitate the proposed study, we designed and implemented a summer PD program for middle school teachers at the NYU Tandon School of Engineering. We recruited 23 science and math teachers, from New York City schools, for a three-week, eight-hours per day, PD program where they learned how to develop robotics-based lessons and how to implement the developed lessons in a classroom environment. We developed a facilitation team (termed as *facilitators*), comprising of three engineering and two education graduate student researchers, two engineering postdoctoral researchers, two engineering and two education faculty, and three education administrators. The facilitation team members, except the faculty and the education administrators, served as the *instructors* for the PD program. One engineering postdoctoral researcher, one engineering graduate student researcher, one education administrator, and one engineering faculty member of the facilitation team are the *authors* of this paper. Among the authors, the engineering postdoctoral researcher and the engineering graduate student researcher are termed as the *researchers*. The three engineering graduate student researchers and two engineering postdoctoral researchers of the facilitation team are termed as the *field researchers* (note that the field researchers also include two researchers).

A three-week schedule was developed to implement the robotics-based PD program. The program included a combination of fundamental educational theories and concepts, robotics fundamentals, and robotics-based math and science lessons. All PD sessions were delivered by the instructors under the mentorship of the faculty and with the logistic supports of the education administrators of the facilitation team. The instructors employed various instructional modes and methods such as lectures, hands-on activities, group discussions, projects, co-generations, assignments, brainstorming sessions, competitions, challenges, question and answer sessions, etc. An online feedback and reflection system was created to obtain teachers' feedback at the end of each day.

3.2. Physical Materials for PD Program: Instructors taught the PD program *participants* (teachers) to develop and use the base robot of Figure 1 [26] for implementing numerous robotics-based middle school STEM lessons [9-12]. The robotics system included (i) a programmable brick, serving as the control unit—with user-interface push buttons and LCD screen—and power station for the robotic system, that can be programmed through a graphical-user interface (GUI); (ii) two large electric motors to provide powerful and precise action and motion of the robotic vehicle under through appropriate program and control; (iii) several useful sensors such as ultrasonic, touch, color, temperature, wheel rotation, gyroscope, etc.; and (iv) two wheels of appropriate sizes, several gears, different types of cables, and various configuration parts and accessories to build the robot structure as required. We used the LEGO Mindstorms EV3 robotics kit being convinced of its relatively affordable cost, easy programming and operations, simple troubleshooting, flexibility in assembly, configuration, and reconfiguration, easy power supply, easy storage, and appropriateness of its functions and capabilities in explaining middle school science and math content [2-3,9-12,26].

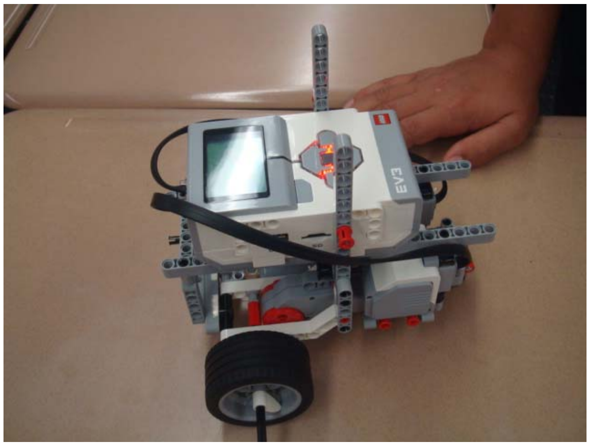

Figure 1: A base robot developed using the LEGO Mindstorms EV3 robotics kit to teach middle school STEM lessons.

3.3. Robotics-based STEM Lessons for PD Program: Over a dozen interesting and potentially useful robotics-based science and math lessons, teaching strategies, hands-on activities and activity sheets, lesson description materials, and learning outcome assessment materials were developed. Prior to the start of the PD program, several lessons were developed by the facilitation team. During the PD, the facilitation team and PD participants collaborated to refine these lessons and develop additional lessons. When planning and developing the lessons, we appropriately relied on various relevant education research theories [5-7,27-33] and ensured that all lessons met the state standards for middle school science and math based on the Common Core State Standards for Math (CCSSM) [34] and the NGSS [19,35]. The science lessons addressed topics such as mass, force, torque, moment, displacement, energy, environment, velocity, speed, acceleration, gravity, friction, design, design optimization, cell division (mitosis), biological adaptation, osmosis and diffusion, etc. The math lessons addressed topics such as ratio and proportion, number line, function, analyzing and interpreting data, least common multiple, statistics, expressions and equations, etc. See [9-12] for illustrative examples of our robotics-based science and math lessons. It was planned that, after completion of the PD program, the teachers would implement the robotics-based lessons in the classroom environment and the field researchers would visit the schools individually and observe the robotics-based lesson implementation.

4. Research Design

We designed and conducted two separate research studies to achieve the purpose of our research (i.e., to determine the prerequisites for students who participated in robotics-based STEM lessons), and to address the research questions, as follows.

Research study 1: In this study, as elaborated below, teachers and field researchers (who performed both field research and data analysis) served as respondents to a survey. First teachers and field researchers engaged in collaborative brainstorming and then they individually self-reflected to provide survey responses that were used by two researchers to determine the prerequisites for middle school students who participated in robotics-based STEM lessons. We also addressed the first two research questions: R.Q.1: What are the prerequisites needed for middle school students to succeed in robotics-based STEM lessons and what are the different categories and themes of prerequisites? R.Q.2: How can the themes of prerequisites be compared to each other in terms of importance and whether or not computational thinking constitutes a theme of prerequisites with significant level of importance for participation of students in robotics-based STEM lessons?

Research study 2: In this study, as elaborated below, the two researchers trained teachers and field researchers to observe and rate their students' prerequisite levels as they engaged in robotics-based STEM lessons. With the aid of these ratings, and based on two researchers' observations of and interactions with teachers, field researchers, and students, the remaining research question was addressed: R.Q.3: What is the current status of students regarding fulfillment of these prerequisites?

Next, in Sections 5 and 6 below, we present the details of the two research studies including adopted research methodologies, research results, and analyses.

5. Research Study 1: Development of Prerequisites for Middle School Students to Participate in Robotics-based STEM Lessons and Understanding the Relative Importance of Computational Thinking

5.1. Research Method: After the summer component of PD program was enacted, teachers went back to their schools and started teaching STEM lessons using robotics. Teachers guided the participating students to implement science and math activities using robots during regular class periods, and their students recorded experimental observations and outcomes of robot activities in supplied activity sheets. The field researchers visited the schools and observed classroom implementation of robotics-based STEM lessons. In this way, we attempted to ensure that the teachers and field researchers gained experiences in how the developed lessons worked and how the students performed and interacted with the robots in classroom. This preliminary engagement of teachers, field researchers, and students with robotics-based science and math lesson was to prime the teachers and field researchers to help identify prerequisites for robotics-based STEM learning.

We developed the *survey* given in *Appendix A* to obtain responses to two questions. We circulated the survey to all the teachers and field researchers, and asked them to separately complete it. The *first question* asked respondents to identify prerequisite knowledge, skills, qualifications, abilities, attitude, and aptitude that they deem necessary for students to possess for successfully participating in robotics-based STEM lessons. Respondents were asked to collaboratively *brainstorm* and independently *self-reflect* based on their experiences of robotics-based lesson planning, development, implementation, and classroom observations. The *second question* asked respondents to rate the level of necessity of each prerequisite that they individually determined. To do so, the responders were asked to follow a *quantitative subjective assessment method* [36] based on a five-point Likert scale, where 1 indicated the least necessary and 5 indicated the most necessary prerequisites.

While responding to the two survey questions, the respondents were also guided by their background, knowledge, and experiences of: middle school curricula, K-12 STEM standards, classroom facilities and environment, basic engineering and lab activities, robotics technology and hands-on activities involved in the targeted lessons, usual class period including school management and administration, basic social and behavioral science, basic management science, contemporary issues, technologies used in daily living, etc. The researchers briefly explained the survey procedure to each respondent separately before they completed the survey. The respondents were not asked to return the completed survey sheets immediately. They were allowed to keep the survey sheets with them for a week so that they had sufficient time to reflect carefully and provide well-thought inputs to the questions asked.

5.2. Research Results: We received responses from 11 teachers (out of 23) and two field researchers (who are also the researchers) to the survey of Appendix A. We believe that these responses were informative and trustworthy because these teachers and researchers had experiences in designing and implementing robotics-based STEM lessons in the classroom environment. Moreover, they had sufficient knowledge of and experiences with their students related to their work habits, skills, qualifications, activities, and performance. Based on the responses to question 1 in Appendix A, we created a cumulative list of all prerequisites suggested by the teachers and researchers. We counted the frequencies of common prerequisites. We then summarized the results as shown in the first three columns of Table A.1. in Appendix A (R.Q.1). The table shows a complete list of prerequisites proposed by teachers and researchers. It also shows the frequency of each prerequisite, i.e., how many times a prerequisite was proposed by the respondents in total. Based on the responses to question 2 in Appendix A, we then determined the mean (average) score indicating the level of necessity of each prerequisite. The fourth column of Table A.1. shows the mean necessity score against each prerequisite. The necessity score informs about the level of necessity of any particular prerequisite.

Next, the authors formed, among themselves, two teams each consisting of two members. The raw data of Table A.1. was analyzed and coded by the two teams separately to determine emergent categories and themes of prerequisites. The final categories and themes were determined by comparing and merging the categories and themes identified by the two teams (see Table A.2.). In order to do so, specially to determine what each theme encompasses, we relied upon our own STEM knowledge, including the conceptual understanding of computational thinking [13,14] in the context of K-12 STEM education and on the knowledge and experiences of K-12 STEM curricula, existing classroom facilities and environment, basic engineering and lab activities, LEGO robotics, subject knowledge, social and behavioral science, management science, etc. It is true that the concept of computational thinking is broad and not widely agreed upon. Nonetheless, for the purpose of creating themes from the prerequisites, we were guided by the fundamental concepts of computational thinking and adapted the aspects of the computational thinking considered mainly in [13,14] as well as in [15-19,23-25]. For example, formulating and solving problems [13-16,19,23-25], analyzing outcomes [16,18], understanding obtained results to make improvements [13,14,24], learning from mistakes [24], handling uncertainty [13,17], and sharing ideas or concepts with others [13,14,24] were all treated as components of computational thinking theme while communicating general information was treated as a managerial skill theme (R.Q.1).

Next, we conducted an analysis to understand the relative importance/necessity of different themes of prerequisites. To do so, we proposed Eq. (1). In Eq. (1), the necessity level (n_l) was multiplied by the number of frequency (f) for each prerequisite to determine the summation for each theme that gave the computed total prerequisite value (V_{prereq}) for each prerequisite theme. Figure 2 shows the computed total prerequisite values for all prerequisite themes. The figure indicates the relative importance of the prerequisite themes at a glance (R.Q.2).

$$V_{prereq} = \sum (f \times n_l) \tag{1}$$

5.3. Analyses of Research Results: As evidenced in Table A.2. and Figure 2, the prerequisites have been split into themes and their relative importance determined (R.Q.2) and, as evidenced in Figure 2, computational thinking theme carries the highest prerequisite value indicating that it is of significant importance for performing robotics-based STEM lessons (R.Q.2). A detailed discussion on each theme of prerequisites shown in Figure 2 is given below.

Computational thinking is the most prioritized theme of prerequisites that students should gain before they start learning STEM through the use of robotics. Otherwise, either the students will not be able to follow robotics-based lessons effectively, or they will fail to get full benefits of learning through robotics-based lessons.

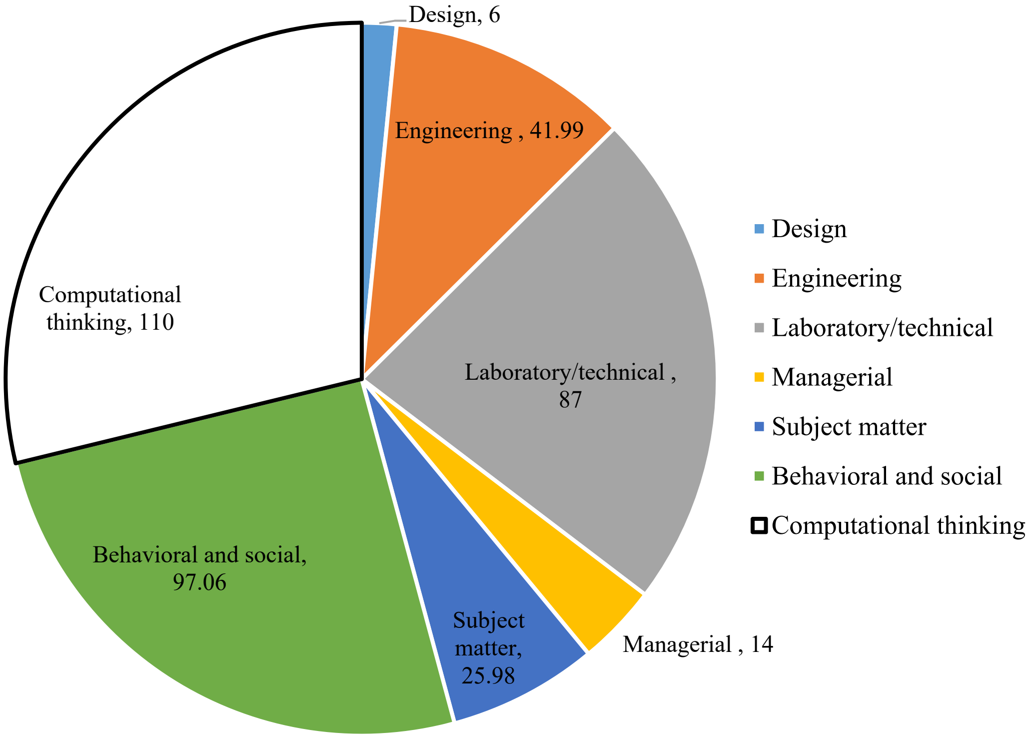

Figure 2: Computed total prerequisite values for different prerequisite themes. The values also indicate the relative importance of the prerequisite themes.

Behavioral and social qualification is important because robotics is a new pedagogical tool, and incorporation of such a tool cannot provide benefits if the learners do not possess appropriate behavioral and social aptitude including a good social relationship among themselves. Students usually work in team during their robotics-based lessons, and they conduct some project-like activities and need to manage resources such as robotics kits, instruments, documents, etc. In such cases, appropriate managerial skills are necessary.

Engineering prerequisites include the students' vocabulary, knowledge, and skills with applications of engineering terms related to robots such as gear, motor, wheel, sensor, shaft, monitor, wire, control, communication, power, troubleshooting, etc., that are necessary for them to use a robot as a learning tool.

Laboratory and technical qualifications and skills are required as students need to perform hands-on activities as a part of their robotics-based lessons. Students need some technical skills and abilities to use general laboratory instruments and facilities and the students cannot perform robotics-based lessons without having such abilities and skills [37].

Design is also important because students also need to design the robot or re-design it during lessons. Hence, design skills especially for robot assembly and re-assembly are necessary [37]. While guided by their teachers students can follow instructions to build the robot for their lessons. This produces only the base robot configuration (Figure 1). Frequently, the lessons require that the robot include additional accessories such as structural elements, grippers, sensors, etc., that cannot be built following the basic instructions. In such cases, students need to develop appropriate design ideas for the required robotics setup of particular lessons. Thus, beyond building the robot following given instructions, the students also need to develop design skills.

Subject matter/content is a prerequisite that students need to follow the math and science lessons using robotics. However, some other skills and qualifications such as engineering, laboratory/technical, behavioral and social, and computational thinking become more important than subject matter prerequisites because these skills and qualifications are necessary to successfully implement the robotics-based lessons to learn the subject matter [37]. It does not reduce the importance of subject matter prerequisites, but adds some other allied skills and qualifications as prerequisites that become essential to implement the robotics-based lessons to learn the subject matter. Thus, the results show that the students need to have a good amount of allied qualifications in addition to the subject matter prerequisites to participate in robotics-based lessons. It may be a burden to the students, but it can also open the door to learn more that can enhance the overall learning outcomes and achievement and upgrade the overall aptitude of the students.

Note that students need to fulfill the prerequisites with specified necessity levels given in Table A.1 prior to starting their robotics-based STEM lessons. Students may be able to acquire and satisfy many of these ideal requirements indirectly in disparate ways during their middle school education and while following the existing STEM curricula. In this study, we are not suggesting to place a hard set of requirements and barriers in front of students. Instead, we simply seek to identify and determine the ideal prerequisites requirements and examine the current status of the targeted students *vis-à-vis* these requirements. Teachers can use the results of this study to plan their lessons effectively thus affecting their students' educational gains with the use of prerequisites in their robotics-based STEM lessons. Through careful identification of various prerequisite requirements that students satisfy or lack, teachers can appropriately differentiate to craft scaffolds, and maintain equity of participations and learning in their classrooms.

6. Research Study 2: Assessing Selected Students for Fulfillment of Prerequisites

6.1. Research Method: For research study 2, four field researchers (including two researchers) observed the implementation of various robotics-based math and science lessons taught by five teachers in the classrooms. The two researchers asked each teacher and two other field researchers to assess selected students following a quantitative subjective assessment method [36] based on a five-point Likert scale against each prerequisite, where 1 indicated the least qualified and 5 indicated the most qualified for a prerequisite. As a preliminary effort, the five teachers and four field researchers assessed 38 randomly selected students. The assessment was based on what the teacher and field researcher observed a student doing during robotics-based lesson activities, responses to short questionnaires by the students, evaluation of activity sheets completed by them, overall knowledge demonstrated by the students while performing activities related to the robotics-based lessons, etc. This assessment was conducted during the first two lessons that the students were taught by their teachers using robots. Before conducting such assessment, the two researchers provided brief training to *raters* (i.e., teachers and field researchers) about how to conduct the assessment. Specifically, they explained what each criterion in Table A.1. means, how to decide an assessment score for each criterion for a student, what types of information or materials (e.g., previous examination results, attendance) the rater should consider to reach a decision of an assessment score, etc. Having received the basic explanation of the assessment, individual raters assessed the students to the best of their abilities. In a future study, to maintain uniformity in assessment, a more rigorous technique can be used with multiple raters assessing individual students along with the measurement of inter-rater reliability.

6.2. Research Results and Analyses: We treated the mean necessity level of Table A.1. as the standard level (or, minimum requirement) of skills and qualifications for different prerequisites. We analyzed the outcome assessment results for all 38 students by examining whether they satisfied minimum requirement for knowledge and skills for each prerequisite given in Table A.1. Table A.3. provides a summary of this analysis, including how many students met each prerequisite (number n, mean $\bar{x}$, and standard deviation σ) and how many did not (number n_c, mean $\bar{x}_c$, and standard deviation σ_c). The results show that the students could satisfy the prerequisite level of ***knowledge and skills*** for many criteria (R.Q.3). However, they failed to fulfill some prerequisites related to ***engineering and computational thinking***. We assume that students did not receive any formal training on robotics-based lessons before participating in the robotics-based lessons. However, they could fulfill many of the other prerequisites perhaps based on their general aptitude and maturity that they gained through their daily life (e.g., household, media, internet, science fiction, game, museum, practical observation, etc.), previous education, and some practice sessions of robotic assembly and applications in previous class, etc. They also learned the ***behavioral and social skills and managerial skills*** through their daily life and other school activities. They learned the ***laboratory and technical skills*** from their usual laboratory practices because they learned many other lessons in the laboratory/classroom environment, and sometimes they might need to use lab instruments for other lessons that were taught without using robotics. The reason of poor qualifications in ***engineering prerequisites*** is perhaps because engineering terms were not formally taught to them in previous lessons. Even if the meaning of engineering terms and engineering procedures might be familiar to students from their daily life, such informal knowledge of daily life was not sufficient to prepare them for the robotics-based lessons that needed formal engineering knowledge and skills. The students also gained some aptitude in

computational thinking through their daily life and previous lessons/grades, but that might not be sufficient to fulfill the formal requirement of computational thinking during the robotics-based lessons [13,14]. Literature shows that continuous practice with suitable artifacts and problem solving by students as well as continuous assessment can improve computational thinking [14,17,23]. Hence, robotics-based lessons and robotics kits can also improve the computational thinking of students as they use and practice with robotics kits as a pedagogical tool and learn lessons through robotics kits [14].

7. Discussion

7.1. Action Plans to Help Students Satisfy Prerequisites: As Section 6 and Table A.3. show, the students may fail to fulfill multiple computational thinking prerequisites as well as other themes of prerequisites to participate in robotics-based lessons in middle schools. It may be treated as usual because the students were not formally trained for this purpose. Their informal knowledge and skills made them able to fulfill many other prerequisites. We propose to implement the following action plans by concerned schools/teachers before they start teaching STEM lessons to students through the use of robotics kits.

1. Arrange some training sessions with the students who are to be taught math and science using robotics. During the training sessions, the teachers (or some external technical experts) may exclusively teach the engineering concepts related to LEGO Mindstorms robotics kits to the selected students [26,37]. For example, the training classes may teach them the fundamentals of actuation, sensing, and control of the robotics kits [26]. The teachers can explain the basic laboratory rules and further demonstrate different laboratory instruments to the students. The teachers can also discuss about the common social, behavioral, and managerial attitudes and skills.
2. For computational thinking, the teachers/schools may develop and teach a new series of allied courses that can help develop computational thinking abilities from the early grades, for example from elementary grades or from the 6th grade. These courses can be hands-on, participatory, and inquiry-based, wherein students can practice thinking, imagination, analysis, reasoning, etc. through various activities, brainstorming, problem-/project-based lessons, co-generation dialogues, group discussion, collaborative learning, collective learning, etc. We believe that such a practice can improve the computational thinking of students in general, helping them during robotics-based lesson activities [13,14]. In addition, the robotics-based lessons and the robotics kits can also improve the computational thinking of students as they use and practice the robotics kits and learn lessons through robotics kits [14].
3. Use of cognitive apprenticeship [6] and scaffolding, and attention to equity, diversity, and individual differences, etc., by teachers before and during the robotics-based lessons can help students learn better as well as gain the prerequisites for robotics-based lessons. For example, if teachers provide additional supports to students by understanding individual needs and

ensuring that each student is cared for to fulfill individual needs, then the students who start out with a deficiency in the prerequisites will be able to learn more and lower their weaknesses in areas such as design, engineering, lab skills, managerial skills, etc., helping them fulfill the relevant prerequisites easily.

4. If the students continue to participate in robotics-based lessons, gain practice in performing robotics activities, and receive on-going feedback from teachers about their progress, they may gradually improve their prerequisites knowledge [14]. However, they may not obtain the complete benefits of the lessons especially in the beginning because they may lack many prerequisites in the beginning that may hinder their smooth learning. This type of practice-oriented concurrent engineering-based continuous learning and quality improvement of education (learning through mistakes) can improve overall learning outcomes [38], but this may not be a good approach where a series of lessons are taught using robotics, and one lesson is different from another lesson in terms of scenarios, activities, and technical requirements.
5. If robotics-based lessons are incorporated in the regular curricula of middle schools, then the existing curricula will need to be revised and some allied lessons/sessions will need to be added from the lower grades that can continuously generate prerequisite knowledge and skills in students before they start learning STEM lessons though robotics at higher grades.

7.2. Limitations of the Study: The following limitations should be considered about this study.

1. It is limited to middle school classes only. There is no guarantee that the results are applicable to elementary or high school classes.
2. It is limited to the use of LEGO Mindstorms robotics kits [26]. If different robotics kits are used, the results may change.
3. It is limited to the selected robotics-based lessons and adopted scenarios [9-12]. If new lessons are developed with completely different scenarios, the results may change.
4. The list of prerequisites was developed based on the surveys of a limited number of teachers and researchers. The results may change if opinions of more teachers are considered.
5. The prerequisites are general for all math and science lessons from grades 6 to 8. However, the prerequisites can be very specific to a specific math or science topic for a specific grade level. Establishing such prerequisites will necessitate significant research work but it may be helpful to obtain improved results.
6. We assume that the selected students do not have prior knowledge and skills with LEGO robotics kits. The results may be different if students somehow possess knowledge and skills with LEGO robotics kits.
7. Whether the selected students meet prerequisites or not (Section 6) was decided based on assessments by teachers and field researchers who utilized simple observations of student activities, general knowledge about the students, and students' responses to a simple questionnaire. Deeper observations and better method of evaluation of student performance, understanding, skills, and abilities are required to make such decisions in a more concrete

manner. Teachers can apply more scientific methods to assess the current status of each prerequisite. For example, game-based programming [23], and self-efficacy in problem solving [24] can be used to assess computational thinking. Evaluations by multiple evaluators (teachers and field researchers) can also make the results more reliable. This may help make correct decision about whether a particular student meets a prerequisite or not and may also help to take correct and specific action plans.

7.3. Manageability and Significance of the Results: Initially, teachers in this study proposed a list of prerequisites without any restrictions from the researchers. This is based on their expertise as formal educators working in the field with students. In this paper, we are reporting the proposed procedures for and awareness of determining and fulfilling prerequisites, respectively, for robotics-based lessons. We have identified a large list of prerequisites and coded them for seven emergent themes as shown in Figure 2. These themes were coded from the raw data in Table A.1 by the authors, collaboratively. It may appear that such a prerequisite list is not manageable. However, we believe that it should be manageable for the following reasons.

1. In-service teachers are expected to assess their student population. Having defined students' prerequisites before they can participate in robotics-based STEM lessons can help teachers access how to support student learning. Teachers could access their students' prerequisites before they teach robotics-based lessons. For example, teachers can assess the targeted students for a whole year to make a decision on who will participate in robotics-based lessons in the following year. Alternatively, teachers may also access their students' prerequisites during the robotics-based lessons in order to support their deficiencies. In addition, continuous assessment can also enable students to satisfy prerequisites gradually. Hence, teachers can decide based on their time constraints and goals how they can use the prerequisites.
2. We used a Likert scale to subjectively assess the status of each selected student based on limited information during our observation. However, teachers can use any source of information or observation based on their experiences that seems to be most suitable and reliable for them to conduct the assessment and decide the assessment score.
3. The assessment of student status for fulfillment of prerequisites based on the proposed method and the proposed list of prerequisites was conducted in the classroom environment. The overall method has some time constraints however field researchers did not find it unmanageable. Nonetheless, in order to address the time constraints of teachers, researchers developed a condensed list of prerequisites (see Table A.2.) from the raw data. This shorter list of prerequisites may be easier to implement. We believe that there could be a tradeoff between the condensed list of prerequisites and its effectiveness. It is important to note that some detailed prerequisites could go overlooked and unaddressed affecting students' knowledge needed to participate in robotics-based lessons. For these reasons we recommend the exhaustive list (see Table A.1.). Future studies can replicate this research and utilize our

condensed list of prerequisite in order to access students' preparedness to participate in robotics-based lessons.

8. Conclusions and Future Work

We organized a PD program for a few selected middle school STEM teachers to train them on developing and conducting math and science lessons through the use of low-cost robotics kits. We also introduced to teachers a few representative robotics- based math and science lessons. We then determined a set of prerequisites with the importance level of each prerequisite through brainstorming and self-reflection by teachers and researchers. Results show that computational thinking is the most important prerequisite theme. The students are expected to fulfill the perquisites before they start learning math and science lessons through the use of robots. We then assessed a few students to give an example of how the prerequisites can be used as standards to identify whether the selected students can individually meet the prerequisites of participating in robotics-based STEM lessons. The results show that the students could not fulfill all the prerequisites. We then discussed what actions can be taken to improve the skills and qualifications of the students so that they can fulfill the prerequisites. We believe that the results of such an analysis inform the needs for additional instruction and scaffolds that should precede the robotics-based lesson for it to be successful. We posit that such an approach can impart the benefits of robotics-based science and math lessons to students in a systematic way while also enhancing their overall skills and abilities including computational thinking abilities, and thus can help incorporate robotics-based lessons into regular K-12 STEM curricula. The results show that the major part of the prerequisites is related to the computational thinking skills of the students. The results also imply that the robotics-based lessons require a high level of computational thinking skills, and in return, the robotics-based lessons can also enhance the computational thinking abilities of the participating students. Teachers, education policy makers, and education administrator can make decision about whether or not and how robotics can be incorporated in the K-12 curricula as a pedagogical tool to teach STEM lessons. The proposed results have some limitations as discussed above. However, the approaches are general and can be applied to many cases as needed.

In future, we will seek input from a larger number of experienced teachers and field researchers and use more scientific survey methods to improve on the prerequisites that we proposed. We will try to further analyze the proposed prerequisites to obtain a shorter and handy list, and also put more efforts and follow more scientific methods to determine appropriate categories and themes for prerequisites. We will also use larger number of evaluators and more scientific evaluation methods such as game-based programming [23], self-efficacy assessment in problem solving [24], etc., to decide whether the selected students can meet the specified prerequisites. We will assess a large population of students (100+) who were taught STEM using robotics based on the developed standard prerequisites, develop a large database, and conduct rigorous research and analysis to understand the general status of whether and how the students meet the specified prerequisites, i.e., how do middle school students achieve the identified prerequisite knowledge, abilities, and skills even though they are not taught through robotics in existing curricula. We will also investigate how robotics can be used in STEM learning as a pedagogical tool that can also improve computational thinking of students. We will specify the prerequisites for math and science lessons separately. We will also specify the prerequisites for similar topics within math and science lessons for each grade of students. We will also investigate based on observed data how robotics-based lessons and the robotics kits can improve the computational thinking of students as they use and practice with the robotics kits as a pedagogical tool and learn lessons through robotics kits.

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Appendix A: Survey to determine prerequisites for middle school students to participate in robotics-based STEM lessons

Teacher Code: Teaching subject: Math/Science

You are a middle school math/science teacher. You want to select a class of students (or a few students) to teach them math/science using LEGO robotics kits. Assume that the students do not have prior knowledge of LEGO robotics. Students are just following the regular curriculum of your school and may not have thought about learning math/science using robotics.

Questionnaires:

Question 1: In your opinion, what prerequisite knowledge, skills, qualifications, abilities, attitude, and aptitude a student should have to successfully participate in your robotics-based math/science lessons?

Question 2: What is the level of necessity of each prerequisite? Assume that you have a 5-point Likert scale between 1 and 5, where 1 indicates the least necessary and 5 indicates the most necessary. Please indicate the level of the necessity for each prerequisite between 1 and 5.

Responses to questionnaires:
Please record your responses using the following table. Please add more rows in the table as you need.

Necessary prior/prerequisite knowledge, skills, qualifications, abilities, attitude and aptitude of a selected student and/or a class of selected students	Level of necessity (between 1 and 5)

Table A.1.: Various prerequisites proposed by teachers and researchers, frequency of each prerequisite (number of times a prerequisite was proposed), mean (average) score indicating the level of necessity of each prerequisite.

S. No.	Necessary prerequisite knowledge, skills, qualifications, abilities, attitude, and aptitude that ought to be possessed by students as jointly perceived by the research team and participating teachers	Frequency of response	Mean level of necessity out of 5
1	Ability to design (assemble) LEGO robotics kits following assembly instructions	2	3
2	Familiarity with the functions of different parts of LEGO robotics kits including various sensors	2	4
3	Ability to operate the LEGO robotics kits (turn the LEGO robotics kits ON and OFF, and to use the buttons to run the specific programs)	1	5
4	Ability to troubleshoot with the LEGO robotics kits especially troubleshooting during robotic-based lessons	3	4.33
5	Block-based robot programming	1	3
6	Basic engineering vocabulary such as wheel, gear, shaft, vehicle/cart, power supply, switch, button, wire, motor, etc.	2	4
7	Familiarity with basic human-machine interface	1	5
8	Ability to understand the activity sheets and complete the activities	1	5
9	Ability and skills to use other allied technologies such as calculator, measurement tape, protractor, ramp, timer, etc.	5	4.2
10	Ability to understand basic drawings, e.g., a number line drawn on floor	1	5
11	Understanding the working procedures of the robotic kits and other instruments used in lesson activities	1	5
12	Basic computer literacy, e.g. operation of a laptop	4	4.75
13	Ability to draw and understand basic graphs	1	5
14	Ability to be aware of basic safety regulations and to maintain safe working environment	1	5
15	Ability to follow visual and verbal instructions for activities during lessons	2	5
16	Basic computing ability	3	4
17	Time maintain ability	1	5
18	Communication ability	2	4.5
19	Satisfying prerequisites of the concerned subject matter or content knowledge (prerequisites of concerned math and science topics)	6	4.33
20	Team work ability	4	4.75
21	Physical and mental ability and attitude to do hands-on activities	1	5
22	Ability to maintain discipline in classroom and to reduce noise	2	4.5
23	Ability to adapt with social and behavioral diversity	1	5
24	Ability to focus on concerned lesson	1	5
25	Ambition to learn through robotics	1	5
26	Positive attitude toward robotics-based lessons and new technologies	7	4.58
27	Ability to be resilient to lesson activities	1	5
28	Appropriate classroom environment	3	4
29	Ability to solve problem in a rational way related to robotics-based activities	5	4.4
30	Reasoning the activities performed with the robotics kits	2	5
31	Ability to make a decision or draw a conclusion based on the activities performed with the robotics kits	2	5
32	Imagination to predict the activities of the robotics kits in a particular situation	1	4
33	Ability to understand the central theme of the practical scenario used to teach math and science topics and to relate the scenarios and the robotics activities to actual meaning of math and science topics	1	5

34	Ability to understand how the robotic kits were designed as a system and how they work as a system	2	4
35	Understand basic formula and computational models	1	5
36	Ability to analyze findings obtained through hands-on activities	1	5
37	Understanding teacher and team member's behavior	1	4
38	Understanding quality and rationality of the obtained results	1	5
39	Understanding the alternative activities related to the lessons and possibility of alternative results through activities	1	5
40	Having confidence in the proposed results	1	5
41	Anticipating the potential impact/consequence of the proposed results in daily and social life	1	5
42	Having motivation to protect the robotic systems from being damaged as well as to possess mental preparation to protect the robotic system	1	4
43	Ability to learn from mistakes or uncertain situations	1	5
44	Memory of recent past robotic activities	1	5
45	Appropriate speed of solving a problem through the activities of robotic kits and making a decision	1	5
46	Ability to develop a hypothesis	2	4.5
47	Ability to share an organized idea or a concept with others (team members, teachers, visiting researchers)	2	4.5

Table A.2.: Summary of determination of different categories and themes of prerequisites.

S. No.	Category of prerequisites	Prerequisite S. No. (in Table A.1)	Total Frequency of responses	Mean level of necessity out of 5	Theme of prerequisites
1	Robot design abilities	1	2	3	Design
2	Fundamental and practical knowledge of Lego robots	2-7	10	4.22	Engineering
3	Understanding the use of lab materials	8,10,11,13,15	6	5	Laboratory/ technical
4	Ability and skill to use lab equipment	9,12,16	12	4.33	Laboratory/ technical
5	Safety awareness	14	1	5	Laboratory/ technical
6	Executive functioning skills	17,18	3	4.75	Managerial
7	Disciplinary content knowledge	19	6	4.33	Subject matter
8	Learning habits/attitudes	21,22,25,26, 28	14	4.62	Behavioral and social
9	Team work ability	20,23	5	4.88	Behavioral and social
10	Learning skills/aptitude	24,27	2	5	Behavioral and social
11	Thinking and reasoning skills	29,30,31,33, 36,38,39,46	15	4.86	Computational thinking
12	Creativity and imagination	32	1	4	Computational thinking
13	Systems thinking and systems modeling	34,35	3	4.5	Computational thinking
14	Sharing thoughts and ideas	47	2	4.5	Computational thinking
15	Understanding teacher and team member's behavior	37	1	4	Computational thinking
16	Confidence in proposed results	40	1	5	Computational thinking
17	Anticipating impact/consequence of results	41	1	5	Computational thinking
18	Motivation to handle the robot system safely to avoid damage	42	1	4	Computational thinking
19	Learning from mistakes or uncertain situations	43	1	5	Computational thinking
20	Memory of recent past robotic activities	44	1	5	Computational thinking
21	Problem solving speed	45	1	5	Computational thinking

Table A.3.: Summary of assessment results for 38 students for fulfillment of prerequisites.

S. No.	Necessary prerequisite knowledge, skills, qualifications, abilities, attitude, and aptitude of students jointly perceived by the research team and participating teachers	Themes of prerequisites	Prerequisite met $n\ (\overline{x}, \sigma)$	Prerequisite not met $n_c\ (\overline{x}_c, \sigma_c)$
1	Ability to design (assemble) LEGO robotics kits following assembly instructions	Design	38 (4.47,0.71)	0 (n/a,n/a)
2	Familiarity with the functions of different parts of LEGO robotics kits including various sensors	Engineering	25 (4.57,0.51)	13 (2.53,0.74)
3	Ability to operate the LEGO robotics kits (turn the LEGO robotics kits ON and OFF, and to use the buttons to run the specific programs)	Engineering	36 (5,0)	2 (4,0)
4	Ability to troubleshoot with the LEGO robotics kits especially troubleshooting during robotic-based lessons	Engineering	10 (4,0)	28 (2.25,0.59)
5	Block-based robot programming	Engineering	7 (3.88,0.64)	31 (1.2,0.41)
6	Basic engineering vocabulary such as wheel, gear, shaft, vehicle/cart, power supply, switch, button, wire, motor, etc.	Engineering	13 (4.15,0.38)	25 (2.92,0.28)
7	Familiarity with basic human-machine interface	Engineering	0 (n/a,n/a)	38 (2.71,0.96)
8	Ability to understand the activity sheets and complete the activities	Laboratory/ Technical	37 (5,0)	1 (3, n/a)
9	Ability and skills to use other allied technologies such as calculator, measurement tape, protractor, ramp, timer, etc.	Laboratory/ Technical	38 (4.37,0.49)	0 (n/a,n/a)
10	Ability to understand basic drawings, e.g., a number line drawn on floor	Laboratory/ Technical	38 (5,0)	0 (n/a,n/a)
11	Understanding the working procedures of the robotic kits and other instruments used in lesson activities	Laboratory/ Technical	29 (5,0)	9 (3.71,0.47)
12	Basic computer literacy, e.g. operation of a laptop	Laboratory/ Technical	38 (4.29,0.46)	0 (n/a,n/a)
13	Ability to draw and understand basic graphs	Laboratory/ Technical	31 (5,0)	7 (4,0)
14	Ability to be aware of basic safety regulations and to maintain safe working environment	Laboratory/ Technical	30 (5,0)	8 (3.36,0.5)
15	Ability to follow visual and verbal instructions for activities during lessons	Laboratory/ Technical	35 (5,0)	3 (3.67,0.52)
16	Basic computing ability	Laboratory/ Technical	34 (4.38,0.49)	4 (2.5,0.58)
17	Time maintain ability	Managerial	32 (5,0)	6 (3.91,0.3)
18	Communication ability	Managerial	34 (4.18,0.39)	4 (3,0)
19	Satisfying prerequisites of the concerned subject matter or content knowledge (prerequisites of concerned math and science topics)	Subject matter	31 (4.06,0.25)	7 (2.86,0.38)
20	Team work ability	Behavioral and social	38 (4.26,0.45)	0 (n/a,n/a)
21	Physical and mental ability and attitude to do hands-on activities	Behavioral and social	34 (5,0)	4 (3.89,0.33)
22	Ability to maintain discipline in classroom and to reduce noise	Behavioral and social	32 (4.34,0.48)	6 (3,0)
23	Ability to adapt with social and behavioral diversity	Behavioral and social	37 (5,0)	1 (4,n/a)

24	Ability to focus on concerned lesson	Behavioral and social	31 (5,0)	7 (4,0)
25	Ambition to learn through robotics	Behavioral and social	29 (5,0)	9 (3.44,0.73)
26	Positive attitude toward robotics-based lessons and new technologies	Behavioral and social	36(4.39,0.49)	2 (3,0)
27	Ability to be resilient to lesson activities	Behavioral and social	27 (5,0)	11 (3.39,1.38)
28	Appropriate class environment	Behavioral and social	35 (4.53,0.51)	3 (3,0)
29	Ability to solve problem in a rational way related to robotics-based activities	Computational thinking	25 (4.37,0.49)	13 (2.75,0.71)
30	Reasoning the activities performed with the robotics kits	Computational thinking	9 (5,0)	29 (3.38,0.56)
31	Ability to make a decision or draw a conclusion based on the activities performed with the robotics kits	Computational thinking	0 (n/a,n/a)	38 (3.66,0.56)
32	Imagination to predict the activities of the robotics kits in a particular situation	Computational thinking	14 (4.38,0.51)	24 (2.4,0.58)
33	Ability to understand the central theme of the practical scenario used to teach math and science topics and to relate the scenarios and the robotics activities to actual meaning of math and science topics	Computational thinking	11 (5,0)	27 (3.37,0.76)
34	Ability to understand how the robotic kits were designed as a system and how they work as a system	Computational thinking	27 (4.11,0.31)	11 (2.8,0.42)
35	Understand basic formula and computational models	Computational thinking	31 (5,0)	7 (3.33,1.03)
36	Ability to analyze findings obtained through hands-on activities	Computational thinking	8 (5,0)	30 (3.85,0.46)
37	Understanding teacher and team member's behavior	Computational thinking	37 (4.24,0.43)	1 (3,n/a)
38	Understanding quality and rationality of the obtained results	Computational thinking	5 (5,0)	33 (3.64,0.55)
39	Understanding the alternative activities related to the lessons and possibility of alternative results through activities	Computational thinking	6 (5,0)	32 (2.41,1.05)
40	Having confidence in the proposed results	Computational thinking	7 (5,0)	31 (3.26,0.68)
41	Anticipating the potential impact/consequence of the proposed results in daily and social life	Computational thinking	2 (5,0)	36 (3.28,0.7)
42	Having motivation to protect the robotic systems from being damaged as well as to possess mental preparation to protect the robotic system	Computational thinking	37 (4.22,0.42)	1 (3,n/a)
43	Ability to learn from mistakes or uncertain situations	Computational thinking	11 (5,0)	27 (3.87,0.34)
44	Memory of recent past robotic activities	Computational thinking	30 (5,0)	8 (2.63,0.74)
45	Appropriate speed of solving a problem through the activities of robotic kits and making a decision	Computational thinking	10 (5,0)	28 (3.71,0.53)
46	Ability to develop a hypothesis	Computational thinking	13 (4.31,0.48)	25 (2.88,0.33)
47	Ability to share an idea with others (team members, teachers, visiting researchers)	Computational thinking	14 (4.29,0.47)	24 (2.88,0.34)