Developing Proportional Reasoning via Lego Robotics: Experiences of a 7th Grade Mathematics Class

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Abstract

A qualitatively oriented mixed methods case study was conducted to investigate the effects of incorporating LEGO robotics into a 7th-grade mathematics curriculum. Using the lenses of Social Constructivist Theory and the Five Stages of Technology Integration, this research focused on the development of proportional reasoning skills. The data show students experienced success in developing their proportional reasoning skills as they completed tasks using the robotics. The quantitative data shows evidence of growth in understanding and development of proportional reasoning. The qualitative analysis provides evidence that students developed their understanding through collaborative discussions as they worked through the different technology stages. Overall, students enjoyed the opportunity to learn with the robotics because it was hands-on and applicable to their lives.

Introduction

The Successful Middle School: This We Believe (Bishop & Harrison, 2021) encourages the development of curricula that is "challenging, exploratory, integrative and diverse" (p. 27). The National Council of Teachers of Mathematics (NCTM, 2014) advocates for curricula that promote access and equity while integrating technology to promote deeper mathematical understanding. Similarly, Common Core State Standards for Mathematics (CCSSM) have "challenged middle level educators to reframe and refine the teaching of mathematics" (Pinter, 2016, para. 4). We posit that incorporating robotics into the mathematics curriculum can be an innovative way to address these challenges. LEGO® robotics has long been used successfully in after school and extra-curricular programs (Allen, 2013; Martinez Ortiz, 2015); however, there is research to suggest they can also be successfully implemented within the mathematics classroom (Casler-Failing, 2018a; 2018b; 2020; Sullivan & Heffernan, 2016). In this paper, we will share research conducted with 7th grade students incorporating LEGO® robotics as an instructional tool to support the development of proportional reasoning in a context that is both challenging and exploratory.

A student's ability to reason proportionally has been shown to be a gatekeeper to higher level mathematics (Jitendra, 2013; Langrall & Swafford, 2000) and has the power to influence real world situations and decision making. Determining whether one has enough money to buy two candy bars or drive 100 miles on the remaining gas in the vehicle is impacted by an individual's development of proportional reasoning skills. However, it is not enough to focus solely on content without considering the instructional strategies that will promote academic success. Research has shown that when students develop understanding through student-driven activities, they are more engaged and can achieve higher levels of academic success while simultaneously improving their critical thinking, problem-solving, and collaborative skills (Knezek & Christensen, 2020; McCoy, 2014; Worthington, 2018). With this knowledge, educators must be innovative in determining the instructional strategies that will support students' development of mathematical understanding in a manner that is supportive, engaging, and hands-on. We propose that using LEGO® robotics as an instructional tool may be a key to supporting students' development of proportional reasoning skills due to their hands-on, *playful* nature. More specifically, the research questions we sought to answer through this research were:

1) What effect do LEGO® robotics have on students' development of proportional reasoning skills when used as an instructional tool?
2) How do students develop proportional reasoning skills when LEGO® robotics are used as an instructional tool?

Theoretical Framework

This research is informed, and analyzed, through the lenses of Social Constructivist Theory

(Vygotsky, 1978) and the Five Stages of Technology Integration (Carbonaro et al., 2014). Vygotsky proposed that students develop understanding through social experiences — questions posed and answered through conversations that occur when working in small groups can support reasoning and decision making. Furthermore, when students work with other students, their differing levels of understanding provide them opportunities to work within, and/or expand, their Zone of Proximal Development (ZPD).

Carbonaro et al. (2014) designed a technology framework incorporating five stages. In the research reported in this paper, all student investigations and activities were designed for (a) *engagement* to occur when students were presented with a task, (b) *investigation* through student discussion of the task to be completed, (c) *exploration* as the students decided on a solution path, (d) *creation* as students developed the solution, and (e) *evaluation* when students determined the success of their solution. All of the investigations and activities developed for this research provided opportunities for the students to apply each stage.

These frameworks naturally combine in this research as student collaboration was required during each technology stage; students were consistently required to discuss their "next steps" or evaluate their chosen solution. The conversations that organically developed during the activities were based on the students' current level of understanding and as the tasks increased in complexity the boundaries of their ZPDs were stretched. All data was analyzed through the lenses of Vygotsky's (1978) Social Constructivist Theory and Carbonaro et al.'s (2014) technology framework.

Literature Review

This literature review will provide background knowledge on proportional reasoning and robotics as an instructional tool. The literature will share the importance of proportional reasoning as a mathematics concept and how robotics can be used to develop the understanding of concepts in K-12 classrooms.

Proportional Reasoning

Proportional reasoning is a concept that has been the focus of much research over the last 40-50 years (i.e., Jitendra et al., 2019; Lamon, 1993; Langrall & Swafford, 2000; Lesh et al., 1988; Wollman & Lawson, 1978). Research has investigated the knowledge of specific mathematical concepts required to achieve proportional reasoning (Lesh et al.; Lamon), the different levels of understanding students may progress through in their development of proportional reasoning (Langrall & Swafford), and the instructional practices that promote the development of proportional reasoning (Casler-Failing, 2018a; 2018b; 2020; Jitendra et al.; Martinez Ortiz, 2015; Wollman & Lawson).

Lamon (1993) determined an important factor in the development of one's proportional reasoning skills is their ability to think relatively rather than additively. That is, students must develop conceptual understanding of proportional reasoning to demonstrate the multiplicative relationship between the two quantities in a ratio and understand it is not an additive relationship. Additionally, students must be able to make sense of the problems they are presented with to apply prior knowledge to the multiplicative relationship between ratios (Lamon). Langrall and Swafford (2000) built on Lamon's work to define four stages that students progress through as they develop proportional reasoning (see Table 1). Each level of understanding is further substantiated through a student's ability to verbally justify their solution process.

Table 1

Stages of proportional reasoning (Langrall & Swafford, 2000, p. 256)

Level / Description	Evidence
Level 0 - Non-proportional Reasoning	(a) guesses or uses visual cues (b) is unable to recognize multiplicative relationships (c) randomly uses numbers, operations, or strategies (d) is unable to link the two measures
Level 1 – Informal reasoning about proportional situations	(a) uses pictures, models, or manipulatives to make sense of situations (b) makes qualitative comparisons
Level 2 – Quantitative reasoning	(a) unitizes or uses composite units (b) finds and uses unit rate (c) identifies or uses scalar factor or table (d) build up both measures
Level 3 – Formal proportional reasoning	(a) sets up proportion using variables and solves using cross-product rule or equivalent fractions (b) fully understands the invariant and covariant relationships

Robotics as an Instructional Tool

In this manuscript, we use the term *instructional tool* to represent any mode of instruction that can be utilized to facilitate student-led instruction. To be considered an instructional tool, the following requirements should be met: students are engaged in learning, new content is presented, visual learning supports are provided, student input is required, feedback is provided, and students' ability to retain and transfer information is enhanced (Smaldino et al., 2004). An instructional tool is different from an instructional strategy, which can be defined as a "technique teachers use to help students become independent, strategic learners" (Alberta Learning, 2002, p. 67) such as learning logs, role playing, or jigsaw activities. In this research, LEGO® robotics were used as a tool to focus the students' learning — the students were responsible for making predictions, revising programming, testing their solutions, and evaluating their success — the robots provided the means to carry out the tasks and allowed students to visually determine if their solutions were valid.

Previous research has investigated critical thinking and problem-solving skills among mathematics students (Ardito et al., 2014); student development in the understanding of math and science topics, such as pi, statistical analyses, acceleration due to gravity, and fluid flow rate (Williams et al., 2012); and proportional reasoning during an extra-curricular program (Martinez Ortiz, 2015) and within a mathematics classroom (Casler-Failing, 2018a; 2018b).

Research shows students can make sense of, and organize, information through discourse and student-focused activities that incorporate robotics (Casler-Failing, 2018a; 2018b; 2020; Martinez Ortiz, 2015). Martinez Ortiz conducted research with 5th grade students during a one-week summer camp and reported that students who learned about ratios and proportions using robotics performed significantly better on a post-test than the control group who learned via a textbook. Ardito et al. (2014) used robotics as an application tool, not an instructional tool, and found that students improved in their ability to think critically and problem solve when applying their understanding to the tasks. Williams et al. (2012) conducted research with mathematics and science classes in the elementary, middle level, and high school grade bands. Their findings showed a 25% increase in mathematical understanding and reported on the student enjoyment of using the robotics.

Casler-Failing (2018a; 2018b) filled a gap in the research by taking the robotics into the mathematics classroom during a unit on ratios and proportions with 7th grade students and found that students were immediately engaged by the robotics; all students showed growth from pre- to post-test, with the highest level of growth experienced by students who had documented deficits in mathematical understanding. When robotics are used to develop and/or support mathematical understanding, students are provided opportunities to reason abstractly, persevere through challenges, and make sense of mathematics (Casler-Failing, 2020).

Methods

This research investigated the effect of LEGO® robotics on students' development of proportional reasoning skills when used as an instructional tool and how students develop those skills. This qualitatively oriented mixed methods (Morse & Cheek, 2015) case study (Yin, 2018) was conducted at a small, Christian school in a rural area of the southeastern United States. We chose to use a qualitatively oriented mixed methods approach, which prioritizes the qualitative nature of the research, for two reasons. First, the data set is extremely small, which prohibited using statistical measures to analyze the quantitative data and only allowed for a representation of the *effect* on student learning — the development in understanding from pre- to post-test. Second, the bulk of the data collected is of a qualitative nature, which afforded us the opportunity to focus our analysis on *how* the students developed the proportional reasoning skills.

The school begins separating students into two different math tracks in the 7th grade; the class participating in this research consisted of five female students who were considered struggling mathematics learners. The teacher of the class was a recent graduate of the local College of Education, with one year of teaching experience, and a former student of Casler-Failing. Due to the depth of knowledge of teaching with robotics, Casler-Failing played a dual role in the class as researcher and participant, acting as a co-teacher of the class working closely with the classroom teacher who possessed little more than introductory knowledge of the robotics, to facilitate all investigations and activities. This mathematics class represented the case being studied in this research.

Curriculum and Implementation

The curriculum utilized for this research included a pre- and post-test six investigations (tasks incorporating the robotics (see Figure 1)), and three activities conducted after investigations 2, 4, and 6 (see Figure 2) designed to apply students' learning of the concepts. The curriculum was implemented in previous research (Casler-Failing 2018a; 2018b), with minor revisions made to provide additional opportunities to develop deeper understanding of ratios in the development of proportional reasoning – a shortfall realized in the original study (Casler-Failing, 2018a). The research was conducted in the classroom over the course of 12 consecutive instructional days (approximately 10 hours of instruction). Each class period lasted approximately 50 minutes, with 5-10 minutes of beginning instruction to introduce the day's lesson and activate prior knowledge, 30-40 minutes of working with robotics to engage with the investigations, and 5-10 minutes for a closing discussion in which students shared their results for given tasks, asked questions to further their understanding, and/or responded to teacher-posed questions to assess students' understanding.

Each of the six investigations incorporated LEGO® robots (see Figures 3 and 4); the first four focused on ratios and developing the understanding of setting up and solving proportions, whereas investigations 5 and 6 focused on growth problems. The technology framework developed by Carbonaro et al. (2014) was incorporated into each investigation – students were *engaged* as they worked in groups of two or three to *investigate* the solution to a given task, *explore* a solution through discussion, *create* a program modification (general programs were provided to students, but they were required to modify the program to meet the requirements of the tasks (see Figure 5)), and *evaluate* the robot's movement regarding the task. Each task required students to justify their decisions and outcomes in written form. The three activity sheets required students to collaboratively apply the understanding developed while completing the investigations, devoid of the use of the robot.

Figure 1

Investigation Example (Casler-Failing, 2018a, pp. 34-35)

Name ____ Date _________________
Rates and Proportions - Investigation 2 How much time do I need?

In Investigation #1, "What is my rate?" you determined the rate at which the robot travels at programming speed 50. In this investigation you will use your knowledge of the robot's rate to determine different times that are needed to travel a specific distance.

[This lesson will allow students to continue to develop their ability to reason proportionally. The objective of this lesson is for students to begin to reason proportionally as they predict how the rates of the robots will change from a programming speed of 50 to a programming speed of 25, or 100.]

Class Discussion:

1) How can I use a known speed to determine how much time is needed to travel a specific distance?
2) What variables could affect your predictions and results?

Group Work:
For each question below, you will first need to predict the time required, program the time using the software, and test your prediction. If your prediction is inaccurate, you will need to continue to test until you find the correct time.

In Investigation #1 you determined your robot's average rate at programming speed 50.

What was your robot's average rate? ________cm/s

1) How much time is needed for your robot to travel at programming speed 50 for 15 cm?
   Was your prediction correct? If not, what was the time needed? Why do you think your calculations were incorrect?
2) How much time is needed for your robot to travel at programming speed 100 for 25 cm?
   a. What do you predict the robot's rate will be at programming speed 100? Why?
   b. Was your prediction correct? If not, what was the time needed? Why do you think your calculations were incorrect?
3) How much time is needed for your robot to travel at programming speed 25 for 50 cm?
   a. What do you predict the robot's rate will be at programming speed 25? Why?
   b. Was your prediction correct? If not, what was the time needed? Why do you think your calculations were incorrect?
4) Develop your own speed rate and distance, make the prediction and test your results. Make sure to record your speed, distance, time prediction and results.

Figure 2

Activity Example

Name ________________________________ Date____________

Rates and Proportions – Check-Up Activity Sheet #1

I would like you to answer each of the following questions. You may work in your groups to complete these problems. You must show all of your work and answer each question completely. Please add any comments you feel are necessary to explain your thinking.

All of these problems were taken from *Connected Mathematics 2* "Comparing and Scaling: Ratio, Proportion, and Percent." (Lappan, Fey, Fitzgerald, Friel, & Defanis Phillips, 2006, p. 34)

A teacher wants to purchase calculators for her class. She has found the following prices for the different types of calculators:

Simple Fraction Calculators: $120 for 20 calculators
Scientific Calculators: $240 for 15 calculators
Graphing Calculators: $800 for 10 calculators

Please use the information about the calculators to answer the questions below.

1) How much does it cost to buy 53 simple fraction calculators?
2) How much does it cost to buy 27 scientific calculators?
3) How much does it cost to buy 9 graphing calculators?
4) How many simple fraction calculators can the teacher buy if she can spend $390?
5) How many simple fraction calculators can the teacher buy if she can only spend $84?
6) How many graphing calculators can the teacher buy if she can spend $2,500?
7) How many graphing calculators can the teacher buy if she can only spend $560?
8) Explain how to determine the *price per calculator*.

Figure 3

LEGO® *robot driving base used in investigations 1 through 4* (Casler-Failing, 2018a, p. 27)

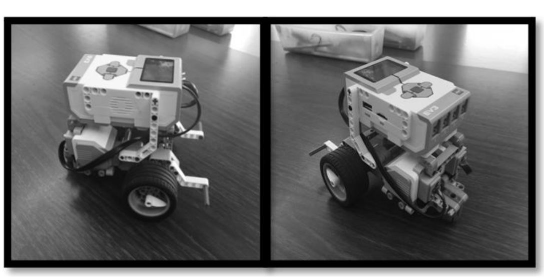


Figure 4

LEGO® *robot "PenBot" used in investigations 5 and 6* (Casler-Failing, 2018b, p. 11)

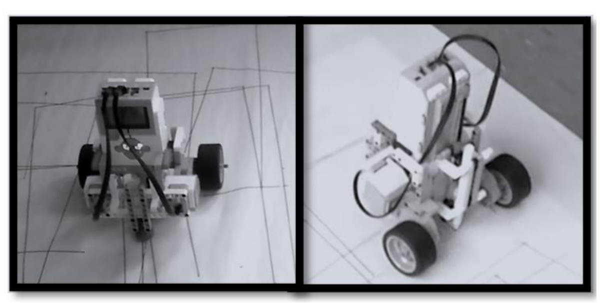
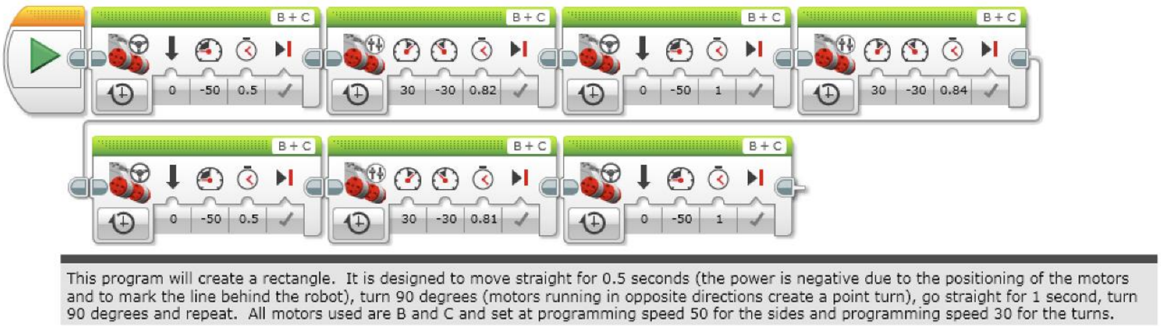


Figure 5

Example of the LEGO® *Mindstorms program used in investigation 5* (Casler-Failing, 2018b, p. 11)



Data and Analysis

Casler-Failing served as the sole researcher during the data collection process and Swann, an undergraduate research assistant, served an important role in the data analysis phase of this research. Data was collected from multiple sources to provide validity and reliability (Yin, 2018) and consisted of student classwork (copies of completed investigations and activities), pre- and post-tests, student reflections, video and audio recordings, student interviews (conducted at the beginning, middle, and end of the research), and observational field notes.

During the first class, students were introduced to the unit and were asked to complete the pre-test. Upon completion of the pre-test, students were split into two working groups (a group of two and a group of three, decided by the classroom teacher), introduced to LEGO® robotics, provided instruction on how to operate and program the robots, and the remaining class time was used to begin working on the first investigation. After class, Casler-Failing met with students individually to conduct the first of three interviews; interview 2 was conducted upon the completion of investigation 4, and interview 3 occurred after the post-test. Every class was audio and video recorded, including collaborative group work, and observational field notes were completed by Casler-Failing upon the completion of each class. All student classwork was photocopied, including the responses to each day's journal question, which was presented at the end of every class.

To respond to the first research question, pre- and post-tests were analyzed as quantitative data utilizing a point system for accuracy to produce a percentage grade and via Langrall and Swafford's (2000) stages of proportional reasoning (see Table 1) to determine growth in proportional reasoning skills. The second research question was answered through the analysis of qualitative data (student artifacts, interviews, video transcriptions of collaborative classwork and discussions, and reflections). These data were analyzed using the Five Stages of Technology Integration (Carbonaro et al., 2004) to determine how, and if, progression through the stages supported the development of understanding leading to the acquisition of proportional reasoning skills. The use of multiple sources of data to determine student learning supports triangulation and produces reliability (Glaser & Strauss, 1965). Both authors independently reviewed the qualitative data to locate evidence of when, and if, the stages occurred to provide inter-rater reliability (Lombard et al., 2010) and reduce the risk of any unconscious bias that may exist from Casler-Failing; Swann had minimal experience with robotics and approached the analysis from an *outsider's perspective*. The inter-rater reliability was determined to be 79% absolute agreement, which is an acceptable level of agreement (Graham et al., 2012).

Findings

The data show that students experienced success in developing their proportional reasoning skills as they completed tasks using the robotics. When reviewing the quantitative data (see Figures 6-11), all students showed growth in their proportional reasoning skills; however, Student 3 received the same percentage of correct responses on both the pre- and post-tests and showed little growth in her advancement in the stages of proportional reasoning (see Figure 9 (Langrall & Swafford, 2000)). As the data show below, and not considering Student 3, the students performed at least 34 points higher on the post-test, with the most growth being 48 points. Although this data provided evidence of student growth, each of the students would still be classified as developing learners, requiring additional support in this concept area.

When evaluating the student data in relation to the stages of proportional reasoning (Langrall & Swafford, 2000), all students showed growth in at least one area (see Figures 7-11). Student 1 showed growth with all types of problems, but the most growth was developed with part-part-whole problems – problems relating "two subsets (e.g., lions or tigers) to one another or one of the subsets to the whole (e.g., number of tigers as compared to the whole population of zoo animals" (Casler-Failing, 2018a, p. 26). The performance of Student 2 on the post-test represents understanding of part-part-whole problems at the highest stage of proportional reasoning, a clear development from the pre-test, with improvement also reflected with growth problems – problems focusing on the dilation or shrinking of figures.

As previously mentioned, Student 3 showed minimal development in her proportional reasoning skills, but her development with associated sets shows she was developing. The data from Student 4 provide evidence of strong development in her proportional reasoning skills in three of the problem types; however, she remained at the same stage when solving well known measure problems – problems that are commonly linked, such as miles per hour. Finally, Student 5 showed the most growth of all students, but also remained at the same stage with well-known measure problems.

Figure 6

Summary of Pre- and Post-test Results

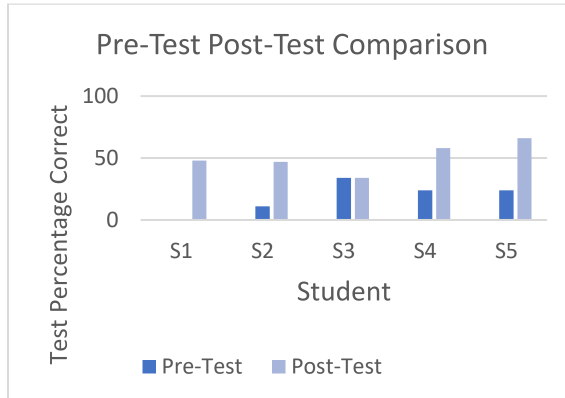


Figure 7

Growth in Proportional Reasoning – Student 1

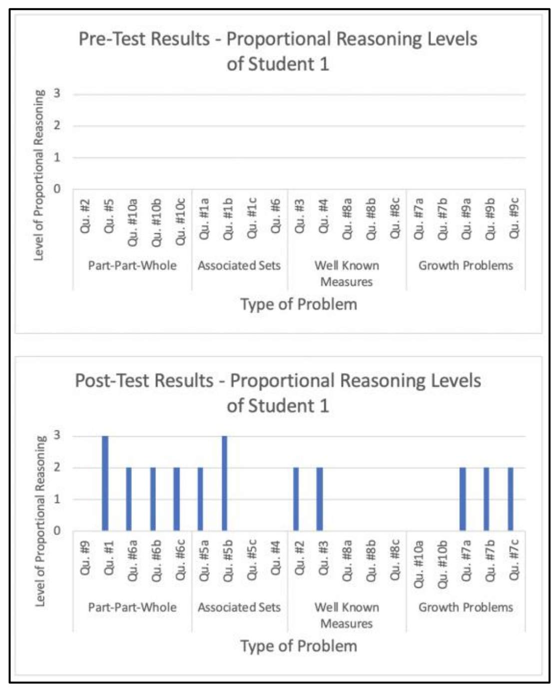


Figure 8

Growth in Proportional Reasoning – Student 2

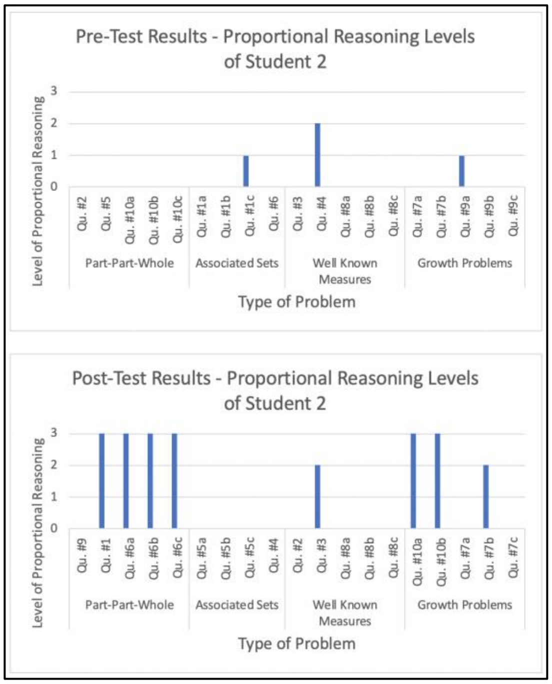


Figure 9

Growth in Proportional Reasoning – Student 3

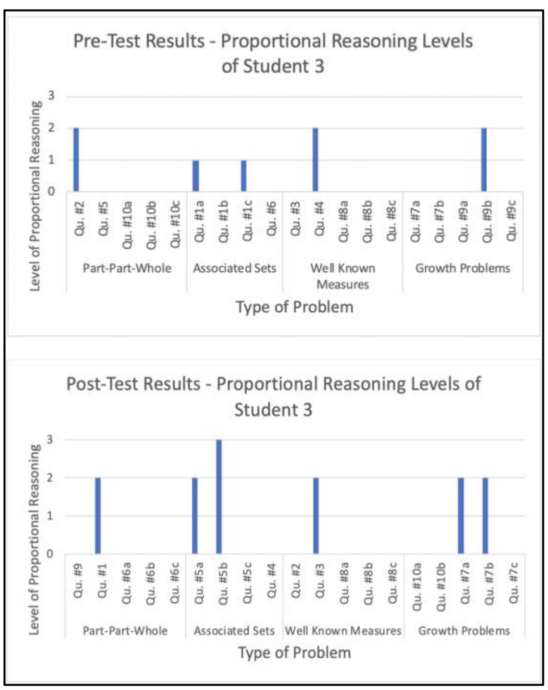


Figure 10

Growth in Proportional Reasoning – Student 4

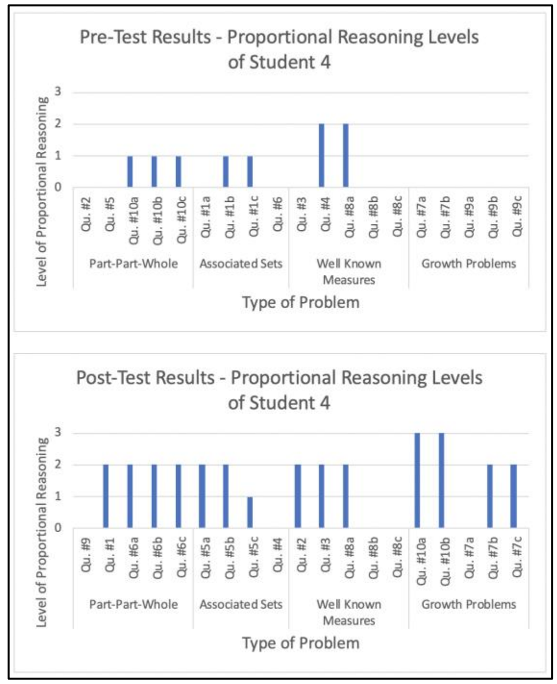
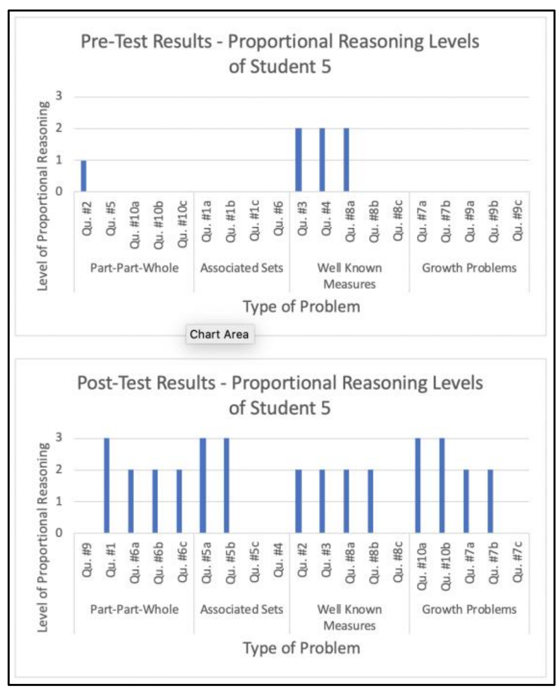


Figure 11

Growth in Proportional Reasoning – Student 5



When analyzing the data through the lens of Carbonaro et al.'s (2004) technology framework, it was evident that students were implementing each stage. However, as found in previous research (Casler-Failing, 2018a; 2018b) the stages are not experienced in a linear manner. As students worked through the investigations they would "jump around" among the stages. For instance, they were consistently *engaged* throughout each task, but while engaging in the *investigation* stage, it was common for students to repeatedly move back and forth between the *creation* and *evaluation* stages.

Figure 12 provides excerpts of how the students interacted at each stage as they worked through the investigations to develop proportional reasoning skills.

Figure 12

Coding Examples for the Stages of Technology Integration

Stage/Code	Description	Evidence in Data
Engagement	• Talking in/among groups about activity • Calculating Numbers • Using Robot • Performing activities as instructed	*Student 1*: We don't really need the distance. It wasn't asking for distance. *Student 5*: I know, but the distance and then the right times—we do the same thing. *Student 1*: It wasn't really asking for the distance. *Student 5*: No, I know. *Researcher*: No, it gave you the distance, remember? *Student 5*: Now, we have the distance. Now, we just need to do whatever we do with the rate, and then we do the same thing we did here and then get an answer that's close to 0.9.
Exploration	• Making suggestions • Discussions leading to choices on times, distances, rates, equations, calculations	*Student 1*: It says, "How much time is needed for your robot to travel at programming speed 25?" The speed is the rate, so 25… *Student 5*: Wait. *Student 1*: …for 50 centimeters. The distance is 50. *Student 5*: Wait, but, see, what we did for number two, and we'd be doing the same thing for number three, just with a different time. *Student 1*: Well, distance divided by rate equals time, then.
Investigation	• Making Predictions • Testing Predictions	*Student 2*: Okay, so it would be zero-point-five plus zero-point-five, which is one—or was it, would you multiply? *Student 3*: What are you doin'? *Student 2*: Does that make it two times the size? *Student 3*: You just do it—you just add point-five plus point-five and the one plus one. Then it would be two times the size.
Creation	• Changing computer programs • Creating proportions/equations	[as Student 2 is making changes to the computer programming] *Student 2*: Well, I know that the—so would it be one second and two seconds? *Student 3*: One second would become two second, and then point-five seconds would become one second. *Student 2*: That's what I thought, but…
Evaluation	• Measuring distances • Making sense of answers • Questioning results	*Student 1*: It's on 28. *Student 5*: It's on 28. The distance said 28. *Student 1*: We were supposed to go to 25, so that went a little farther than expected.

Discussion

Although this study included a small number of participants, the findings provide promising results for using robotics as an instructional tool and corroborate the findings of previous research using robotics (e.g., Casler-Failing, 2018a; 2018b; Martinez Ortiz, 2015). As students worked through each investigation, their discussions (Vygotsky, 1978) throughout each technology stage played an important part in developing proportional reasoning skills. Each investigation built on the learning gained from the previous investigation(s), which created the opportunity for the transfer of knowledge. Additionally, as students progressed through the investigations, they were required to apply a deeper level of proportional reasoning. For instance, in the first investigation, students were merely collecting data on the distance traveled by the robot for several different time durations. The data was then used to calculate unit rates to determine the *average rate of travel* of the robot. This rate then became the key piece of information carried into Investigations 2-4. Using the robots as an instructional tool to gain, and apply, this information provided meaning to the students' learning and allowed them to *see* what it meant to be proportional as they worked through each task throughout the unit. Student 1 reported that the visual aspect of the robots were more beneficial to her than just hearing information and all five students shared the importance of the hands-on aspect of the robots to facilitate their learning. Next, we share how the findings address each research question.

- **What effect do LEGO® robotics have on students' development of proportional reasoning skills when used as an instructional tool?**

Findings show LEGO® robotics support the development of proportional reasoning skills. Students' performance on the post-test (Figure 6) increased by at least 34 points for four of the five students; however, the test scores are still representative of developing learners. In regard to the stages of proportional reasoning development (Langrall & Swafford, 2000), all students showed growth (see Figures 7-11), but this growth was most evident for Student 5. Although Student 3 received the same percentage score on the pre- and post-test, her development of proportional reasoning improved as the problems answered represented level 2 and 3 understanding. Additionally, students 1, 4, and 5 reflected a minimum of level 2 understanding with each problem type. Although Student 2 did not reflect development regarding *associated sets* problems, she and Students 4 and 5 were the only students to reflect level 3 understanding with growth problems, the most difficult type of proportional reasoning problem (Lamon, 1993).

- **How do students develop proportional reasoning skills when LEGO® robotics are used as an instructional tool?**

Findings show students learn best when provided multiple paths to develop understanding (Wollman & Lawson, 1978). The investigations incorporating robotics allowed students opportunities to learn through open-ended, hands-on tasks. Students developed their understanding through collaborative discussions as they worked through the different technology stages (Carbonaro et al., 2014 (see Table 2)) to complete each investigation. The tasks required students to make predictions (*explore*), revise the computer programs (*create*), test their predictions (*investigate*), and *evaluate* the accuracy of their solutions, with engagement being the overarching stage that occurred throughout each investigation and activity. Students supported one another to develop their understanding and expand their Zones of Proximal Development (ZPD; Vygotsky, 1978) through discussions within their small groups and during whole class discussions and through scaffolding in the form of purposeful questioning from both their teacher and Casler-Failing, as the co-teacher and researcher.

An example of how proportional reasoning was developed can be found in Student 1's progression from additive reasoning to multiplicative reasoning. While working on the first investigation, after the average rate of the robot was determined, students were tasked with predicting the distance it would travel in 1.5 seconds. Student 1 suggested they add the distance traveled in one second (17.6 cm) and the distance the robot would travel in one-half of a second (8.8 cm), which reflects an additive reasoning strategy. On Day 12, while working on Activity 3, the following problem was presented:

> *Calculators are on sale at a price of $1,000 for 20. How many can be purchased for $1,250?*

Student 1 provided evidence of her development of proportional reasoning, and her movement from additive reasoning to multiplicative reasoning, when stating:

> *Yeah, so, like 1,000 divided by 20 equals 50. Then, you do 50 times 1,250 equals – okay, 625…that doesn't make sense…Divide by 50…Then you have to divide that [1,250], not multiply.*

Although Student 1 initially made a mistake by multiplying, she evaluated the reasonableness of her answer and realized the need to divide rather than multiply; this solution process represents her understanding of the multiplicative relationship between the total cost and the number of calculators purchased.

Overall, students reported they enjoyed the opportunity to learn with the robotics because it was "more hands on" (Student 3, interview) and they could "relate to it [the concepts learned] more" (Student 1, interview). Additionally, the students felt working in small groups was beneficial because "you have somebody that you can help explain it to you, and then you can explain it to them if they don't understand it" (Student 4, interview).

Implications and Limitations

Bishop and Harrison (2021) advocate for a "responsive middle school curriculum" focused on personal or social issues integrating "complex tasks" (p. 27). Students experience forms of robotics in many aspects of their lives without even realizing it. Students may have automated vacuums in their homes (e.g., Roomba), parents who drive vehicles that can park themselves and detect traffic lanes, or have an *Alexa* or *Google Assistant* in their homes. These are all forms of robotics that can help them make connections with LEGO® robotics.

This research adds to the current body of research on instructional strategies that promote the development of proportional reasoning and the use of LEGO® robotics as an instructional tool. This paper adds to Casler-Failing's previous research (2018a; 2018b) as it incorporates revised investigations and was conducted in a different U.S. region with students with a history of struggling with mathematics. Although this study included an extremely small sample size, a limitation of the study, it does provide evidence of the learning that can be achieved through instructional practices that incorporate robotics and advances the research from prior studies conducted in extra-curricular programs (Martinez-Ortiz, 2015). The robotics tasks integrated into each activity created an environment that promoted collaboration and discussion (Vygotsky, 1978) that enabled the students to construct their understanding of ratios and proportions. Furthermore, learning via robotics is an innovative way to "foster learning that is active, purposeful, and democratic" by creating opportunities for students to participate in discourse via questioning that "foster[s] critical and creative thinking" (Bishop & Harrison, 2021, p. 35). This type of instruction allows students to learn mathematics in a very non-traditional manner that encourages hands-on engagement throughout the tasks by incorporating technology in a meaningful manner (NCTM, 2014). Notwithstanding, although the findings of this research are promising and support previous research, further studies are required, with more diverse student populations and larger classes, to further substantiate the benefits of robotics in the development of proportional reasoning skills.

When looking at the data from a performance level, a limitation is presented as the students would still not be considered *proficient* or *distinguished* in their level of understanding, since the post-test grades ranged from 34% to 66%. This was an interesting outcome of this research, as it does not align with Casler-Failing's previous findings (2018a; 2018b) in which students achieved at the proficient, or higher, level. However, the contexts of the classes were different and in the original study, Casler-Failing was the sole teacher of the class, was familiar with prior curriculum, and was able to build upon student's prior knowledge at a more comprehensive level. Additionally, it is not clear why each of the students showed varied understanding of the growth problems – often showing growth in one type of problem, either the rectangular-focused problem *or* the triangular-focused problem. When reviewing the problems, the authors posit it may be due to the rectangular-focused problem being word-based, whereas the triangular-focused problem was picture-based; the differences in performance may be connected to the students' learning preferences or other academic traits (e.g., reading comprehension or spatial-visual acuity).

Conclusion

This research investigated if LEGO® robotics supports the development of mathematical understanding, specifically proportional reasoning. This research provided evidence that LEGO® robotics provide an innovative way to engage students in hands-on learning that is student-focused and inquiry driven. Students were engaged in each investigation as they discussed solution strategies, made predictions, created program revisions, tested their creations, and evaluated their results. The findings presented in this research add to previous research (Ardito et al., 2014; Casler-Failing, 2018a; 2018b; Williams et al., 2012) to support the benefit of robotics as an instructional tool in the mathematics classroom. Students reported they enjoyed the hands-on aspect of the investigations (Student 3, interview), the collaborative nature of the learning (Student 1, interview), and that the robotics were fun to learn with (Student 5, interview). Is not this what learning should be – hands-on, collaborative, and fun? There are different types of robotics available for classroom use (e.g., TI-Innovator Rover, LEGO® Spike Prime, Ozobot, Dash Robot) – we challenge middle level mathematics educators to bring innovative robotics learning to their students.

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