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Building Trust in Robots in Robotics-Focused STEM Education under TPACK Framework in Middle Schools

Dr. S. M. Mizanoor Rahman, New York University

Mizanoor Rahman received Ph.D. degree in Mechanical Engineering from Mie University at Tsu, Japan in 2011. He then worked as a research fellow at the National University of Singapore (NUS), a researcher at Vrije University of Brussels (Belgium) and a postdoctoral associate at Clemson University, USA. He is currently working as a postdoctoral associate at the Mechanical and Aerospace Engineering Department, NYU Tandon School of Engineering, NY, USA. His research and teaching interests include robotics, mechatronics, control systems, electro-mechanical design, human factors/ergonomics, engineering psychology, virtual reality, artificial intelligence, computer vision, biomimetics and biomechanics with applications to industrial manipulation and manufacturing, healthcare and rehabilitation, social services, autonomous unmanned services and STEM education.

Sonia Mary Chacko, New York University, Tandon School of Engineering

Sonia Mary Chacko received her B.Tech. degree in Electronics and Communication Engineering from Mahatma Gandhi University, Kottayam, India, and M.Tech degree in Mechatronics Engineering from NITK, Surathkal, India. She is currently a Ph.D. student in Mechanical Engineering at NYU Tandon School of Engineering, Brooklyn, NY. She is serving as a research assistant under an NSF-funded DR K-12 project.

Dr. Vikram Kapila, New York University, Tandon School of Engineering

Vikram Kapila is a Professor of Mechanical Engineering at NYU Tandon School of Engineering (NYU Tandon), where he directs a Mechatronics, Controls, and Robotics Laboratory, a Research Experience for Teachers Site in Mechatronics and Entrepreneurship, a DR K-12 research project, and an ITEST research project, all funded by NSF. He has held visiting positions with the Air Force Research Laboratories in Dayton, OH. His research interests include K-12 STEM education, mechatronics, robotics, and control system technology. Under a Research Experience for Teachers Site, a DR K-12 project, and GK-12 Fellows programs, funded by NSF, and the Central Brooklyn STEM Initiative (CBSI), funded by six philanthropic foundations, he has conducted significant K-12 education, training, mentoring, and outreach activities to integrate engineering concepts in science classrooms and labs of dozens of New York City public schools. He received NYU Tandon's 2002, 2008, 2011, and 2014 Jacobs Excellence in Education Award, 2002 Jacobs Innovation Grant, 2003 Distinguished Teacher Award, and 2012 Inaugural Distinguished Award for Excellence in the category Inspiration through Leadership. Moreover, he is a recipient of 2014-2015 University Distinguished Teaching Award at NYU. His scholarly activities have included 3 edited books, 8 chapters in edited books, 1 book review, 59 journal articles, and 133 conference papers. He has mentored 1 B.S., 21 M.S., and 4 Ph.D. thesis students; 38 undergraduate research students and 11 undergraduate senior design project teams; over 400 K-12 teachers and 100 high school student researchers; and 18 undergraduate GK-12 Fellows and 59 graduate GK-12 Fellows. Moreover, he directs K-12 education, training, mentoring, and outreach programs that enrich the STEM education of over 1,000 students annually.

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1. Introduction

Recent years have witnessed an accelerated growth in the advancement and diffusion of technology. For example, open source hardware (such as Raspberry Pi, Arduino, e-health sensors), open source software (for operating system, embedded computing, vision, graphics, animation, robotics), 3D printers, mobile communication and computing, the Maker movement, and online learning resources have democratized access to technology, unparalleled in human history. Moreover, cascading advances in machine learning, big data analytics, virtual and augmented reality, and robotics are poised to significantly and pervasively impact our society. In this backdrop, it is of paramount importance that all students receive high quality educational experiences in science, technology, engineering, and math (STEM) fields so that they become designers and creators of our technology-rich future instead of being mere consumers of technological products.

There are numerous on-going educational programs that seek to integrate and infuse varied manner of technologies in STEM instruction and learning (e.g., computers, internet and mobile applications, robotics, etc.). Recent research[1,2] has shown that robotics can serve as an effective pedagogical tool in STEM education. Educational robotics kits have been shown to enhance student engagement in STEM content.[3] Moreover, robotics is known to stimulate excitement and encourage participation of students in the classroom.[3] It is important to note that educational robotics kits are capable of addressing a wide array of content knowledge, e.g., computer programming,[4] engineering,[5] medical sciences[6] (including nursing procedures and medical operations), among others. In fact, a robotics-based educational framework can help learners visualize and understand abstract content knowledge in a tangible and concrete manner, enrich their kinesthetic learning, promote active learning, intrinsically and extrinsically motivate teachers and students, and thus improve the overall learning environment and outcomes.[7,8] Not surprisingly, in recent years, application of robotics in STEM education has witnessed a growing interest, becoming an area of active research,[9] and attracted significant efforts to incorporate robotics into STEM curricula.[10]

Middle school STEM (mainly math and science) curricula include a wide range of content that can benefit from the incorporation of robotics in teaching and learning. Application of robotics in middle school STEM education is appropriate since the age and maturity level of students demand a greater emphasis on the consideration of situated learning,[11] situated cognition,[12] cognitive apprenticeship,[13,14] intrinsic and extrinsic motivations,[15,16] collaborative learning, inquiry-based learning, and problem- and project-based learning,[17,18] anchored instruction,[19-21] etc. These myriad constructs of education research can be appropriately adapted and integrated in STEM teaching and learning through the use of robotics. Thus, mindful application of educational robotics kits in middle school pedagogy needs special attention and priority. However, research efforts to improve STEM teaching and learning outcomes in middle school that employ educational robotics kits, guided by the aforementioned educational research paradigms, are still nascent and include only a few preliminary initiatives.[1,2,22,23]

Nonetheless, based on our experience, we believe that leveraging the tremendous potential of robotics for its broad incorporation in STEM education requires teachers and students to develop sufficient *trust* in robotics. In this paper, by trust of teachers and students in robotics, we mean their willingness to believe in, understand, and accept the solutions provided by robots and to rely on the contributions of robots in STEM teaching and learning.[24] Many factors of robots may affect the trust of teachers and students towards robots.[25] However, two critical factors, *viz.*, the robot's overall performance and its incomprehensible or erroneous response while working with its human counterparts (teachers and students) usually affect a human's trust in the robots.[26] Human trust in robots has been widely explored in fields such as service, manufacturing,[27] etc. Moreover, in these fields, research has been conducted to assess and improve users' trust in the collaborating robots in order to enhance the effectiveness of the services provided by the robots and the efficiency of the human-robot collaborative operations. The concept of trust has also been studied in the context of education[28,29] and it usually concerns the relational trust among students, teachers, and parents. However, trust of teachers and students in robots in robotics-focused STEM education has not been studied yet. Thus, the impact of incorporation of robots in STEM education needs to be carefully examined using the construct of trust to establish and improve its efficacy.

Since middle school students are of a young age, not fully mature yet, and impressionable, they may fail to accept robots as a learning tool and may develop a permanent distrust in educational robotics technology if the robots used in their STEM lessons are not carefully designed to be trustworthy. Since educational robotics activities are often designed to promote situated cognition and learning, we believe that the lack of trust in robotics may adversely affect student's cognition and understanding of STEM concepts underlying the robotics lesson. Note that the concept of trust in robots for young age middle school students, who may have less experience with technologies in general and robots in particular, may differ from the concept of trust in robots for more experienced technology persons, including the teachers. Moreover, it may be necessary to examine whether different STEM disciplines and gender affect students' trust levels in robots for their robotics-aided lessons. The concept of trust in robots may also be connected to teachers' self-efficacy *vis-à-vis* using robotics as a pedagogical tool for teaching and learning disciplinary content. This requires that teachers consider trust in robotics when teaching robotics-focused STEM lessons. Unfortunately, no prior studies have investigated the aforementioned issues, thus limiting the broad and successful adoption of robotics-based STEM lessons in middle school classrooms.

Motivated by the above background, in this paper, we investigate the trust building of teachers and students in robots in robotics-focused STEM lessons in middle schools. Under the so called technological, pedagogical, and content knowledge (TPACK[30,31]) framework, our newly designed learning activities facilitate teaching and learning of pedagogically challenging science and math content by carefully adapting educational robotics technology. The work reported in this paper is based on the collaboration of project team (consisting of engineering and education faculty, researchers, and graduate students) with 20 middle school teachers (10 pairs of science and math teachers at 8 New York City schools) and observations of more than 250 middle school students in their robotics-based STEM lessons.

To begin, using appropriate questionnaire design techniques, we develop a "trust vocabulary" that elicits what the participants (i.e., teachers and students) mean by trust in the robots for their lessons and what factors and features of robotics may affect their trust. Next, we develop a qualitative trust assessment method using a Likert scale and derive a quantitative trust computational model. We compare the qualitative and quantitative trust measurements, validate the quantitative trust model, and also assess the trust levels of the participants in the robots that they use in their robotics-aided lessons. We propose several hypotheses and investigate whether there are any statistically significant differences in trust in robots between the teachers and students, disciplines such as science and math, and participants' genders. Based on classroom observations, we examine whether the level of trust of the teachers in robotics affects their pedagogy and the level of trust of the students affects the learning environment and their learning methods. Based on the trust assessment results and the results of a survey conducted with the participants, we show that there is a significant scope to enhance the trust levels of the participants in robots for robotics-based STEM lessons. The results are novel in that they advocate using robotics as a trust-worthy pedagogical tool under the TPACK framework, argue incorporating robotics into middle school STEM education curricula, and help maintain appropriate levels of trust of participants in robots, which may increase the effectiveness of the robotics-focused STEM learning framework and the overall learning outcomes.

The rest of the paper is organized as follows. Section 2 introduces a base robot that we used in robotics-focused STEM lessons. Section 3 introduces several illustrative robotics-aided science and math lessons that were implemented in middle school classrooms, and also provides information on the participating schools, teachers, and students. Section 4 presents trust modeling and trust measurement framework. Section 5 presents the implementation of the robotics-aided lessons in classroom settings and classroom observation procedures and protocols. Section 6 discusses the observation results while Section 7 presents the impact of trust on teachers' pedagogy and students' learning styles and outcomes. Section 8 presents a set of recommendations to improve trust in robotics for teaching and learning in middle school STEM classrooms. Section 9 considers limitation of this work and Section 10 presents concluding remarks and suggests future research directions.

2. The Base Robot

To implement various robotics-focused STEM lessons, we created a base robot, shown in Figure 1, using the LEGO Mindstorms EV3 robotics kit. The 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 held a three week long professional development (PD) workshop for the participating teachers. Through the PD workshop, using the LEGO kits, the teachers learned myriad robot-related tasks, such as assembly, programming, actuation, motion planning, sensor integration, operations, and troubleshooting.

Figure1: LEGO Mindstorms EV3 base robot.

3. Developing Robotics-Focused STEM Lessons and the Targeted Student and Teacher Population

The project team and participants of the PD workshop collaborated to plan and develop robotics-based lessons under the TPACK framework. The teachers identified 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 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, project personnel and teachers employed a design-based research (DBR) approach,[34] wherein iterative changes improved 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 redesign the lessons based on their local environment and circumstances prior to the actual classroom implementation. While the project personnel observed 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 (addition and subtraction), least common multiple (LCM), 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, etc. The teachers designed and constructed needed attachments for the base robot, created new or modified existing computer programs for the corresponding lessons, and developed the appropriate activity sheets before implementing a lesson in the classroom setting with students. The teachers guided the students to implement the activities using the robots during the actual class period and the students recorded the observations in activity sheets. Two representative lessons, one on science and another on math, are briefly reviewed in Table 1.

Table 1: Description of two representative lessons, one on science and another on math.

Subject	Lesson topics	Lesson description
Science	Force, mass, center of mass, inclination, gravity, friction, and displacement	As shown in Figure 2, a cardboard is used to create an inclined plane. The angle of incline is measured with a protractor. Altering the location of the LEGO brick changes the mass distribution of the robot structure and its center of mass. A program is developed to command the robot to travel along the inclined plane for various locations of the brick and for different angles of the incline. The distance traveled by the robot along the incline is measured using the ultrasonic sensor and the measurement is verified by the students using a tape measure. The direction of the vehicle movement is recorded for each condition. 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 mass, center of mass, inclination, gravity, friction, displacement, force, etc. The outcomes of the lesson are assessed by the teachers. Throughout the lesson, the following basic assumptions are made: (i) the students are familiar with the use of the protractor and the measurement tape; (ii) the readings of the ultrasonic sensor are accurate; (iii) the students can alter the location of the LEGO brick; etc.
Math	Least common multiple (LCM)	The teacher verbally teaches the theoretical concepts of LCM. The objective of the lesson was to teach how we apply the LCM of two whole numbers to a real life scenario. In this lesson, students apply the LCM concept by analyzing a scenario involving two subway cars (represented using two LEGO robots, see Figure 3). Both

		subway cars are on the same route, with one running local and the other running express. The students are provided two programmed LEGO robots and tasked to find the LCM of two whole numbers by analyzing and executing a problem-based scenario involving the local and express subway cars. The following scenario is presented to student using the LEGO robots: “You are on your way to watch a zombie apocalypse movie. Your BFF takes a local train and you are on an express train. You want to determine the subway stop at which both of you can meet to travel together.” This scenario is modeled using LEGO robots as follows. The local robot moves forward and stops every 3 seconds while the express robot moves forward but stops every 5 seconds. If the robots start together at the same time, will they ever stop at the same stations? If yes, then the students need to find out the first stop that the local and express robots will arrive at? This lesson aligns with the CCSSM (6.NS.B.4) and the NGSS (MS-ETS1-2, MS-ETS1-3). The students record the observations on the activity sheets. From the robot activities, the students learn and practice the concepts of LCM. Throughout the lesson, the following basic assumptions are made: (i) the students are familiar with the subway transportation system; (ii) the students are familiar with whole numbers; etc.

Figure 2: Learning the concepts of force, mass, center of mass, inclination, gravity, friction, and displacement in a middle school science lesson implemented using robotics kits.

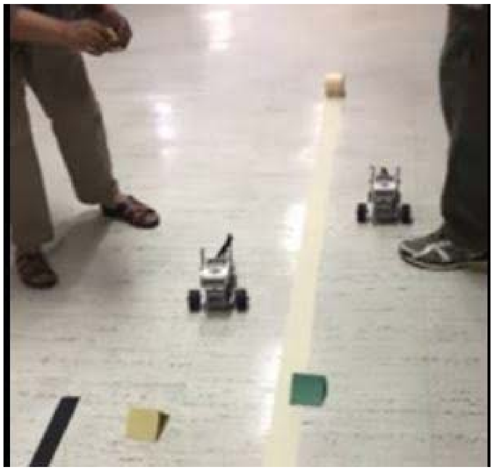

Figure 3: The classroom environment where the students learn the concepts of least common multiple (LCM) using the movement and stopping of two LEGO robot cars (local and express). The colored paper pieces help identify the locations where the robots stop temporarily.

Throughout the two lessons, the following general assumptions are made: (i) the robots are well-designed and the programs are accurate; (ii) the students possess basic skills to operate the LEGO robots, e.g., commanding the robots by pressing buttons; (iii) the students are able to use the activity sheets and the selected activities truly reflect the lesson topics; (iv) the students are interested to perform hands-on activities in teams; (v) the lesson topics and the activities align with the CCSSM and the NGSS; etc.

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

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

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	270
Number of male (boy) students	131
Number of female (girl) students	139
Number of girl students who attended math lesson	82
Number of girl students who attended science lesson	57
Number of boy students who attended math lesson	84
Number of boy students who attended science lesson	47
Student grade levels	6th to 8th
Usual length of a lesson	45 min.
Number of students in a class	10-25

4. Trust Modeling and Measurement

4.1. *Trust Modeling*

Trust is a matter of perception and a person may perceive trust in another person or in an artificial agent (e.g., a robot). Although physiologically it is not possible to measure a human's trust in another human or in an artificial agent, nonetheless, the human may express his/her trust in different ways. Intuitively, a human's trust in another human or agent may depend on such human or agent's past and present activities, behaviors, and interactions with the human. In addition, the trust may be dynamic and may change with time and situations. However, a computational model of a human's trust in a robot may be proposed. Though the trust of a human in another agent may depend on myriad factors, to model and compute a human's trust in a robot, a time-series model has been proposed[27] utilizing only the performance and fault status of the robot. Based on the framework of Ref. 27, a general computational model of human trust (i.e., trust of a student or a teacher) in the robot (i.e., the LEGO robot) can be expressed as below:

$$T(t)=\phi_0 T(t-1)+\phi_1 PF_{\mathrm{R}}(t)+\phi_2 PF_{\mathrm{R}}(t-1)+\phi_3 FF_{\mathrm{R}}(t)+\phi_4 FF_{\mathrm{R}}(t-1)+u(t) \tag{1}$$

where $T(t)$ is a teacher or student's trust in the LEGO robot after an interaction period of t with the robot during the robotics-aided STEM lesson in the classroom environment, $PF_{\mathrm{R}}(t)$ and $FF_{\mathrm{R}}(t)$ denote the contributions of the performance factor and fault factor, respectively, of the robot to the trust $T(t)$, ϕ_i, i=0,1,…4, are real-valued constants relevant to specific human-robot system (student/teacher-robot interaction system), and $u(t)$ is a random perturbation or uncertainty (if any) during the period t. The proposed model may be an ordinary deterministic regression model and an error-based learning algorithm regarding the robot's performance and fault making behaviors, but here it is treated as the computed trust of the student/teacher in the robotic kits.[27]

We consider the trust of the teachers and students in the robot based only on the interactions that the teachers and students make with the robot for a particular period of lesson in the classroom. Thus, t is the length of the lesson period (e.g., 45 minutes) and we ignore the teachers and students' prior trust in the robot as the teachers and students' prior trust and the robot's prior performance and fault making status are either unknown or unavailable. Hence, in (1), we ignore the terms $\phi_0 T(t\text{-}1)$, $\phi_2 PF_{\mathrm{R}}(t\text{-}1)$, and $\phi_4 FF_{\mathrm{R}}(t\text{-}1)$. By assuming that there is no perturbation or uncertainty in the trust assessment, we can also ignore the term $u(t)$ in (1). In this case, the trust model of (1) is simplified as in (2) below.

$$T(t)=\phi_1 PF_{\mathrm{R}}(t)+\phi_3 FF_{\mathrm{R}}(t) \tag{2}$$

That is, we now consider a computational model of trust only for the current period of interaction, and the model is simply a computational model instead of a dynamic model.

4.2. Trust Measurement

As seen from (2), we need to measure the robot performance, the robot fault making status, and the values of ϕ_1 and ϕ_3 to measure the trust of a teacher or a student for the period of interaction (lesson period) with the robot. Two almost similar questionnaires are developed for collecting responses of the teachers and students after their interactions with the robots performing robotics-aided science or math lessons. The teacher and student questionnaires are shown in Appendix A and Appendix B, respectively. Questions Q5 and Q6 of the questionnaires are intended to measure a participant's responses about the performance level and the fault making status of the robot for the period of interaction with the robot during the classroom robotics lesson. The responses are collected on a Likert scale, where 1 is the lowest score and 7 is the highest score. Here, the score of 7 for the robot performance means that the robot shows the highest level of performance during interaction with the teachers and students. In contrast, the score of 7 for the robot fault status means that the robot either makes least amount of mistake or does not make any mistake during interaction with the teachers and students.

Prior to conducting a robotics-aided STEM lesson during which trust measurements are to be performed with the teacher-student cohorts, a practice session may be arranged to allow the cohort to experience interacting with the robot. The information obtained on the robot performance and the robot's fault making status during the practice sessions may be used to compute the constants ϕ_1 and ϕ_3 of the trust model in (2) following the Autoregressive Moving Average Model (ARMAV) method.[35] However, in this paper, we do not consider any practice lesson with the teachers and students using the LEGO robots. Instead, we simply inherit the values of ϕ_1 and ϕ_3 from similar human-robot collaborative activities as reported in Ref. 27, i.e., we estimate ϕ_1=0.553 and ϕ_1=0.447. Alternatively, we may determine the values of ϕ_1 and ϕ_3 based on the proportion of contribution of the factors related to robot performance and robot fault affecting participants' trust using the responses of the Questions Q2 and Q4 in the Appendices A and B, to be addressed later. We expect that $\phi_1 + \phi_3 \approx 1$. Hence, the maximum and minimum computed trust in (2) will be $T_{\max}(t)$=7 and $T_{\min}(t)$=1, respectively.

5. Classroom Observations

Each science and math teacher randomly selected a robotics-aided science or math lesson from the list of lessons introduced in Section 3 and implemented it individually in his/her classroom. The project personnel visited the classrooms and observed the teachers and students performing the robotics-based science or math lessons. We adopted the following two hypotheses for investigation during our classroom observations.

1. **Hypothesis I**: There are noticeable differences in trust levels in robotics between teachers and students, science and math lessons, and male and female participants.

2. **Hypothesis II**: Teachers and students' varying trust levels in robotics affect the teachers' pedagogy and the students' learning styles and learning outcomes.

We then asked the teachers and students to respond the questionnaires in Appendices A and B, respectively. Thus, each teacher and student responding to the questionnaires had experience of teaching/learning at least one science or math lesson using robotics in a classroom setting. The teachers explained the questionnaires to the students before the students started responding to it. We also recorded major findings during our observations, especially we recorded student engagement, behaviors, attitude towards the robots, their learning styles, levels of understanding, etc. We also completed a general observation protocol sheet to form ideas and opinions about teachers' pedagogy and classroom environment.

6. Classroom Observation Results

6.1. Perceived Definitions of Trust

We analyzed the responses to Q1 in the questionnaires for the teachers and students and tried to identify the key terminologies that the respondents used to define their trust in the robot used in their science or math lessons. Then, we counted the frequencies of the terminologies and determined their relative contribution to the entire pool of frequencies of terminologies (see Figure 4). The figure shows that 41.57% of respondents perceived trust as their reliance on the activities of the robots used in their lessons. Similarly, 30.71% of respondents perceived trust as believing the results produced by the robots in the classrooms lessons. We see that 13.48% of respondents expressed their trust in the robots as the loyalty and obedience of the robots with respect to the commands the respondents gave to the robots. The results show that 10.11% of respondents defined their trust in the robots as their confidence in the functions, abilities, and strengths of the robots to solve the problems related to the classroom lessons. Finally, only 1.13% of respondents perceived their trust as the compatibility of their expectation and desire with the behaviors that the robots showed during the classes.

6.2. Factors Affecting Teachers and Students' Trust

We analyzed the responses to Q2 and Q4 in the questionnaires for the teachers and students and tried to identify the key terminologies that the respondents used to express their opinions regarding the factors/characteristics of the robots used in their science or math lessons that might influence their trust in the robots. Then, we counted the frequencies of the terminologies and determined their relative contribution to the entire pool of frequencies of terminologies (see Figure 5). The figure shows that the major factors/characteristics of the robots that might affect the trust of respondent are the accuracy or correctness of the results produced by the robots (e.g., sensor readings), capability of the robot, quality of the robot speed and displacement, and the ease of programming and control.

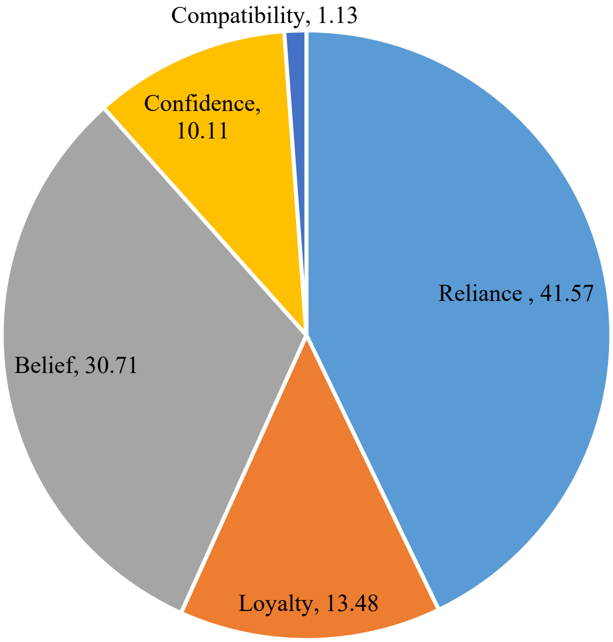

Figure 4: Terminologies with their relative contribution (%) that the responding teachers and students used to define their trust in the robots used in the classroom lessons.

Figure 5 shows, 2.8% of respondents expected that the robots should have stable behavior (e.g., should not shutdown unexpectedly or malfunction during classroom activities); 1.6% expected that the robots should act promptly while serving the students; 1.6% expected that the robot activities, especially its programming, should be more transparent; 0.4% expected that the robot should have the ability to express love and affection to the students; 0.4% expected that the robots should have better lighting features (e.g., LED in buttons); 2.8% thought that the robots should have capability to produce more sounds and speak with the students and the teachers; 1.2% expected that the robot appearance needs to be more attractive and colorful; 0.8% thought that all the robots were identical in appearance and there should have been some features to identify each robot easily; 2% opined that they would trust the robots more if they could own the robots; 1.6% thought that the robots should be more human-like in appearance and functionalities; 2% opined that they would trust the robots more if the robots had more versatility and flexibility in configurations and functions; 3.2% thought that the robot components (motors, sensors, buttons, bricks, wires, wheels, etc.) should be better; 1.2% thought that they should be able to operate the robots remotely; 2.8% thought that the robots should be more intelligent (able to understand obstacles, dangerous paths, surrounding humans, etc.); 1.6% said that the robot functions and features should be more relevant and suitable to exemplify the contents of the lessons; 1.2% expected that the robots should be more compliant (safe, harmless); 2.8% expected that the robots should produce more repeatable results; and 0.4% said that the robots would meet their overall expectations during their use in classroom lessons.

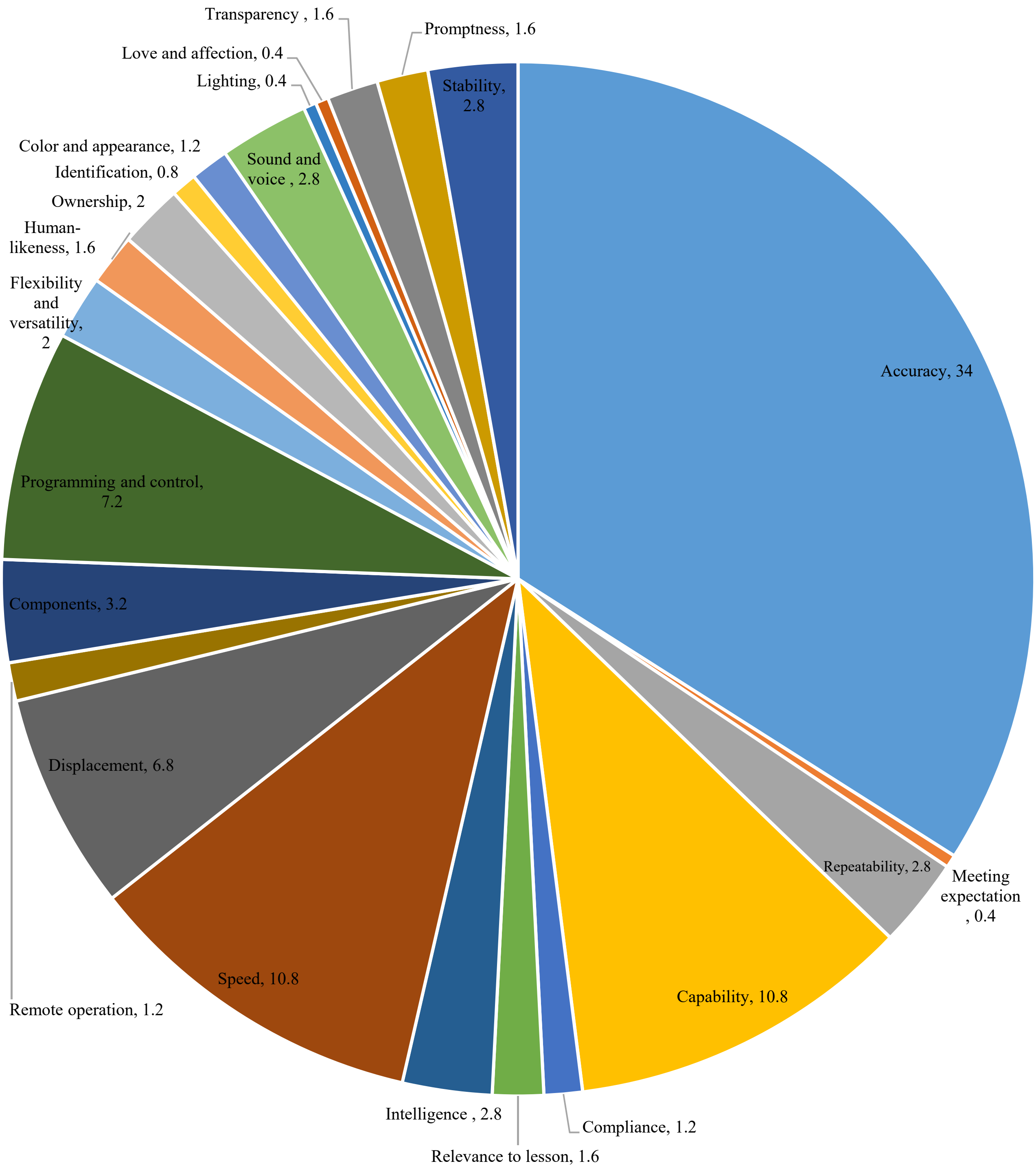

Figure 5: Terminologies with their relative contribution (%) that the responding teachers and students proposed as factors/characteristics of the robots influencing their trust in the robots for using the robots in science/math lessons in middle school classrooms.

6.3 Determination of Weights of the Performance and Fault-related Trust Factors

We identified the trust factors shown in Figure 5 that are directly or indirectly related to the performance and fault generation of the robots, and re-categorized the factors into two major groups: (i) performance factors (e.g., speed, capability, sound and voice production, intelligence level, displacement, remote operation, programming and control, flexibility and versatility, performance of components, lighting production, relevance of robot activities to lesson, and promptness in activities) and (ii) fault factors (i.e., stability, repeatability, accuracy, and compliance). Figure 6 shows the relative contributions of the performance and fault factors to the total pool of the factors affecting trust. Figure 6 shows that 92% of factors are related to robot performance and faults, of which 51.2% are related to performance and 40.8% are related to faults. Based on this information, we determined the weights of the robot performance ϕ_1 and robot fault ϕ_3, as shown below in (3) and (4), respectively, for use in the computational model of trust in (2).

$$\phi_1 = \frac{51.2}{92} = 0.5565 \tag{3}$$

$$\phi_3 = \frac{40.8}{92} = 0.4535 \tag{4}$$

6.4. Analysis of Assessed and Computed Trust

We analyzed the responses to Q3 in the questionnaires for the teachers and students and determined the mean trust of the teachers and students. Moreover, we distinguished the responses by subjects (science or math), status (teacher or student), and gender (male or female). We call this trust the *assessed trust*. The results are shown in Figure 7, which is based on responses from 130 male students (boys) and 138 female students (girls), among whom 165 were in a math lesson and 103 were in a science lesson. The results in Figure 7 show that the boys had more trust in the robots than that the girls. A one-way Analysis of Variance (ANOVA) test shows that the assessed trust in the robots between the boys and girls has a statistically significant difference ($F(1, 266)=7.72$, $p=0.0059$). However, as evidenced in Figure 7, opposite results were obtained for the male versus female teachers, i.e., the female teachers had more trust in the robots than that the male teachers. As seen in Figure 7, the students who participated in a science lesson with the robots had better trust in robots than that the students who participated in a math lesson. A one-way ANOVA test shows that the assessed trust of the students in the robots between science and math lessons has a statistically significant difference ($F(1, 266)=26.86$, $p=0.43\times10^{-6}$). Similar results were also obtained for the teachers, i.e., teachers who participated in a science lesson with the robots had better trust in robots than that the teachers who participated in a math lesson. We believe that the differences in the nature of robot activities and the required levels of accuracy and performance between science and math lessons may have resulted in different trust levels of respondents for science and math lessons. The aforementioned results also support Hypothesis I.

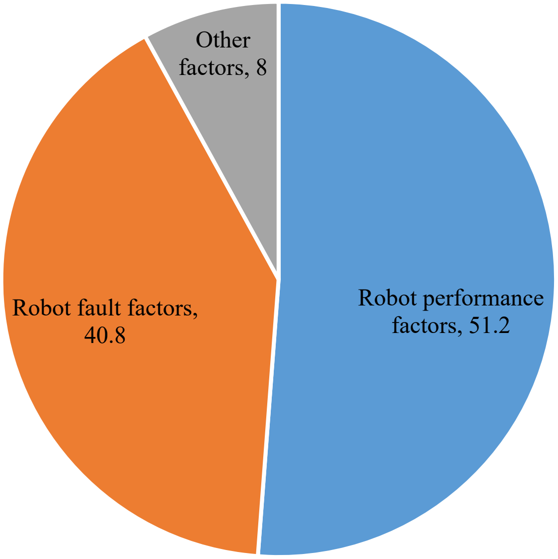

Figure 6: Relative contribution (%) of the factors related to robot performance and robot faults affecting the trust.

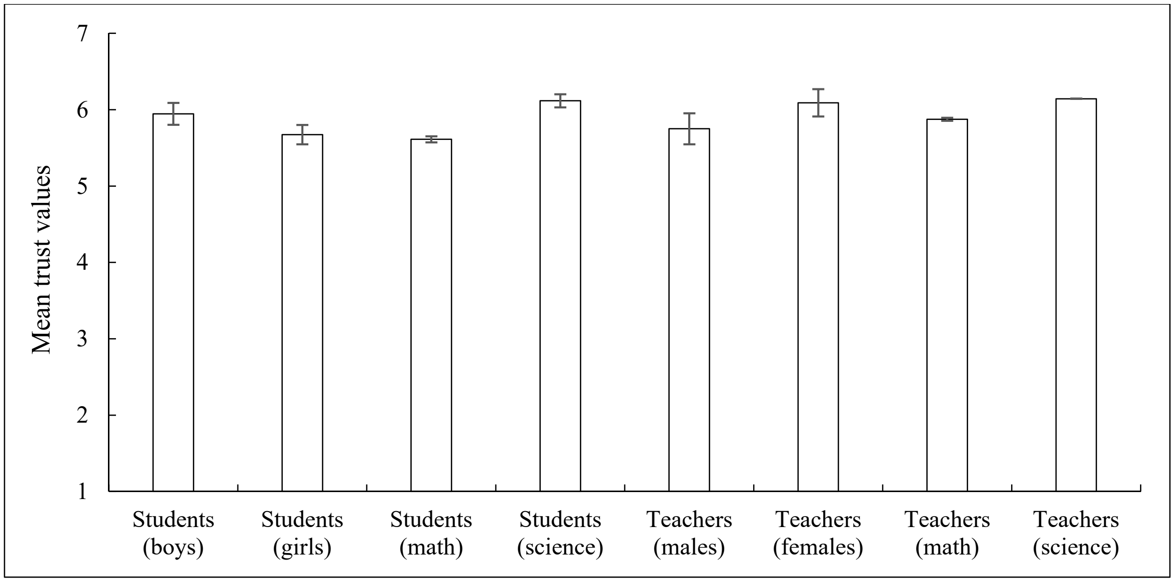

Figure 7: Distinguishing the trust in robots by subjects (science or math), status (teacher or student), and gender (male or female) for the *assessed trust*. The error bars represent 95% confidence interval.

Similarly, we analyzed the responses to Q5 and Q6 in the questionnaires for the teachers and students and used these values along with the values of ϕ_1 and ϕ_3 in (3) and (4), respectively, and computed the mean trust of the teachers and students in robots using (2). As above, we also distinguished the trusts by subjects (science or math), status (teacher or student), and gender (male or female). We call this trust the *computed trust*. The results are shown in Figure 8, which is based on responses from 128 boys and 126 girls, among whom 153 were in a math lesson and 101 were in a science lesson. A one-way ANOVA test for the computed trust in the robots between the boys and girls is found to yield a statistically significant difference ($F(1, 252)=12.59$, $p=0.0005$). Next, a one-way ANOVA test for the computed trust of all students in the robots between math and science lessons is also found to yield a statistically significant difference ($F(1, 252)=9.41$, $p=0.0024$).

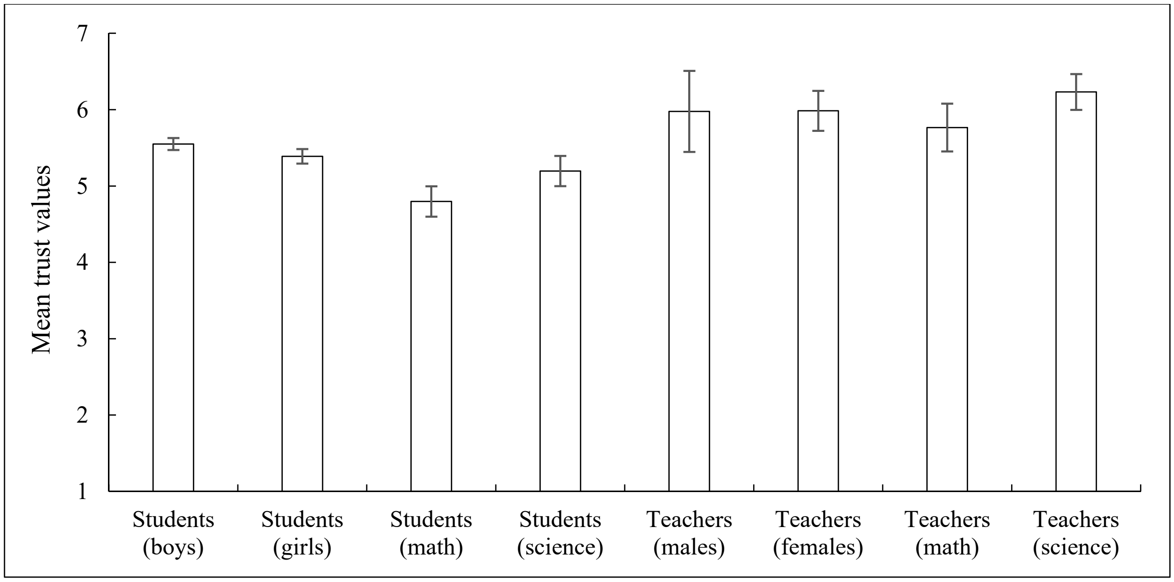

Figure 8: Distinguishing the trust in robots by subjects (science or math), status (teacher or student), and gender (male or female) for the *computed trust*. The error bars represent 95% confidence interval.

We also conducted a one-way ANOVA test between the assessed and computed trusts for all students (number of student respondents: 268 for assessed trust and 254 for computed trust) and found that the difference between the assessed and computed trusts is not statistically significant ($F(1, 520)=2.49$, $p=0.115$), which validates the computational models of trust in (2), i.e., it is verified that the human's trust in robot is really related to robot performance and its fault history as modeled in (2), but with varying weights. Finally, Figure 9 shows the comparison for all students' and all teachers' trust in robots for the assessed trust values. The results show that the students had less trust in the robots than their teachers. We believe that the age differences between the teachers and students influenced the students to trust the robots less.

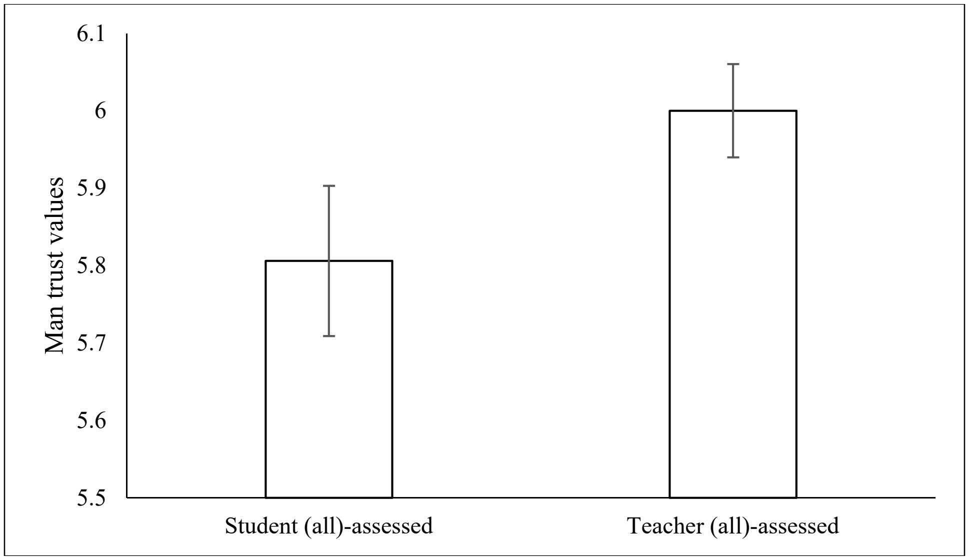

Figure 9: Distinguishing the trust in robots by status (teacher or student). The error bars represent 95% confidence interval.

7. Effects of Trust on Pedagogy, Learning Styles, and Teaching and Learning Effectiveness and Outcomes

We analyzed the responses to Q7 in the questionnaires for the teachers and students to understand the effects of trust of teachers and students in robots on the pedagogy of the teachers, the learning styles of the students, and the overall teaching and learning effectiveness and outcomes.

7.1. Effects of Trust on Pedagogy

We observed that if teachers trusted the robots less, they wanted to engage in more discussions with students. This indicates that the teachers with low trust in robots did not deem the results to be very reliable and thus discussed the results more critically with students to reach a reliable or credible level of results or findings. The opposite happened when the teachers trusted the robots more. In such cases, the teachers depended on the results produced by the robots, thought the results as perfect, and felt less inclined to discuss the results with the students. Instead, the teachers asked students to follow what the robots were showing. This indicates that the teachers' participatory or authoritative teaching strategy was guided by their levels of trust in the robots. During the evaluation of students' performance, the teachers who trusted the robots less became stricter and less receptive to the solutions proposed by the students. The opposite happened for the teachers who trusted the robots more. Such teachers became less strict and more receptive to the solutions proposed by the students, agreeing with what the students were proposing to do with the robots. The teachers who trusted the robots more were observed showing more interest about project-based learning and exploratory learning strategies. Such teachers were more interested and hopeful about incorporating the use of robots and other technologies as pedagogical tools into their curricula. The opposite was observed for the teachers who trusted the robots less. They showed pessimism and less interest in incorporating robots and other technologies into their lessons and curricula. Instead, they expressed interest to observe the performance of robots on trial basis for a long time before considering the incorporation of robots into curriculum formally.

7.2. Effects of Trust on Students' Learning Styles, and Teaching and Learning Effectiveness and Outcomes

The project personnel's observations indicate that the students who trusted the robots less asked more questions from their teachers because they felt less confident about the results as well as about their own knowledge and skills. Such students showed a tendency of verifying their results with other students or with the students who learned the similar lessons without using robots. These students tried to avoid robots and other technologies in classrooms and sought opportunities to perform activities manually. The opposite was observed with the students who trusted the robots more.

We observed that the use of robotics in lessons made the activities visible and the students found a tangible tool to practice and learn. If the students trusted the robots more, they became more attentive with the robots, which helped grow their engagement with lessons. The students were less distracted and less noisy and the classroom environment was calm if the students trusted the robots more. The opposite was observed with the students who trusted robots less.

The teachers reported and our observations confirmed that the students understood better and learned better if they trusted the robots more. This is further validated by the students' responses to questionnaires and their classroom performance assessment by the teachers. For example, after the completion of the lesson with robotics and after responding to the trust assessment, a quiz session comprising of 10 questions on the subject matter was administered by the teacher. The questions were displayed on a computer monitor and every student needed to respond to a single question. The researcher observed that the students who could not respond to the questions correctly usually also rated their trust in robotics as comparatively lower. The opposite happened for the students who trusted the robots more, i.e., they could respond the questions accurately and demonstrated better reasoning behind their responses.

It was observed that the students who trusted the robots more could remember their lesson more and could express their understanding in better ways. For example, in one classroom, the researcher briefly discussed a few events that happened in lesson(s) conducted with the students in recent past. The researcher observed that the students who could not recollect the events from the past lesson(s) properly usually also rated their trust in robotics as comparatively lower. The opposite happened to the students who trusted the robots more, i.e., they could remember the events from the prior lesson(s) more, explain the events as well, and demonstrate their understanding in better ways. We posit that the students who trusted the robots more perhaps developed a deeper interest in the robot, which persisted in their memories as ‘good, memorable events’ and affected their cognition and comprehension positively. The above results validate the Hypothesis II.

8. Scope to Develop/Improve Trust in Robots for STEM Education in Middle Schools

Figure 5 shows the factors affecting the participants’ trust in the robots. We believe that guided by the factors identified in Figure 5, it is possible to develop trust in robots or improve the existing trust levels of teachers and students in robots. Table 3 shows the factors and the descriptions of how we can improve these factors to develop trust of teachers and students in robots. Note that more emphasis ought to be placed on factors that have more weight on trust as evidenced in Figure 5.

Table 3: The ways of developing/improving trust in the robots eliciting the trust factors

Trust factors	Proposals on how the trust factors can be addressed to develop/improve trust
Accuracy	A major factor/characteristic of the robot that can affect the trust of teachers and students is the accuracy or correctness of the results produced by the robots (e.g., sensor readings). The sensors should be properly selected considering the task context, integrated into the program carefully, calibrated properly, tested before actual use, etc. It is also necessary to remove all objects from the working environment that may adversely affect the functioning of the sensors. Floor surface should be appropriate. Parameters set in the programming should be checked carefully.
Capability of the robot	Capability and functionality of the robot can be improved by selecting appropriate robot configuration, making the design appropriate for the intended activities, programming the function properly, etc.
Quality of the robot speed and displacement	Quality of the robot speed and displacement may be improved by using suitable wheels and floor surface, setting appropriate power level, avoiding abrupt change in motion or direction of movement, removing obstacles from the intended path of the robot, arranging the wires properly so that these do not impede the motion, keeping the LEGO brick in the middle of the structure, etc.
Ease of programming and control	The teachers should simplify programming and also transfer the ideas to the students, if possible. The programming should be made less complex by using appropriate sensors, simple logic, and maintaining modularity in functions, etc.
Stability	The stability of the robot may be enhanced by checking the power level, wiring, button functioning, etc., properly before the lessons start. This will help reduce unexpected shutdown or malfunctioning of the robot during classroom activities.
Promptness	To reduce delay in robot operations, unnecessary sleep times added in the program should be removed or reduced. An easily distinguishable name of the program should be given so that the program can be easily identified when operating the robot based on the program commanded through the buttons.
Lighting	Better lighting features such as LED in buttons should be ensured.
Sounds and voice	The robot should be given more capability to produce more meaningful sounds based on situations during lessons.

Robot color	The robot appearance may be made more attractive and colorful.
Identification	The robots should not be identical in appearance and should include some features to identify one robot from others easily.
Versatility and flexibility	Versatility and flexibility in configurations and functions may be achieved through proper design, use of robot components, sensors, and programming.
Robot components	Robot components such as motors, sensors, buttons, bricks, wires, wheels, etc. can be made better in terms of appearance and functionalities by the manufacturers and be selected in better ways by the teachers and students.
Intelligence and compliance	The robots should be made more intelligent and compliant (safe, harmless) through the use of control and decision-making algorithms and sensors so that the robots are able to understand obstacles, dangerous paths, surrounding humans, etc. and do not do any harm to humans (students and teachers).
Relevant to lesson content	The robot functions and features can be made more relevant to the lessons so that it becomes easy for the teachers to exemplify the contents of the lessons using robotics.
Repeatability	The results produced by the robot should be made repeatable. The level of accuracy may also affect the repeatability.

9. Limitations of this Work

This work has several limitations. First, we qualitatively assessed the impact of participants' trust in robots used in the STEM lessons on pedagogy, teaching effectiveness, and learning outcomes. Reformulating this assessment using quantitative methods can help reveal the impact more accurately. Second, we did not consider any connections between teachers' trust in robotics and their corresponding TPACK self-efficacy. Third, we examined the participants' trust in robots while conducting robotics-focused science and math lessons in actual classroom setting in middle schools. Nonetheless, these robotics-focused STEM lessons were conducted during a pilot study, wherein the robots are not fully integrated in the curriculum. Thus, the teachers, students, and school administrators may have considered such robotics-focused lessons as special events, introducing a novelty effect, which may have resulted in participants' performing significantly different *vis-à-vis* regular classroom lessons. Fourth, we introduced robotics-focused STEM lessons without assessing students' preconceptions, prior knowledge, and self-efficacy of robots. Integration of robotics in STEM lessons can offer several learning benefits to students, e.g., acquisition of new knowledge about robots, learning robotics-related vocabulary, gaining skills in robotic design, and developing proficiency in performing basic operations of the robot. Nonetheless, we did not seek to determine the minimum pre-requisite knowledge and skills in robotics that students need to possess to participate in robotics-focused STEM lessons. Thus, it is not possible to determine how much of students' lack of trust in robotics resulted due to poor performance of the robots versus their lack of understanding about how a robot works. Fifth, we developed the instrument of Appendix B to assess students' trust in robots. The appropriateness of question used in this instrument was discussed with some teachers and, when seeking student responses, the teachers verbally explained the questions to them. The responses obtained from the students imply that they understood the questions. However, we did not formally examine whether the instrument of Appendix B is appropriate for the age and maturity level of middle school students.

10. Conclusion and Future Work

Under a summer PD program, we developed several middles school science and math lessons that incorporate LEGO robotics. The participating teachers received training in the design, development, and implementation of robotics-based science and math activities. During the academic year, the teachers implemented the lessons in the classroom environment. We modelled the trust of teachers and students in robots for the involvement of the robots in the lessons. We observed the implementation of the robotics-focused science and math lessons. Based on our observations and the responses provided by the teachers and students, we developed a trust vocabulary, which reveals what the teachers and students actually mean by their level of trust in the robots. We also identified the factors and characteristics of the robots that affected the trust of teachers and students in the robots. We determined the relative importance of the factors. The students and the teachers assessed their trust in the robots subjectively based on their experience with the robots. We compared the qualitatively assessed and the quantitatively computed trust measures, validated the quantitative trust model, and also determined the trust levels of teachers and students in the robots that they used in their robotics-aided lessons. We investigated whether there were statistically significant differences in participants' trust in robots, e.g., by subjects (science or math), status (teacher or student), or gender (male or female). The results showed that the trust levels differ for male and female participants and those who participate in science and math lessons. Based on classroom observations, we analyzed whether the level of trust of the teachers in robotics affected their pedagogy. Moreover, we examined whether the level of trust of the students in robotics affected the learning environment, learning methods, and the learning outcomes. The results showed that the level of trust affects teachers' pedagogy and students' learning styles and learning outcomes. We showed that there is significant scope to enhance the trust levels of teachers and students in the robotics for STEM education. The results are novel in that they advocate using robotics as a trust-worthy pedagogical tool under the TPACK framework, argue incorporating robotics into middle school STEM education curricula, and help maintain appropriate levels of trust of teachers and students in robots, which may increase the effectiveness of the robotics-focused STEM learning framework and the overall learning outcomes.

In future work, we will consider following aspects. First, we will develop additional instruments to quantitatively assess the impact of trust of teachers and students in robotics used in STEM lessons on pedagogy, teaching effectiveness, and learning outcomes. Second, we will examine how teachers' trust in robots may be connected to their corresponding TPACK self-efficacy. Third. we will seek to determine the minimum pre-requisite knowledge and skills in robotics that students require to effectively participate in robotics-focused STEM lessons. Fourth, we will formally investigate the validity of instruments used in this study. Fifth, we will investigate how robotics can be made more trustworthy and incorporated into regular STEM curriculum. Sixth, we will conduct our studies with a larger number of students and teachers to increase the statistical significance of the results and prove the generality of the results.

Acknowledgements

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Appendix A

Questionnaire for teachers

Subject: Math/Science Teacher's gender: Female/Male Date: School name:

Q 1: How do you define your trust in the robot that you have used in your lesson?

Q 2: Do you trust the robot for your lesson? If yes, then please write why? If no, then please write why?

Q 3: Please rate your level of trust in the robot for your lesson? Please circle the most appropriate statement.

- I strongly distrust the robot (score: +1)
- I distrust the robot (score: +2)
- I slightly distrust the robot (distrust somewhat) (score: +3)
- I am neutral/undecided/uncertain (score: +4)
- I slightly trust the robot (trust somewhat) (score: +5)
- I trust the robot (score: +6)
- I strongly trust the robot (score: +7)

Q 4: What features/characteristics and performance levels the robot should have to gain your trust? (What the robot should have more or what the robot should do more for the lesson so that you can trust it more)

Q 5: What is the performance level of the robot? (Examples, appropriateness of the robot speed such as the robot was too fast or too slow; stability of the robot; functionality/suitability of the wheels, buttons, sensors, wires, etc.). Please circle the most appropriate statement.

- Very low (score: +1)
- Low (score: +2)
- Slightly low (score: +3)
- I am neutral/undecided/uncertain (score: +4)
- Slightly high (score: +5)
- High (score: +6)
- Very high (score: +7)

Q 6: What is the fault-avoidance ability of the robot? (It means the ability of the robot that it does not make any mistake or the ability of being the correct. A few mistakes may be that the sensor does not show correct reading, the robot does not follow the commanded path exactly, for example, the program says that the robot should go straight, but it slightly deviates from the straight path, or the robot should make a 90 degree turn, but it turns with a significantly different angle, etc.). Please circle the most appropriate statement.

- Very low (score: +1)
- Low (score: +2)
- Slightly low (score: +3)
- I am neutral/undecided/uncertain (score: +4)
- Slightly high (score: +5)
- High (score: +6)
- Very high (score: +7)

Q 7: What strategy do you follow/use to integrate the robot into your regular curriculum as a pedagogical tool?

Appendix B

Questionnaire for students

Student's grade: Subject: Math/Science Student's gender: Boy/girl Date: School:

Q 1: How do you define your trust in the robot that you have used in your lesson?

Q 2: Do you trust the robot for your lesson? If yes, then please write why? If no, then please write why?

Q 3: Please rate your level of trust in the robot for your lesson? Please circle the most appropriate statement.

- I strongly distrust the robot (score: +1)
- I distrust the robot (score: +2)
- I slightly distrust the robot (distrust somewhat) (score: +3)
- I am neutral/undecided/uncertain (score: +4)
- I slightly trust the robot (trust somewhat) (score: +5)
- I trust the robot (score: +6)
- I strongly trust the robot (score: +7)

Q 4: What features/characteristics and performance levels the robot should have to gain your trust? (What the robot should have more or what the robot should do more for the lesson so that you can trust it more)

Q 5: What is the performance level of the robot? (Examples, appropriateness of the robot speed such as the robot was too fast or too slow; stability of the robot; functionality/suitability of the wheels, buttons, sensors, wires, etc.). Please circle the most appropriate statement.

- Very low (score: +1)
- Low (score: +2)
- Slightly low (score: +3)
- I am neutral/undecided/uncertain (score: +4)
- Slightly high (score: +5)
- High (score: +6)
- Very high (score: +7)

Q 6: What is the fault-avoidance ability of the robot? (It means the ability of the robot that it does not make any mistake or the ability of being the correct. A few mistakes may be that the sensor does not show correct reading, the robot does not follow the commanded path exactly, for example, the program says that the robot should go straight, but it slightly deviates from the straight path, or the robot should make a 90 degree turn, but it turns with a significantly different angle, etc.). Please circle the most appropriate statement.

- Very low (score: +1)
- Low (score: +2)
- Slightly low (score: +3)
- I am neutral/undecided/uncertain (score: +4)
- Slightly high (score: +5)
- High (score: +6)
- Very high (score: +7)

Q 7: Did the robot help you learn your lesson? How?