OPENBRICK: ENCOURAGING EQUITY IN STEM EDUCATION THROUGH OPEN SOURCE EDUCATIONAL ROBOTICS

A Dissertation

by

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ABSTRACT

In this three-article dissertation, I present findings from three interconnected yet unique research studies. The focus of each research study was to assess the effectiveness of open source Arduino hardware in STEM classrooms. Literature spanning last three decades strongly suggests the effectiveness of ER in STEM classrooms, all students do not have access to the potential power of ER. This disparity is propagated by the high cost of proprietary ER kits, teachers' incorrect perceptions about the usability of ER in STEM classrooms, and the difficult and often complex nature of open source instructional technologies. There is a need for a low cost tool that is based on open source Arduino yet is user friendly and easy to adapt to teaching and learning activities in STEM classrooms.

In the first research study (chapter 2), I meta-analyzed the effects of open source Arduino- and Scratch- based interventions on students' CT skills. The second article (chapter 3) contains the findings of a randomized experimental research study in which students engaged in hands-on STEM learning using a 3D printed Mars rover based on the open source Arduino hardware and other off the shelf components. In chapter 4 of this dissertation, I introduce readers to OpenBrick, a low cost open source Arduino based ER kit that can compete with proprietary and expensive LEGO and VEX ER kits. Then I present the findings from the usability study of OpenBrick ER kit

The findings from the meta-analysis suggested that Arduino- and Scratch-based interventions were effective in improving students CT skills. Hands-on engagement with

Arduino based 3D printed Mars rover helped to improve students perceptions and attitudes towards STEM subjects and careers. Building, coding, and testing Arduino based Mars rover also improved students affect towards engineering as a profession. Finally, the results of the OpenBrick usability study indicated that participants found OpenBrick ER kit effective, efficient, and satisfactory for delivering ER STEM lessons. Each research study in this dissertation utilized a unique research methodology but the combined findings of all three research studies suggest that open source Arduino based tools and interventions are effective in STEM classrooms.

DEDICATION

To my parents for teaching me the value of struggle, honesty, and loyalty; especially in the face of poverty and adversity.

To my wife Beenish and kids Adan and Aman for supporting my crazy ideas.

To all my students for teaching me so much.

&

To Tahir. You left us too soon.

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1. INTRODUCTION

1.1. Statement of the Problem

The opportunities for exposure to high quality STEM education through Educational Robotics are not equitably distributed among all students. Minority students and those belonging to low socio-economically situated (SES) families have historically lacked exposure to ER and the high-quality STEM education that can be delivered using ER. There are three major factors that affect the disparities in students' access and opportunities to high quality STEM education through ER. **First**, some student from low-SES families often suffers from the unavailability of material resources due to a high cost attached to new and innovative instructional materials such as ER. **Second**, teachers' incorrect and possible negative perceptions keep them from undertaking effective hands-on learning practices using cutting edge instructional technologies such as ER denying students at these school access to quality STEM education. Low-cost open source Arduino based ER have been shown to induce positive change in students' perceptions towards STEM careers and improve students' academic outcomes. However, the level of complexity involved in implementing the low-cost Arduino based ER kits often has a detrimental effect on teachers' willingness to adapting them in their day to day teaching and learning practices and serves as the **third** factor affecting the disparities in students' access to high quality STEM education through ER. There is a plethora of research indicating the effectiveness of low-cost open source Arduino based ER, but these ER kits are not regarded as true alternatives for off the shelf proprietary ER due to the difficulty involved in their assembly, coding, and implementation. These three factors result in a gap between the potential benefits of ER and its affective implementation in instructional settings contributing to the disparities in some student's exposure to quality STEM education. Therefore, the purpose the research undertaken in this dissertation is to advocate for an increased integration of low-cost open source Arduino -based ER to solve the problem of high cost of ER in STEM classrooms, encourage positive teacher perceptions towards open source ER and determine the usability of OpenBrick, an easy to use open source ER kit.

1.2. Literature Review

Educational Robotics (ER) can help students improve their STEM academic skills. Researchers have indicated that teachers used ER to provide students with effective learning opportunities in classrooms such as hands on STEM learning (Eguchi, 2014) in both formal and informal learning environments and contextualized learning that was situated in real-world scenarios (Ioannou & Makridou, 2018). Despite the abundance of research showing the effectiveness of ER in teaching and learning practices (e.g., Atmatzidou & Demetriadis, 2016; D'Amico et al., 2020; Jung & Won, 2018; Zhong & Xia, 2020) this innovative instructional technology is not accessible to all students (Chalmers et al., 2014; Yuen et al., 2013). The main reasons for disparity are high cost of proprietary ER and teachers' incorrect perceptions towards ER. Open source Arduino based ER can encourage greater access for students to ER and they have also been shown to improve teachers' perceptions towards ER, but the complicated nature of most DIY Arduino based ER requires that the users possess the technical knowhow to put together electronic peripherals such as microcontrollers, motor controllers and sensors and a lot of wires to build an ER. Most teachers are not equipped with the expertise needed to take on such a DIY project. So, despite the low cost, the potential of open source Arduino based ER stays unfulfilled due difficulty in the building process adding to the disparity in access to ER for some students. There is a need for a user focused low-cost open source STEM teaching and learning device which is easy for users to implement so that all student groups can take advantage of the potential of ER in improving their STEM academic skills.

1.2.1. High Cost of Proprietary ER

Proprietary ER kits have been shown to help improve students' academic experiences, but commercial ER kits are expensive. A typical LEGO or VEX IQ ER kit costs approximately $500 (LEGO Group, n.d.; VEX, n.d.). Because of the high cost, use of ER in low-SES neighborhood schools is an impractical idea (Chalmers et al., 2014). A classroom set of proprietary ER kits can cost thousands of dollars so even if the school administrators decide to invest in ER, they are limited in their options due to budgetary constraints (Zhong & Xia, 2020). Teachers are encouraged to borrow ER kits and use them for demonstration purposes so students can be exposed to the instructional tool. However, this means that students in poorly funded schools are unable to experience hands-on engagement with ER and benefit from the positive outcomes of ER (Daniela & Lytras, 2018). Open source Arduino based ER can solve the problem of high costs attached to ER (Fidai, Jarvis, et al., 2019; Fidai, Kwon et al., 2019). Arduino ER kits can cost as little as $25 and can provide students with opportunities to engage in hands on

STEM learning activities (Fidai et al., 2020). Combining the open source Arduino hardware with visual coding environment of Scratch allows for STEM teachers to engage students with ER at a personal level while incurring very low cost.

1.2.2. Teacher Positioning

Teachers can be positioned for successes or failure based on two critical variables: their perceptions of and their perceived self-efficacy with ER. While these two can work in tandem they also exist as isolated factors (Ross et al., 2001). Therefore, it is essential to unpack each one and the research supporting the affordances and barriers for implementing the ER.

Teachers' perceptions of new instructional technology have a great effect on their willingness to employ it in their classrooms. When teachers have positive attitudes towards the use of technology in classroom, they are more likely to integrate it into their teaching and learning practices (Wood et al., 2008). Teachers' attitudes and beliefs towards the efficacy of technology use in instruction are formed through four major constructs: performance expectancy, effort expectancy, social influence and facilitating conditions (Vankatesh et al., 2003). The perceived benefits of the use of technology and the number of added efforts involved in employing the technology in teaching and learning in practices help determine teachers' willingness to integrate technology into their classrooms. But it is the facilitating conditions such as: access, training, peer encouragement and role-modeling which may be the most important factors in teachers' integration of instructional technology in classrooms (Ertmer, 1999). Even when teachers are willing to integrate instructional technology into teaching and learning practices, the high cost of proprietary hardware and software serves as an impeding factor towards those intentions (Kepple, 2015). Low-cost open source Arduino hardware and freely available visual coding software maybe the possible solutions to the problems created by adverse facilitating conditions.

Teachers' self-efficacy about their abilities in employing ER can help or hinder students' successful engagement with innovative learning practices. When teachers have a higher self-efficacy towards ER, they are more likely to integrate ER in their lessons and assessments (Bilici et al., 2013; Tschannen-Moran & Hoy, 2001). But a low self-efficacy towards ER may increase some teachers' challenges for implementing ER into their day to day teaching practices (Schmidt et al., 2009). In the latter case, teacher's low self-efficacy becomes a barrier to students' exposure to innovative and effective instructional technology (Mallik et al., 2018; You & Kapila, 2017). Professional development activities have shown positive results (Castro et al., 2018; Hu & Garimella, 2015; Mallik et al., 2018; You & Kapila, 2017) in introducing teachers to ER and improving teachers' self-efficacy toward implementing ER. The current literature is very limited in reporting on the effects of using open source ER to improve teachers' self-efficacies towards ER in teaching and learning practices. This limited empirical research indicates that teachers are often afraid of open source technology solutions such as Arduino microcontrollers (Kirikkaya & Basaran, 2019) due to the trial and error approach required to build the DIY kits (Agatolio & Moro, 2017). Teachers new to ER and especially open source ER are also more likely to be limited in skills needed to fit the ER into their lessons effectively. This process requires them to ask for help which may be accessible online through the numerous forums dedicated to open source technology. New open source users may not find this help overly accessible or useful due to their limited skill set. This dilemma highlights the need for professional development aimed at easing some of the obstacles faced by teachers new to open source instructional technologies. There is general consensus that teachers' self-efficacy towards instructional technologies such as ER can be improved using professional development activities.

1.2.3. Open Source Instructional Technology

Open source technology is seen as a direct opponent to proprietary license-based products and services. Open source technology has three basic tenants: free to access, free to use and free to modify (Open Source Initiative, 2020). The open source movement in technology was pioneered by Richard Stallman who is considered the father of open source software (Pearson, 2000). Stallman's advocacy for open source software resulted in the development of the Linux operating system which later gave birth to Android (Priestley, 2019). Open source software and hardware hold many advantages over proprietary technologies. Open source software can be freely accessed and modified (Bosio et al., 2002; DeLano, 2005; Min, 2006). The schematics, wiring diagrams and even the machine level source code for open source hardware can be accessed freely and can be custom modified as well. The freely available technical details allow prototyping of such hardware using readily available electronic components (Gibb & Abadie, 2014; William et al., 2012). Open source software and hardware have revolutionized the technology industry by creating more access and opportunity.

Open source technology is also reshaping STEM education. Freedom from high cost of ownership, licensing fees and rigid proprietary environments have made open source technologies an attractive option for educational settings. Increased servicing options, community supported continued improvement and little to no cost speak to the democratizing power of open source technology in STEM education (Lakhan & Jhunjhunwala, 2008; Tong, 2004). Recent research has already shown promising results of incorporating open source technology in software development (Müller et al., 2019), algebra (Kuprianoff et al., 2018), statistics (Fox & Andersen, 2005; Tishkovskaya & Lancaster, 2012), geometry (Prodromou, 2014) and computer science education (Yamakami, 2012; Yue et al., 2004). The integration of open source software and hardware in K-12 and post-secondary classrooms is helping to increase accessibility to quality STEM education for all students.

1.2.4. Open Source ER and Its Challenges

Open source has been the driving force behind democratizing knowledge in recent years. Open source Arduino based ER have shown the potential for encouraging access for all students to quality STEM education through ER (Atmatzidou & Demetriadis, 2016; Ioannou & Makridou, 2018. However, adopting and implementing an open source ER kit for classrooms use can become a tricky business. School administrators could opt to invest in the prefabricated and assembled open source ER kits, but they can cost as much as proprietary ER kits (Terranova, 2017). On the other hand, the school could buy affordable DIY kits which come with all the parts in a box ready to be assembled for around $25 (Amazon.com, n.d.). But working with DIY ER kits can be difficult due to a lack of assembly instructions, missing or broken parts and the sheer amount of work involved in assembling these kits. All these issues are enough to discourage the technologically unskilled users from adopting and implementing these kits in the classroom settings (Alsoliman, 2018; Gläsel, 2018). The difficulty in working with these complicated kits may specially discourage teachers who are already skeptical of the benefits of ER in classrooms (Alsoliman, 2018; Khanlari, 2016). There is a need for an open source ER device that can compete with proprietary ER kits while remaining affordable and usable. I believe that OpenBrick, an Arduino based 3D printed device can provide teachers with an easy to use and effective tool to engage students in ER based lessons. Furthermore, OpenBrick can help schools adopt and integrate ER in everyday teaching and learning practices at a fraction of the cost of proprietary ER kits and without the complication of DIY ER kits.

1.3. Research Questions

My research was guided by the following three sets of questions.

1. To what extent do Arduino- and Scratch-enabled interventions effect students' overall computational thinking (CT) skills?

a. What are the effects of Arduino- and Scratch-enabled interventions on each dimension (concepts, practices, and perspectives) of students' CT skills?

b. What are the moderating effects of students' grade level and the duration of intervention on the effectiveness of Arduino- and Scratch-enabled interventions on students' CT skills?

2. What are the effects of participation in an Arduino Rover building activity on students' interest and attitudes towards STEM subjects and career fields?

b. To what extent have students' affects towards engineering as a profession

a. What are the moderating effects of race/ethnicity and gender on these changes?

changed as a result of participating in the Arduino Rover activity?

3. What was the perceived usability of the OpenBrick Robotics module for implementing the STEM ER based lesson and activities for participating user?

a. What characteristics of the OpenBrick Robotics module did users find to be helpful in completing the tasks outlined in STEM ER lesson?

b. What were the concerns about the efficiency with which the participating users were able to implement STEM ER lesson using OpenBrick Robotics module?

c. What was the satisfaction level for users of OpenBrick Robotics module for implementing STEM ER lesson?

d. What connections could be observed between participants' composite SUS scores and their perceptions of usability of OpenBrick ER kit?

1.4. Significance of the Dissertation

In our current STEM education system, all students do not have the same opportunities to engage in innovative, hands-on, and effective learning through ER. The research undertaken in this dissertation and the findings from the research provide possible solutions to the problems of disparity in STEM education. The findings provide empirical evidence towards the efficacy of open source Arduino in improving student's academic skills, their interests and attitudes towards STEM subjects and careers and their affects towards engineering as a profession. In addition to contributing to the current literature and knowledge base of STEM education, this dissertation introduces the academic and professional communities to an innovative new open source ER tool, OpenBrick. The results from the usability study of OpenBrick serve as evidence of the power of Arduino to compete with the likes of LEGO and VEX when packaged in a user-friendly form factor. The findings serve as an encouragement for current and future researchers to invest time and efforts in disruptive innovations that can help change the status quo and level the playing field for all students regardless of their zip code. Finally, this dissertation is a first of its kind in curriculum and instruction because in this dissertation I used the industry standard ISO 9241-11 criteria and survey to test the usability of an instructional tool. The integration of practices usually found in engineering disciplines with research focused on STEM education should serve as an example for future scholars who wish to work at the intersection of multiple academic fields. Finally, the problems of inequity and lack of access experienced by so many of our students are too expansive to be solved with one sweeping solution. Therefore, a multifaceted approach is needed to solve the problems of disparity in STEM education. This dissertation adds several new evidence-based solutions to the knowledge base of STEM education. These solutions are unique because they are situated at the intersection of technology, socio-economics and practice reform and can effectively contributing to the ongoing efforts in encouraging equity and access for all students to in quality STEM education.

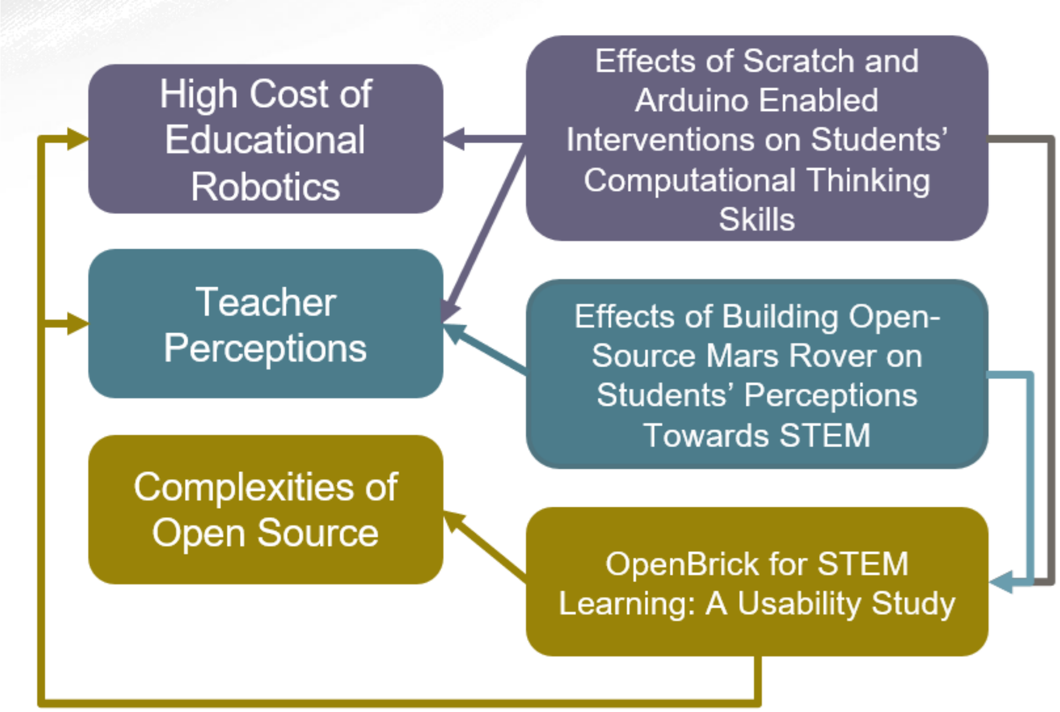
1.5. Organization of the Dissertation

This dissertation is organized into five chapters. In Chapter 1, I state the problem of disparity in students' exposure to ER along with the three main causes of this disparity. Additionally, I also describe the purpose of the dissertation, present a review of current and relevant literature, state the research questions that guided each of the research studies, and discuss the dissemination of research findings contained in the three research articles contained in Chapter 2 - 4.

In Chapter 2, I present the findings from a meta-analytic study of the effects of Scratch- and Arduino- enabled interventions on students' Computational Thinking (CT) skills. For the meta-analysis, I undertook techniques such as calculation of individual and aggregate effect sizes in the form of Cohen's d, I^2 statistic and Q statistic. I also conducted moderator analysis and an analysis of publication bias. I then present all results and findings using tables, forest plots and funnel plots. The manuscript is entitled "Scratch"-ing computational thinking with Arduino: A meta-analysis and has been accepted for publication in *Thinking Skills and creativity*. In Chapter 3, I present the findings form a randomized experimental study that was conducted to determine the effects of building, coding, and testing a 3D printed Arduino based Mars Rover with 4th grade students. I present the Cohen's d effect sizes for the impact of the intervention on the students in the experimental group compared to the students in the control group and discuss the moderator effects. In Chapter 4, I present the findings from a usability study of OpenBrick. The relationship between the three research studies (presented in Chapter 2, 3 and 4) is described. In each of the Chapters 2, 3 and 4, I present research findings that serve as possible solutions to the problems identified in Chapter I (see Figure 1.1). And finally, in Chapter 5, I share the broader impacts and intellectual merit obtained through the research that comprises my dissertation.

Figure 1.1

Relationship Between the Problem Statement and The Three Research Articles Contained in Chapter 2-4 of this dissertation



Note. The arrows depict the flow of information (influence) between the three research studies and their interconnectedness.

2. “SCRATCH”-ING COMPUTATIONAL THINKING WITH ARDUINO: A META-ANALYSIS[*]

2.1. Introduction

Traditional views of computers in K–12 education have focused on helping students learn problem-solving skills and develop logical thinking. These skills allow students to tackle real-life problems and become familiar with abstract mathematical tasks, thereby creating a sound mathematical foundation for computer careers (Vashanti, 2013). Generally speaking, however, the computer science landscape, both as a profession and as an academic field, is changing, and traditional K–12 computer education may no longer be adequate. Over the years, there has been an increase in the use of computational and simulation software in all science, technology, engineering, and mathematics (STEM) professions (Wing, 2008). Computational thinking skills are becoming a core part of all STEM professional training (Weintrop et al., 2016), and in most STEM disciplines, a lack of computational thinking skills is considered a handicap (Wing, 2008). Computational thinking skills allow students to become adept at using software tools and gain methods to solve computational problems in efficient and clever ways. Computational thinking also enables students to learn new software quickly and model simulation solutions for solving real-life and abstract problems (Magana & Silva

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[*] Reprinted with permission from ““Scratch”-ing computational thinking with Arduino: A meta-analysis” by Aamir Fidai, Mary Margaret Capraro, & Robert M. Capraro, 2020. *Thinking Skills and Creativity*, 38, 100726, Copyright [2020] by Elsevier Ltd.

Coutinho, 2017). The changing landscape of STEM as a profession (National Research Council, 2011) dictates the integration of computational thinking in K–12 settings.

Computational thinking skills development in K–12 is a logical first step in building the future engineering workforce. To that end, the use of open source Arduino hardware and open source Scratch, a visual coding environment, provide an ideal opportunity for introducing students to computational thinking (for a detailed review, see Zhang & Nouri, 2019). Recent years have seen an expansion of research on the efficacy of combining the powers of Arduino-based microcontrollers and Scratch-based visual coding environments to teach computational thinking skills. To understand how these open source computational thinking tools facilitate learning, we conducted a meta-analytic study.

2.2. **Background**

Robotics, programmable toys, and microcontrollers have been used in STEM classrooms for teaching, learning, and exploration since the early 1990s. The precursor to Arduino was the BASIC stamp kit that came to market with a price tag of $139 U.S. dollars (Benchoff, 2015) in 1993. That amount is equivalent to $251.72 in today's market (see https://www.saving.org/inflation/inflation.php?amount=139). Despite its high cost, the miniature development kit was extremely popular with educators in K–12 and post-secondary integrated educational STEM classrooms, wherein BASIC stamp was used to teach fundamentals for programming and electronics (Buckley, 1997, 1998).

2.2.1. Open Source STEM Instructional Technology

Open source teaching tools have not always been an option for K–12 schools. Prior to the 1980s, instructors were reliant on proprietary software and hardware designs, which could be prohibitively expensive. This changed with the actions of Richard Stallman, the father of the open source concept (Pearson, 2000), who was frustrated by the lack of freedom users had in modifying software they purchased and, in the ability, to share their property without penalty. His frustrations led to the pioneering of the open source idea in both software and hardware, which greatly altered the way classroom instructors could engage with hands-on instruction. Open source teaching tools continue to improve in ease of use and accessibility, and there has been an increase in recent years in the integration of open source instructional technology in K–12 and post-secondary settings.

The term "open source" has led to confusion since its inception in the early 1980's. Open source has come to mean a myriad of different things for people in diverse industries (Delano, 2005). According to the Open Source Initiative (OSI), the non-profit global organization charged with advocacy of open source software and hardware initiatives, to be considered open source, the source code for the software must be available to the general public and further development of the software must be allowed without a requirement for royalties (OSI, 2020). This allows developers to port an open source software that may have been written for a specific operating system to another operating system without requesting permission or paying royalties.

Open source software and hardware products have many inherent advantages compared to proprietary counterparts. Open source software is usually available on-demand, free to try, vendor independent, flexible, and built on open standards (Bosio et al., 2002; DeLano, 2005; Min, 2006). Because such software is built on open standards, it is not limited by black box mentality where the inner workings of the software are hidden from the user and made inaccessible by the software producer. Open source hardware has the same advantages as open source software. Freely available schematics, wiring diagrams, and machine-level code facilitate individuals who may want to easily build their own prototype circuits on breadboards using readily available electrical components (Gibb & Abadie, 2014; William et al., 2012). These advantages have helped make open source software and hardware a mainstream phenomenon.

Open source software and hardware have also been shown to be valuable tools for STEM education in academic settings. Open source software and hardware carry the promise of the democratization of STEM education through eliminating licensing fees and providing flexibility, continuity of service, continued improvement, and reduced cost (Lakhan, & Jhunjhunwala, 2008; Tong, 2004). Recent research has recognized the benefits of integrating open source instructional resources in computer science education (Yamakami, 2012; Yue et al., 2004), algebra (Kuprianoff et al., 2018), geometry (Prodromou, 2014), statistics (Fox, & Andersen, 2005; Tishkovskaya, & Lancaster, 2012), and software development (Müller et al., 2019). The adoption of open source software and hardware in K–12 and post-secondary classrooms is making STEM education accessible for all students at more affordable prices.

2.2.2. **Open source Arduino Hardware and Scratch Software**

Arduino, the palm-sized microcontroller, has become ubiquitous in schools and universities around the world. The low-cost open source electronic device has essentially changed the way students, DIY enthusiasts, and STEM instructors conduct experiments with, and eventually learn to build, working models. Thanks to the ever-growing library of online Arduino projects on Instructables.com (Instructable Team, 2020) and GitHub (GitHub, 2020), a community of learners and teachers is evolving because of the Creative Commons (CC) license share: electronic prototyping is not just the domain of a few anymore. Arduino has truly allowed for the democratization of engineering education by allowing anyone to prototype and invent (Blikstein, 2013). Yet, there is more to Arduino's popularity in education than its intellectual accessibility.

The secret of Arduino's success is its low cost, simplicity, and ease of use in a wide range of settings, and its ability to be programmed using a diverse set of open source programming languages. The inventors of Arduino have even made the design and code details for building Arduino hardware and the embedded software open source. Because Arduino is an open source hardware and software product, there are droves of vendors who produce Arduino prototyping boards. Due to this fact, Arduino boards can be bought at prices as low as $2. Before the advent of open source Arduino, educators and educational institutes were forced to choose between buying expensive proprietary microcontrollers, robotics equipment, programmable toys, and engineering lab equipment. Using Arduino allows educators to instead build low-cost educational devices (Moya, 2018; Oliveira & Hedengren, 2019; Serrano-Perez & Lopez, 2019) and even produce prototypes that compete with commercial engineering equipment (Wang et al., 2018). The low cost, ease of use, and the support of an online community of Arduino users, developers, and DIY enthusiasts make Arduino a choice platform to use in K–12 settings for introducing students to computational thinking-focused engineering activities. It is no accident that Arduino has become a common device in many STEM instructional settings.

Scratch, a software tool, is the evolution of text-based programming into a visual coding environment. Scratch is a visual coding environment geared towards introducing students to the basics of coding and engaging them in computational thinking, and it eases learning by removing the need to learn complex syntax and new vocabulary. Furthermore, the Scratch programming environment has been translated into more than 70 languages and has become a nomenclature in coding classrooms all over the world (Scratch, 2020). Because of its ease of use and accessibility, Scratch has become one of the most used programming environments today.

The online visual programming environment of Scratch has been available to the general public since 2013, but the coding environment as a standalone had been available to educators and researchers since 2003. The scratch coding environment is made up of visual blocks that represent programming primitives. Programming primitives are the simplest logical elements of a given programming language that students can use to perform coding tasks. The beauty of Scratch is that it allows students to use programming primitives to employ computational thinking and code without being restricted by the syntax limitations of any programming language. Scratch code can then be synthesized and translated into any number of popular programming languages. The translation is achieved using the Blockly libraries (Google Developers, 2020) that are the foundation of Scratch, as Scratch is one of many implementations of the Blockly library.

In the last decade, Arduino hardware has been paired with Scratch to introduce students of all ages to microcontroller programming using visual coding blocks instead of text-based coding. The concomitant integration of Scratch visual coding and Arduino hardware has resulted in greater access for students and teachers at all levels of STEM education. Scratch was not designed to be used as a microcontroller coding tool, but the open source nature of both Arduino and Scratch have allowed developers to come up with novel ways to combine them. Scratch4Arduino and mBlock are two of many commercial and non-commercial Scratch-based coding tools available that allow users to code Arduino and Arduino-based microcontrollers in a visual coding environment.

2.3. Literature Review

2.3.1. Arduino in STEM Education

The usefulness of Arduino has been the focus of many studies in STEM teaching and learning. Teaching and learning facilitated by Arduino has been shown to improve students' academic skills (Chen & Chang, 2018; Hsiao et al., 2019; Psycharis & Kotzampasaki, 2019; Wang, 2018; Yasin et al., 2018; Yin et al., 2019), perceptions towards STEM courses (Chen & Chang, 2018; Yin et al., 2019), and perceptions toward STEM careers (Chen & Chang, 2018; Kuo et al., 2019). Additionally, Arduino instruction has been found to facilitate computational thinking (CT) skills that are an essential aspect of engineering education (Bartholomew & Zhang, 2019; Pala & Turker, 2019; Pratiwi & Nanto, 2019). There are empirical studies, however, that claim Arduino-enabled activities do not contribute to an improvement in students' academic achievement (Lahana, 2016; Sohn, 2014). Overall, there is more evidence that Arduino enabled-teaching and learning improved academic and psycho-social aspects across many different populations and grade levels. However, the results are far from conclusive and without meta-analytic review.

2.3.2. Scratch in STEM Education

Teaching and learning practices integrated with Scratch have been shown to have positive effects on students' academic achievement as well. Scratch has successfully been implemented in STEM classrooms to aid in teaching students the basics of computer programming (Chang, 2014; Gruenbaum, 2014; Malan, & Leitner, 2007; Sáez-López et al., 2016) and even advanced computer science principles (Armoni et al., 2015; Franklin et al., 2013; Grover & Basu, 2017) while also improving students' mathematical thinking skills (Amador & Soule, 2015; Calao et al., 2015) and computational thinking skills (Kalelioglu & Gülbahar, 2014; Korkmaz, 2018; Zhang & Nouri, 2019). Furthermore, integrating Scratch into classroom activities has been shown to improve students' attitudes towards coding and computer programming (Korkmaz, 2016; Nikou & Economides, 2014; Quille, & Bergin, 2016). Scratch has additionally been integrated into lesson plans in the form of fun activities, such as music making (Fields et al., 2015; Ruthmann et al., 2010) and game development (Funke et al., 2017; Wu, Chang, & He, 2010), and in project-based learning settings (Husna et al., 2019; Sáez-López et al., 2016; Wang et al., 2014).

2.3.3. **The Nexus of Arduino and Scratch**

Arduino was initially limited in its use in education. The text-based programming used in Arduino kept the program's use limited to advanced users who were acclimated with text-based coding. As a result, Arduino and its associated powerful, open source microcontrollers were only being used in post-secondary courses and by instructors with in-depth experience and knowledge of text-based coding. Adoption into K–12 settings were mitigated by a lack of instructors with the skills necessary to use and teach text-based coding as well as the steep learning curve required of students. This situation was solved by the introduction of Scratch, a block-based visual coding environment.

The original version of Scratch did not provide connectivity to Arduino hardware, but the developers of Scratch soon realized that there was a growing demand for coding Arduino hardware using the block-based visual coding language. To allow people to experiment in physical computing using Scratch, the MIT Media Lab released an experimental version of Scratch called ScratchX. This software, which was built on the foundations of Scratch, provided connectivity between Arduino hardware and a visual coding environment using software (Hanning, 2015) and hardware connectors called firmata (Hoefs, 2014). The release of Scratch4Arduino in 2010 and mBlock in 2014 eliminated the need for cumbersome extensions or fermata and allowed users to easily and directly code Arduino hardware using a visual block-based coding environment. The easy pairing of the visual coding abilities of Scratch and Scratch based visual coding environments and Arduino hardware have encouraged schools nationally to integrate Arduino- and Scratch-enabled coding labs into their courses.

Recent years have seen the pairing of Scratch and Arduino in the form of visual coding labs. The visual coding labs address curriculum standards that include computer coding, which many states have adopted (National Research Council, 2010; NGSS, 2020). Furthermore, they have been shown to improve academic achievement and psycho-social development in students (Hoffer, 2012; Mellodge & Russell, 2013; Perenc et al., 2019; Serrano-Perez & Lopez, 2019). Working with Arduino microcontrollers in visual coding environments, students showed excitement towards Arduino-enabled engineering lab activities (Moya, 2018) and had more positive experiences in engineering labs (Oliveira & Hedengren, 2019), perhaps because the ability to physically manipulate real-life objects through visual code makes learning more interesting and rewarding (Przybylla & Romeike, 2014). The visual coding lab environment also promotes experiences with electronic components, hardware, and tools and offers the opportunity to learn how to use them (Brocker et al., 2019; Hawkins et al., 2019). This hands-on technical experience affords students who are activity centric an opportunity to be physically engaged with hands-on construction tasks that scaffold both the coding and Arduino experiences. There is an urgent need to expose K–12 students to engineering education early during their academic life. Using Arduino- and Scratch-enabled visual coding labs to introduce students to fundamentals of engineering and computer programming has shown to improve their interest in engineering (Serrano-Perez & Lopez, 2019) and their joy towards instructional activities (Belfadel et al., 2019). Arduino- and Scratch-enabled visual coding labs are more engaging and produce more positive results than their traditional counterparts, resulting in an improvement in students' engineering academic achievement.

2.3.4. **The Evolution of Computational Thinking through Arduino and Scratch**

Open source Arduino and Scratch has revolutionized how CT is taught. The integration of Arduino- and Scratch-enabled activities that engage students in physical computing is an ideal way to integrate computational thinking skills. Coding and programming activities have long been the dominant method for introducing students to computational thinking skills, but the availability of microcontrollers and robotics (Felicia et al., 2017; García-Peñalvo & Mendes, 2018) has fostered a change toward a more kinesthetic and engaged model in which there is a synthesis between the static computer programming and the building of a model to embody the coding. Model building using Arduino microcontrollers and other peripherals, such as motor controllers, servos, sensors, and motors, enables students to use their CT skills to manipulate physical objects. The physical manifestation of their visual coding using Scratch helps them learn and use engineering domain-specific technical language (Somanath et al., 2017) and provides them a deeper understanding of electronic devices (Blancas et al., 2019). The combination of Arduino and Scratch software is proving to be an effective set of tools for encouraging computational thinking skills in K–12.

Open source Arduino and Scratch further allow traditional CT skill building activities to be easily adapted to physical computing. Proven and effective pedagogical techniques such as the 5E model (Engage, Explore, Explain, Enrich, and Evaluate) of lesson developments (Bybee et al., 2006) have been successfully used in STEM and non-

STEM classrooms. Burke (2014) demonstrated how this traditional lesson planning method can be enriched by adding another ‘E” (for Engineering) to include CT skills that are focused on engineering design and inquiry that lead to student-centered learning and an ownership of the content by students (Lin et al., 2020). When students engage in hands-on problem-solving activities enabled with Arduino and Scratch, they improve their CT skills (Durak et al., 2019.; Hsiao et al., 2019) and are afforded an opportunity to think in creative ways (Fields et al., 2019; Howe, 2015). Hands-on physical computing activities, when used with proven pedagogical approaches, can improve students’ CT skills.

2.3.5. CT Skills and CT Dimensions

CT skills refer to more than just students’ coding abilities. There are many competing definitions of CT in the literature, all of which contribute to the debate over the proper description of the CT skill set (Lye & Koh, 2014). Román-González et al. (2017) attempted to provide clarity by categorizing these definitions as generic, operational, and educational/curricular. At the generic level, CT skills include a student’s ability to think like a computer scientist so that a solution can be implemented using a computing device (Wing, 2011). This requires that students undertake problem-solving methods and develop algorithms to solve those problems using computing devices. The operational definitions for CT skills come from the Computer Science Teachers Association (CSTA) and the International Society for Technology in Education (ISTE). They define CT skills as the ability to engage in problem solving using computing devices; utilizing computing systems both online and offline; collecting, organizing and presenting data visually; using data to achieve abstraction and solve problems; developing algorithms to efficiently use computing devices using sequences, loops, events, and conditions; and the ability to modify, iterate, test, and debug those algorithms individually and as a collective (Computer Science Teachers Association, 2017; International Society for Technology in Education, 2014). Both the generic and operational definitions speak to what skills students should possess to be considered proficient in CT.

The educational and curricular definitions of CT skills focus on how to help students develop CT skills using teaching and learning practices. There are many CT skill frameworks that attempt to provide guidance on how to incorporate CT skill development in teaching and learning practices. For a review of these frameworks see Zhang & Nouri (2019). In our study, we focus on the curricular definition of CT skills described by Brennan and Resnick (2012). Their frame development used Scratch as a major tool for CT skill development and divided the teaching and learning of CT skills into three dimensions: CT concepts, CT practices, and CT perspectives. CT concepts are those computer science and coding concepts that students engage with as they practice problem solving. These concepts include sequences, loops, events, parallelism, conditionals, operators, and data. CT practices are those actions that students perform in order to construct solutions. These practices include being incremental and iterative, testing and debugging, reusing, and remixing, and abstracting and modularizing. Students' understanding of concepts and the application of those concepts through practice leads to shifts in how students think about problem solving using computational devices. Finally, CT perspectives refers to a student's ability to express the impact of the solution they have created, how they connect their particular solution to a wider set of general problems, and their ability to question the applicability of their solution and how it could be improved. The CT dimensions of concepts, practices, and perspective combine to provide a sound foundation for classroom implementation of CT skills development.

2.4. Statement of Problem

A greater focus is being placed on improving students' CT skills in K–12 education, and there have been many attempts to address the development of CT in K–12 schools. Despite this emphasis, there is no single clear pathway and no consensus on how to utilize open source software and hardware to enhance CT. Furthermore, the use of robotics, microcontrollers, and programmable toys, though shown to effectively improve students' CT, has been inhibited by the high cost of these devices (Hendricks, 2013). Research indicates that open source Arduino and Scratch can achieve many of the same educational benefits as their more expensive counterparts, thereby reducing acquisition costs while democratizing access for students in poorly financed schools. Even though the last decade has seen much research on the use of open source Arduino and Scratch as an intervention for teaching CT, there is no systematic aggregation of those studies. To address this, we conducted a meta-analysis of the effects of Arduino- and Scratch-enabled interventions to provide aggregated evidence of the impact of open source Arduino and Scratch on students in STEM classrooms.

2.5. Research Questions

This meta-analysis was guided by the following research questions:

1. Do Arduino- and Scratch-enabled interventions improve students' overall CT skills?
2. What are the effects of Arduino- and Scratch-enabled interventions on each dimension (concepts, practices, and perspectives) of students' CT skills?
3. What are the moderating effects of student grade level and the duration of intervention on the effectiveness of Arduino- and Scratch-enabled interventions on students' CT skills?

2.6. Methodology

In this study, we used meta-analysis first suggested by Glass (1976) and further improved by Glass et al. (1981). This methodological research technique requires researchers to combine similar quantitative research studies and calculate a cumulative effect size. For the current study, a systematic search was conducted for studies published between 2010 to 2019 that met the inclusion criteria. The first emergence of Arduino hardware was in 2005, and the public availability of Scratch software occurred in 2007. The 2010 date was selected because it was the earliest date during which we were likely to locate articles combining both the open source software and hardware. The first published articles wherein both Arduino and Scratch were being used were published in 2014.

2.6.1. Inclusion and Exclusion Criteria

Randomized and quasi-experimental studies that satisfied the following criteria were included in this meta-analysis: (a) published in the English language, (b) participants were students in K–12 or post-secondary settings, (c) focus was on the use of Arduino or Arduino-based microcontroller units (MCU) in combination with Scratch or Scratch-based visual coding, (d) published in an online accessible format as either a peer-reviewed journal article, conference proceeding, or committee-approved dissertation or master's thesis, (e) published between 2010 and 2020, inclusive, and (f) provided effect sizes in a standardized form or statistics that could be used to compute an effect size. Articles that were not available from online sources or were only available for a fee were excluded from this study as were studies that did not meet the inclusion criteria.

2.6.2. Literature Search Procedure

A two-step literature search approach was used for this study. First, Google Scholar was used to search for literature using keywords. Google Scholar was chosen because it provides links to full documents and pointers to the documents not available for immediate download (i.e., copyright, and non-open access journals held by publishers). Another benefit of using Google Scholars lies in its ability to provide links to resources without bias. When Google Scholar cannot provide access to the articles, it informs interested parties that the article exists and allows them to read the article's abstract. This democratizes knowledge and allows non-subscribers to major journal indexing firms and publishers (e.g., Web of Science, Elsevier, etc.) to know about the existence of otherwise inaccessible articles.

Using the search criteria listed above, the initial search with the keywords "Scratch" and "Arduino" resulted in more than nine thousand articles. We further limited the search using the phrase "computational thinking," which reduced the number of articles to 1,190. To limit our search to quantitative articles, we added the keyword "pretest OR posttest" to our search keywords. The resulting 171 articles were added to our Google Scholar library (this is done by clicking on the star symbol underneath the reference). Each article was then downloaded either directly from the link provided by Google Scholar or by requesting it through the author(s)' academic institution library. Articles that were not available directly from Google Scholar, through the university library, or were only available for a fee were excluded from this study. Ultimately, 12 studies were selected for inclusion in the meta-analysis.

Six of the studies were peer-reviewed articles from scholarly journals, four studies were published conference proceedings, and two studies were dissertations. For a brief summary of studies included in this meta-analysis, see Table 2.1. All but one study (Sáez-López et al., 2019) used Arduino UNO. The study that did not use an Arduino UNO used mBot, an Arduino-based educational robot. Seven studies implemented a pre-experimental matched group research design, four studies used quasi-experimental design, and only one study implemented a true experimental design.

Once the final studies were selected, the second step of the literature search was undertaken in the form of a reverse search to find more articles that might fit the inclusion criteria. During the reverse study, the references in each of the 12 articles' references were scanned to locate other relevant literature. The promising references were reviewed, but all resulting articles had already been reviewed for selection. Details and chronology of the literature search is provided in Figure 2.1.

2.6.3. Coding Procedure

A Microsoft Excel worksheet was developed to code specific characteristics of each study. For each study, we assigned a study number and documented the author, year, publication type, grade level of participants, duration of the study in weeks, research design, and experimental curriculum. The dependent variable in this meta-analysis was the students' CT skills. We chose to follow the CT framework proposed by Brennan and Resnick (2012) in which the researchers proposed three dimensions of CT skills: concepts, practices, and perspectives. We divided the single dependent variable into three dependent variables reflecting these three dimensions of CT skills: 1) if the reported outcome reflected a change in students' CT skills relating to sequences, loops, events, parallelism, conditionals, operators, and data, then the effect was categorized as CT concepts; 2) the effect was categorized as CT practices if the outcome reported a change in students' ability to successfully modify code with incremental and iterative changes using reasoning, remixing, abstracting, and modularizing; and 3) when the outcome reported a change in students' skills in expressing, connecting, and questioning the effect was categorized as CT perspectives.

2.6.4. **Computation of Effect Sizes**

Twelve studies were included in this meta-analysis, providing 19 data sets in total. Seven of the data sets were CT concepts, nine were CT practices, and three were CT perspectives. Out of the 19 data sets, three data sets reported Mann-Whitney U statistics, one reported the log odds ratio, and eight datasets reported means and standard deviations. For the studies that provided means and standard deviations, the standard mean difference was calculated in the form of Cohen's *d*. The reported Mann-Whitney U statistics were converted to standardized *z* (Siegal, 1956), which was then used to calculate a Cohen's *d* effect size (Cohen, 1988). The log odds ratio was converted to Hedges' *g* effect size (Borenstein et al., 2009). Once standardized effects were calculated for each dataset, standard error for each effect size was calculated (Fritz et al., 2012). Both effect sizes and standard errors were entered in STATA 16 along with other independent variables.

2.6.5. Statistical Analysis

STATA 16 was used to conduct the meta-analysis. Weighted effect sizes were combined to compute an overall effect size. Weighted effect sizes properly represent the contribution of each study according to its sample size (Lipsey & Wilson, 2001). Funnel plots were then used to identify potential publication bias (Tang & Liu, 2000). Funnel plots present the effects of each study against the standard error associated with that effect (Sterne & Eggert, 2011). The x-axis of the funnel plot represents the effect size, and the y-axis denotes the standard error of the effects. To aid in our analysis of publication bias, we employed the trim and fill method proposed by Duval and Tweedie

(2000). We also assessed for heterogeneity between studies to determine a need for moderator analysis. The heterogeneity of the variance between studies was tested using Cochran's *Q* (Q statistic) and visual analysis of the forest plots. The Q statistic is calculated by summing the weighted squared deviations of the effects and is considered instrumental in assessing the heterogeneity of the effect sizes within the meta-analysis (Hoaglin, 2016).

Heterogeneity within the effect size suggests moderator effects and encourages moderator analysis. A moderator analysis divides the independent moderator variable into groups and can help investigate the strength and direction of the effects (Frazier et al., 2004). Age is a common moderator variable used in the investigation of effects (Thompson, 2006), but because most studies included in this meta-analysis did not provide the ages for student participants, we examined grade level as a possible moderator. To conduct the moderator analysis, we implemented subgroup analysis based on our hypothesized moderators. For each moderator, the studies were divided into subgroups based on the different levels of that moderator. The grade level moderator was divided into three subgroups: elementary, middle, and post-secondary. The duration of the study was divided into two subgroups: 13 weeks or less and more than 13 weeks. For each moderator variable, the test of difference between subgroups indicated if the hypothesized moderator had any moderating effect on the outcome. This process was repeated for each CT skill dimension.

2.7. Results

2.7.1. Effect Size on Overall CT Skills and CT Dimensions

To answer our first research question, we calculated an overall effect size of Arduino- and Scratch-enabled interventions on students' CT skills. The findings from this meta-analysis demonstrate that Arduino- and Scratch-enabled interventions improved students' overall CT skills. The effect of Arduino and Scratch enabled interventions on improving students' overall CT skills was $d = 1.03$ ($CI = [0.63, 1.42]$). Out of the 19 effect sizes, 12 were statistically significant, whereas 7 effect sizes subsumed zero within their 95% confidence interval (See Figure 2.2).

To answer our second research question, we meta-analyzed effects pertaining to each of the three dimensions of CT skills (concepts, practices, and perspectives) proposed by Brennan and Resnick (2012). The effect of Arduino- and Scratch-enabled interventions on student's CT concepts skills was $d = 1.16$ ($CI = [0.41, 1.91]$). Four out of seven effect sizes for CT concept skills were statistically significant, while three included zero effect in their 95% confidence interval. The effect of Arduino- and Scratch-enabled interventions on students' CT practices skills was $d = 0.72$ ($CI = [0.42, 1.02]$). Six out of nine effect sizes for CT practices skills were statistically significant, while three included zero effect in their 95% confidence interval. Finally, the effect of Arduino- and Scratch-enabled interventions on students' CT perspective skills was $d = 1.68$ ($CI = [0.08, 3.27]$). Two out of three effect sizes for CT perspective skills were statistically significant, whereas one effect size included zero effect in its 95% confidence interval. The effects on the concepts, practices, and perspectives dimensions of CT skills are presented in Figures 2.3, 2.4, and 2.5, respectively. Table 2.2 provides a description of the overall effect size, along with the effects on each CT dimension as well as its 95% confidence interval and % weight.

2.7.2. **Homogeneity of Effect Sizes and Publication Bias**

The hypothesis of homogeneity for the overall effect in this study was rejected due to the statistically significant Q value of 135.03 (df = 18, $p < .001$), which indicated that effects were grouped according to moderating variables (Ellis, 2010). The hypothesis of homogeneity was rejected for the studies reporting effects on student CT concepts skills ($Q = 40.85$, $df = 6$, $p < .001$), CT practices skills ($Q = 30.14$, $df = 8$, $p < .001$), and CT perspective skills ($Q = 35.87$, $df = 2$, $p < .001$). The indications of heterogeneity in the overall CT skills effect size and in the effect sizes for the three dimensions of the CT skills necessitated the need for moderator analysis based on our hypothesized moderators: grade level and duration of the intervention.

The results of the trim and fill funnel plot, provided in Figure 2.6, suggested there were no relevant studies missing from this meta-analysis. The dispersion of the studies around the overall effect size inside and outside the 95% confidence level is very symmetrical. This leads us to believe that there were no indications of publication bias.

2.7.3. Moderator Effects

To answer our third and final research question, we conducted an analysis of the effects of our hypothesized moderating variables (student grade level and the duration of the study in weeks) on CT dimensions.

2.7.3.1. Effects Moderated by Grade Level

Two studies reported effects on elementary students' CT concepts skills ($d = 1.46$ $CI = [-1.40, 4.32]$). Only one of those studies reported statistically significant effects, and the overall effect also failed to show statistical significance. The effects of these studies were not homogeneous and showed unexplained between-study variances ($I^2 = 95.5\%$, $p < .001$). Three studies reported effects on middle school students' CT concepts skills ($d = 1.11$ $CI = [-0.27, 2.36]$). The effects of these studies were not homogeneous and showed unexplained between-study variances ($I^2 = 82.96\%$, $p < .001$). Only one of those studies reported statistically non-significant effects, and the overall effect showed statistical significance. Two studies reported effects on post-secondary freshmen's CT concepts skills ($d = 1.05$ $CI = [-0.27, 2.36]$). The effects of these studies were not homogeneous and showed unexplained between-study variances ($I^2 = 78.92\%$, $p < .001$). Only one of those studies reported statistically significant effects, and the overall effects also failed to show statistical significance. The test of group differences revealed that grade level had no statistically significant moderating effect on students' CT concepts skills ($Q_b = 0.07$, $df = 2$, $p = 0.97$), as there were no statistically significant differences in students' CT concept skills outcomes between elementary, middle, and post-secondary grades.

Three studies reported effects on elementary students' CT practice skills ($d = 0.80$ $CI = [0.02, 1.58]$). Only one of those studies reported statistically non-significant effects, and the overall effects showed statistical significance. Five studies reported effects on middle school students' CT practice skills ($d = 0.70$ $CI = [0.30, 1.10]$). Only one of those studies reported statistically non-significant effects, and the overall effects showed statistical significance. Only one study reported effects on post-secondary freshmen's CT concepts skills ($d = 0.66$ $CI = [-0.20, 1.52]$). The lone study reported statistically non-significant effects. The test of group differences revealed that grade level had no statistically significant moderating effect on students' CT practice skills ($Q_b = 0.07$, $df = 2$, $p = 0.97$), as there was no statistically significant difference in students CT practice skills outcome between elementary, middle, and post-secondary grades.

Two studies reported effects on elementary students' CT perspective skills ($d = 1.21$ $CI = [-1.08, 3.5]$). Only one of those studies reported statistically significant effects, and the overall effects also failed to show statistical significance. In the study on middle school students' CT perspective skills ($d = 2.57$ $CI = [2.08, 3.06]$), a statistically significant effect was reported. No effects were reported on post-secondary students' CT perspective skills. The test of group differences revealed that grade level had no statistically significant moderating effect on students' CT perspective skills ($Q_b = 1.29$, $df = 1$, $p = 0.26$), as there was no statistically significant difference in students CT concepts skills outcomes between elementary, middle, and post-secondary grades.

2.7.3.2. **Effects Moderated by Study Duration**

Concept skills were differentially affected by study duration. Two studies lasting 13 weeks or less reported effects on CT concepts skills ($d = 0.06$ $CI = [-0.37, 0.70]$). Both studies contained statistically non-significant effects, and the overall effect also was not statistically significant. The effects of these studies were homogeneous and showed no between-study variances ($I^2 = 0\%$, $p = 0.52$). Five studies lasting more than

13 weeks reported effects on students' CT concepts skills (d = 1.55 CI = [0.74, 2.35]). The effects of these studies were not homogeneous and showed unexplained between-study variances (I^2 = 84.71%, $p < .001$). Only one of those studies reported a statistically non-significant effect, and the overall effect was statistically significant. The test of group differences revealed that the length of studies had a statistically significant moderating effect on students' CT concepts skills (Q_b = 7.89, df = 1, $p < .001$), as there were statistically significant differences in students CT concepts skills outcomes between studies of different lengths.

For the CT practice skills that lasted 13 weeks or less, the effect of Arduino- and Scratch-enabled interventions was d = 0.78 (CI = [0.19, 1.38]). Three studies contained statistically non-significant effects, but the overall effect was statistically significant. The effects of these studies were not homogeneous and showed between-study variances (I^2 = 80.63%, $p < .001$). Four studies lasting more than 13 weeks reported effects on students' CT practice skills (d = 0.63 CI = [0.40, 0.86]). The effects of these studies were homogeneous and showed no between-study variances (I^2 = 0%, p = 0.73). In these four studies, statistically significant effects were shown, and the overall effect was statistically significant. The test of group differences revealed that the length of studies had no statistically significant moderating effect on students' CT practice skills (Q_b = 0.21, df = 1, p =0.64), as there were no statistically significant differences in students' CT practice skill outcomes between studies of different lengths.

The length of the study had an overall positive moderating effect on students' CT perspective skills. One study lasting 13 or less weeks reported effects on CT perspective skills ($d = 0.06$ $CI = [-0.63, 0.75]$). Two studies lasting more than 13 weeks reported effects on students' CT perspective skills ($d = 2.53$ $CI = [2.10, 2.96]$). The effects of these studies were homogeneous and showed no between-study variances ($I^2 = 0\%$, $p = 0.75$). All but one study reported statistically significant effects, and the overall effect showed statistical significance. The test of group differences revealed that the length of a study had statistically significant moderating effects on students' CT perspective skills ($Q_b = 35.77$, $df = 1$, $p < .001$), as there were statistically significant differences in students CT perspective skill outcomes between studies of different lengths.

2.8. Discussion

The results of this meta-analysis provide evidence for the efficacy of Arduino- and Scratch-enabled interventions in improving CT skills. The findings indicate that the combination of Arduino and Scratch had an overall positive effect on students' CT skills and that these skills were improved in the areas of problem solving (Felicia et al., 2017), creative thinking (Hsiao, 2019), application of engineering concepts (Jaithavil & Kuptasthien, 2019), use of engineering instrumentation and electronic and electrical components (Blancas et al., 2020), computer programming (Booth & Stumpf, 2013; Felicia et al., 2017), hands-on engineering ability (Karaahmetoglu & Korkmaz, 2019), and the academic areas of biology, mathematics, and science (Sáez-López, 2019). The findings from this meta-analysis also indicate that Arduino- and Scratch-enabled interventions had the largest effect on students' CT perspectives skills; this was followed in magnitude by the effect on students' CT concepts skill, then CT practices skills. The positive overall effect size determined through this meta-analysis shows that Arduino and Scratch are linked to positive effects across sample demographics. Furthermore, no negative effects were reported for Arduino- and Scratch enabled interventions on students' CT skills. This should not be taken to mean that all such interventions have a positive effect on students' CT skills, however. Although our investigation of publication bias did not report any evidence of publication bias, we believe that due to the nature of research and publication, there is a strong possibility there are studies that did not attain positive outcomes.

Multiple studies reported more than one positive effect size corresponding to different CT skill dimensions. Analysis of effects grouped by their parent study reveals an interesting observation. We found that either all the effects reported by a study were statistically significant or none of them were. This indicates that the manner in which the combination of Arduino and Scratch were implemented as an intervention turned out to be either statistically significant for all CT skill dimensions at all grade levels regardless of the length of the study or none at all. We do not believe that this is by chance, because all studies that reported statistically non-significant effect sizes (i.e., Booth & Stumpf, 2013; Felicia et al., 2017; Karaahmetoğlu & Korkmaz, 2019; Merkouris et al., 2017) used Scratch derivatives (ModKit and Scratch4Arduino) rather than the original Scratch software to code the Arduino hardware. This is not to say that no Scratch derivative produced statistically significant positive effect sizes. Studies that implemented Visualino and mBlock produced statistically significant positive results. The mixed results indicate that compared to Scratch, students had varying levels of success with Scratch derivatives.

Another interesting set of results of this meta-analysis came from the analysis of the hypothesized moderating variables. The grade level of students did not have any moderating effect on students' overall CT skills nor on the CT skill dimensions. Results revealed that although the length of the studies had a moderating effect on the CT concepts and CT perspectives skills, it did not have a moderating effect on CT practices skills. Usually, the effects of the duration of treatment are more pronounced in clinical trials (Gibbs, 1997; Seibel et al., 2004); thus, finding a possible relationship between the positive results of Arduino- and Scratch-enabled interventions moderated by the length of those interventions opens another avenue of research and inquiry to be explored.

There are some limitations to this meta-analysis. It should be noted that the 12 studies chosen to be included in the meta-analysis do not exist in a vacuum. These studies occupy an expanding body of empirical literature that speaks to the efficacy of Arduino- and Scratch-enabled teaching and learning practices and their ability to improve students' CT skills. However, a majority of those studies either report qualitative or theoretical results dealing with lesson or project developments using Arduino, Scratch, or both. The small number of empirical studies selected for final analysis indicates that there is a need for further quantitative research on the subject. Also, of importance is the kind of quantitative research being conducted and reported. Only two out of the 12 studies included in this meta-analysis implemented a randomized experimental research design. We believe that this meta-analysis brings into focus a need for more true experimental research on the efficacy of Arduino and Scratch in improving students' CT skills.

Another limitation of this meta-analysis is the absence of negative effect sizes. Failure is often considered a very strong motivator for continued research, and reporting failure indicates that the researchers in the field are committed to the efficacy of their proposed interventions and are willing to improve it through peer review. The reporting of negative results allows the researchers who conducted the study and others in the field to learn from failure (Kicinski, 2014). We conducted an exhaustive literature search and analyzed all available literature on the subject for inclusion in the meta-analysis, but we did not find any studies that reported negative effects of Arduino- and Scratch-enabled interventions. However, we did find studies that had reported effect sizes that were statistically non-significant. The inclusion of statistically non-significant effects within this meta-analysis also reduces a chance of publication bias. Publication bias can cause validity issues in a meta-analysis, and reporting negative results helps to mitigate this issue. We strongly believe that negative effects of empirical endeavors should be reported to increase the breadth of the education knowledge base.

2.9. References

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3. BUILDING FUTURE ENGINEERS BY BUILDING 3D PRINTED OPEN SOURCE ARDUINO MARS ROVER WITH 4TH GRADERS

3.1. Introduction

Many factors influence students' perceptions towards science, technology, engineering, and mathematics (STEM) courses and careers. Students often see STEM subjects as difficult and miserable (Zambo & Zambo, 2006). Many students feel unmotivated in STEM courses because of previous academic experiences, peer interactions, or after discussions with advisors and teachers (Reed, 2014; Suresh 2006). These negative feelings often lead to apathy and disengagement with STEM coursework. Hands-on STEM learning has the potential to encourage positive feelings and perceptions toward STEM careers by exposing K–12 students to motivating STEM classroom experiences. These positive experiences are important because constructive attitudes towards STEM topics can lead to students ultimately entering STEM fields (Fredrickson, 2001). When students are excited about a STEM career, they are more likely to participate enthusiastically in STEM courses. That enthusiasm often leads to success in STEM coursework in post-secondary settings (Nelson et al., 2017) and eventually to securing a STEM job. The path to improving students' perceptions towards STEM careers can have long-lasting effects and might be precipitated by certain instructional practices that support and encourage positive learning experiences.

Traditional instructional methods are failing to hit their mark in fostering STEM interests for most students. There is evidence that teacher-centric and lecture-based learning experiences increase apathy towards learning (Newhouse, 2017; Staats, 2014), whereas, when compared directly with traditional teaching methods, innovative new methods of teaching and learning, such as project-based learning (PBL), have been shown to be more effective at increasing student STEM interest (Mahasneh & Alwan, 2018; Newhouse, 2017; Schneider et al., 2002; Yao et al., 2019). The problem of apathy towards STEM is even more severe for students from low-socioeconomic status (SES) backgrounds and minority groups. The positive impacts of non-traditional teaching and learning practices on students from low-SES backgrounds and minority groups is especially of interest. In fact, research where non-traditional teaching practices, such as PBL, educational robotics (ER), and hands-on learning integrated teaching practices, have been used, the results for students from low-SES and minority families have been an enhanced self-efficacy (Chen et al., 2015; Leonard et al., 2016), improvement of academic skills (Craig & Marshall, 2019; Han et al., 2015; Holmes & Hwang, 2016; Seage & Türegün, 2020), and development of positive attitudes towards STEM subjects and careers (Anwar et al., 2019, Fidai et al., 2021; Leonard et al., 2016). There is a need for encouraging non-traditional methods of teaching and learning in STEM classrooms to improve learning experiences and thereby STEM attitudes and perceptions of students in general and those from low-SES and minority backgrounds specifically.

3.2. **Background**

3.2.1. Open source hardware and software

Open source technology is seen as a direct opponent to proprietary license-based products and services. Open source technology has three basic tenants: free to access, free to use, and free to modify (Open Source Initiative, 2020). The open source movement in technology was pioneered by Richard Stallman, who is considered the father of open source software (Pearson, 2000). Stallman's advocacy for open source software resulted in the development of the Linux operating system, which later gave birth to Android (Priestley, 2019). Open source software and hardware hold many advantages over proprietary technologies. Open source software can be freely accessed and modified (Bosio et al., 2002; DeLano, 2005; Min, 2006). The schematics, wiring diagrams, and even the machine-level source code for open source hardware can be accessed freely and custom modified as well. This allows anyone to build a prototype of such hardware using readily available electronic components (Gibb & Abadie, 2014). Open source software and hardware have revolutionized the technology industry, and they can also help to create more access and opportunities for all students in STEM education.

3.2.2. **Arduino and Scratch**

Open source Arduino is a microcontroller device that allows rapid prototyping of electronics projects. Arduino, due to its low cost and ease of use, has become the most well-known electronics prototyping platform in the world. The first Arduino device was developed in 2005 at the Interaction Design Institute Ivrea in Ivrea, Italy (Hughes, 2016). Three years later in 2008, Arduino UNO R3 was released, which until this day is considered the most widely used prototyping board by students and do-it-yourself (DIY) enthusiasts. This fact is evident by the vast community of Arduino UNO loyalists and the large number of Arduino UNO projects available on community websites such as GitHub (GitHub, 2020) and Instructables.com (Instructable team, n.d.). In addition to a plethora of projects freely available online, users who are new to Arduino also have access to question-and-answer websites, such as Stack Exchange, Stack Overflow, Reddit, and Arduino Project Hub. This free flow of information and exchange of ideas makes Arduino Uno a device of choice for people interested in prototyping and making.

Scratch is a freely available, open source visual coding tool that has been available to the general public since 2013. Users can use visual coding blocks in the Scratch environment to write code or programs without writing textual commands, as required in traditional programming environments. Scratch is based on the Blockly libraries developed by Google (Google Developers, 2020). The Blockly libraries provide the foundation for Scratch and many other visual programming tools, such as mBlock, MIT App Inventor, and Microsoft MakeCode, to name a few. Scratch allows instructors to introduce students to programming and the fundamentals of computer science (CS) and computational thinking (CT) in a friendly environment. This evolution in programming environment eliminates the need for a student to learn any specific programming language and instead helps instructors focus their energies on engaging students in CT and CS skills. Due to the ease of use, multiple language support (Scratch, 2020), and a smooth learning curve, Scratch and Scratch-like visual coding environments have become extremely popular in classrooms all over the world.

Arduino and Scratch are prime examples of the power of open source hardware and open source software. The low cost of Arduino and Scratch’s freely available visual coding environment make them a perfect pair to be used in STEM classrooms. In this experimental research study, we combined the Arduino microcontroller with threedimensional (3D) printed parts to build a Mars Rover-type ER and used Scratch – based mBlock (Makeblock, n.d.), a freely available visual coding software (see Figure 3.1), to engage students in the engineering design process and experiential learning.

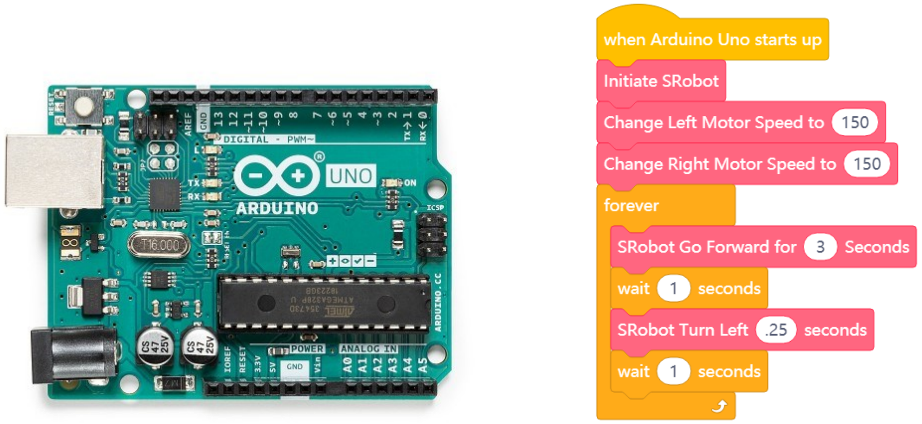
3.3. Literature review

3.3.1. Educational robotics in STEM Education

Educational robotics can be successfully implemented in STEM classrooms to help improve many aspects of students' academic skills. A recent systematic review of the impact of ER (Benitti et al., 2012) concluded that engagement in hands-on ER activities improves students' STEM academic achievement (Barker & Ansorge, 2007; Hussain et al., 2006, Lindh & Holgersson, 2007; Whittier & Robinson, 2007; Williams et al., 2007) and their attitudes towards STEM (Hussain et al., 2006; Nugent et al., 2010). Interventions based on ER have also been shown to be effective in introducing students to data acquisition through electronic sensors (Karalekas et al., 2020). Use of ER allows STEM teachers to help engage students with academic concepts in an informative and playful environment to increase their understanding and participation (D'Amico et al., 2020; Hussain et al., 2006). ER also enhances students' social interactions by increasing their confidence and communication skills (Melchior et al., 2005). Use of ER additionally improves students' technology self-efficacy and positive self-perceptions (Beisser, 2005). Recent empirical research into the use of ER has produced a plethora of evidence of the efficacy of ER in STEM education, establishing ER as a viable instructional tool.

Figure 3.1

Open Source Arduino Uno Microcontroller and a Code Block From Scratch Visual Coding Environment



```
when Arduino Uno starts up
Initiate SRobot
Change Left Motor Speed to 150
Change Right Motor Speed to 150
forever
  SRobot Go Forward for 3 Seconds
  wait 1 seconds
  SRobot Turn Left .25 seconds
  wait 1 seconds
```

The falling costs of additive prototyping has made 3D printed ER more accessible. 3D printing has come a long way from its inceptio4.4

n a half century ago. Machines that used to be behemoth in size, costing thousands of dollars, now sit on desks next to a laptop and costing as little as $99 (Banggood, n.d.). The easy availability and low cost of current 3D printers have helped instructors introduce students to “making” and prototyping by as early as the elementary grades. Engaging students in 3D printed ER allows teachers to expose students to CT skills (Angelopoulos et al., 2020) and improve academic achievement in STEM subjects (Cheng et al., 2020; Hansen et al., 2020; Ng et al., 2020; Smith & Tyler–Wood, 2020).

The use of 3D printed ER in STEM lessons as a technology tool has opened the door to hands-on learning for more students than ever before.

3.3.2. **Arduino and Scratch in STEM education**

Arduino and Scratch have been useful for improving students' self-efficacy and self-perceptions. Engaging with an Arduino controller was shown to improve students' perceptions towards STEM courses (Chen & Chang, 2018; Kafai et al., 2014; Martín-Ramos et al., 2017) and STEM careers (Chen & Chang, 2018; Kuo et al., 2019; Yin et al., 2019). While the psycho-social aspect and expectancy outcomes have been enhanced through the use of Arduino, academic skills have also benefitted (Chen & Chang, 2018; Hsiao et al., 2019; Psycharis & Kotzampasaki, 2019; Yasin et al., 2018). Furthermore, open source Arduino is increasingly being used to enhance students' computing skills. Arduino-integrated teaching and learning practices have been linked with improvements in students' CT skills (Bartholomew & Zhang, 2019; Pala & Türker, 2019; Pratiwi & Nanto, 2019), CS skills (Chou, 2018; Perenc et al., 2019; Sohn, 2014; Tan et al., 2017), and understanding of physical computing systems (Choi & Kim, 2016; Psycharis et al., 2018; Psycharis & Kotzampasaki, 2019). The mounting evidence in support of Arduino for improving academic skills is establishing it as the quintessential tool for engaging students in hands-on academic learning

Instructors are also increasingly using Scratch to introduce students to coding and computer programming skills. Exposure to CT and CS skills has often been relegated to the last few years of K–12 education or reserved for select students in specialized courses (Gal-Ezer & Stephenson, 2010), but Scratch has enabled instructors to democratize CT and CS experiences for all K–12 students (Fidai et al., 2020). Scratch has been used in STEM classrooms to introduce students to CS (Chang, 2014; Franklin et al., 2020; Gruenbaum, 2014; Pérez-Marín et al., 2020; Sáez-López et al., 2016), and instructors have successfully used Scratch and its variants to improve students' CT skills (Fagerlund et al., 2020; Pérez-Marín et al., 2020; Rodríguez-Martínez et al., 2020). In STEM classrooms, Scratch has been shown to positively impact students' scientific process skills (Turan & Aydoğdu, 2020) and also their academic skills in STEM subjects (Fidai et al., 2020; Iskrenovic-Momcilovic, 2020; Rodríguez-Martínez et al., 2020). These successes mean that Scratch and its many derivatives are helping instructors engage students in CS, CT learning, and STEM education all around the world.

3.4. Statement of problem

Proprietary ER kits have been shown to help improve students' academic experiences, but those kits are expensive. A typical LEGO or VEX IQ ER kit costs approximately $500 (LEGO Group, n.d.; VEX, n.d.). At this price point, the use of ER in low-SES neighborhood schools is an impractical idea (Chalmers et al., 2014). A classroom set of proprietary ER kits can cost thousands of dollars, so even if the school administrators decide to invest in ER, they are often limited in their options due to budgetary constraints (Zhong & Xia, 2020). This means that students in poorly funded schools are not afforded the opportunity to engage in ER activities (Daniela, & Lytras, 2018), limiting their STEM learning experiences and thus their opportunities to develop positive perceptions of STEM careers. There is a need for innovative and low-cost solutions to bring the power of ER to all students.

3.5. **Research Questions**

This experimental research study was guided by following research questions:

1. What are the changes in students' perceptions towards STEM subjects and career interests as a result of engaging with an Arduino ER activity?
2. How do students' attitudes towards STEM change as a result of participating in an after-school STEM club where they participated in an Arduino ER activity?
3. To what extent did students' affect towards engineering as a profession change as a result of engaging in an Arduino ER activity?
4. What were the mediating effects of students' race/ethnicity and gender on changes to their perceptions and attitudes towards STEM subjects and careers and, specifically, towards engineering as a profession?

3.6. **Methodology**

3.6.1. Participants

Fourth-grade students from a public elementary school in the southwestern United States were the participants in this experimental research study. We invited all fourth-grade students who attended the school to participate in an after-school STEM Club. There was one exclusion criterion for this study: those students who had previous experience with Arduino and Scratch were not eligible to participate in either the experimental or control groups. The resulting participants were then randomly divided into experimental and control groups. The experimental group received instruction based on the engineering design process, which focused on designing, building, coding, and testing a 3D printed replica of the Mars Rover. The experimental group is referred to as the *Arduino Mars Rover group* henceforth. The control group engaged in coding activities using the Scratch visual coding environment and will be referred to as the *Scratch group*. Coding activities were used in the control group because they have been shown to improve students' CT skills (Fagerlund et al., 2020; Pérez-Marín et al., 2020; Rodríguez-Martínez et al., 2020). Because of its free availability and ease of use, teachers with limited resources who are interested in introducing their students to coding and programing in class or during afterschool STEM clubs use Scratch an alternative to robotics. The pool was selected by placing names on index cards, folding them in half, and placing them into an opaque container. Names were then drawn and assigned to one of the two groups, and the next name drawn was assigned to the other group. This alternated group assignment and was done until all names were drawn. Initially, 31 students registered to participate in the study, but nine students did not complete the study, so their data were not included in the final analyses ($N = 21$). Descriptive statistics are provided in Table 3.1.

3.6.2. **STEM club format**

The after-school STEM Club was conducted for nine weeks. Each session lasted between 60 and 90 minutes. A summary of weekly STEM Club activities are presented in Table 3.2. The after-school STEM Club was held at the elementary school the students attended. Students in the Scratch group engaged in coding activities using freely available Scratch lesson plans from Scratch website. The students in the Arduino Mars Rover group were introduced to engineering professions and the engineering design process as they engaged in building, coding, and testing a 3D printed Mars Rover type ER.

3.6.3. **Materials**

In the Arduino Mars Rover group, students worked with 3D printed parts, open source Arduino hardware, and mBlock visual coding software. They were introduced to open source repositories such as Yeggy and Thingiverse, which house design files, instructions, and other materials for a multitude of 3D print projects. We helped students select design files for the Mars Rover type ER and assembled them at a local university's 3D printing lab. During the subsequent sessions, students assembled and coded the 3D printed Mars Rover ER and conducted experiments with it.

A DIY version of the Mars Rover, called "JPL open source rover," was freely available online at NASA's website (Jet Propulsion Laboratory, 2019). The plans are detailed and could assist in building a working replica of a Mars Rover. However, these plans could not be used during this study because of the high cost (approximately $2500) of prefabricated metallic parts and proprietary electronic components only available from certain suppliers. Instead, we used open source Arduino, mBlock, 3D printed parts, and commonly available electronic components to build a similar Mars Rover type robot (see Figure 3.2). We chose to 3D print the Mars Rover ER due to the easy availability of open source design files and the low cost of the Arduino microcontroller. This 3D printed open source Rover behaved similarly to the JPL DIY rover but costed considerably less.

3.6.4. **Survey Instruments**

We used three survey instruments as pre and posttests in this experimental study to measure the effects of an after-school STEM Club on students' perceptions and attitudes toward STEM and their affect toward engineering. The survey instruments were the following:

1. STEM Semantics Survey (Tyler–Wood et al., 2010)
2. Upper Elementary School Student Attitude Toward STEM (S-STEM) (Unfried et al., 2015)
3. Affect Towards Engineering Professional Practice (Patrick et al., 2017)

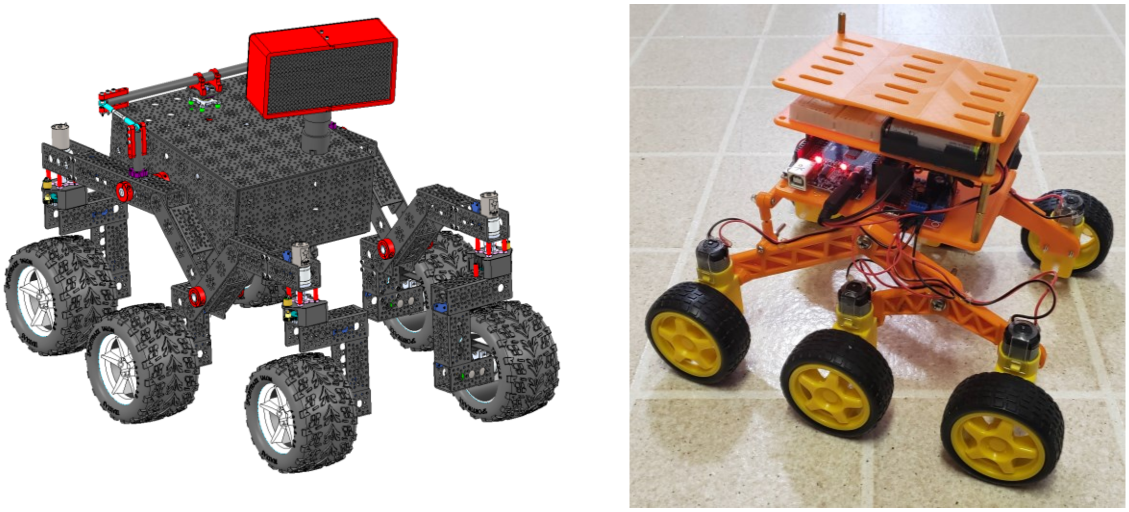
The Cronbach's Alpha value for the STEM Semantics Survey was reported to be between .78 and .94. The Upper Elementary School Student Attitude Toward STEM (S-STEM) survey's reliability was reported to be above 0.83. Finally, the Affect Towards Engineering Professional Practice survey's reliability was reported as being between 0.74 and 0.88.

3.6.5. **Data Analyses**

All survey data were imported into STATA 16 for analysis. Data from the STEM Semantics Survey was grouped into five STEM perception dimensions (Science, Mathematics, Engineering, Technology, and STEM Career). Similarly, the data from the Upper Elementary School Student Attitude Toward STEM (S-STEM) survey were

Figure 3.2

JPL open source rover and Open Source 3D Printed Mars Rover



clustered into four STEM attitude dimensions (Mathematics, Science, Engineering and 21st Century Skills). Finally, the data from the Affect Towards Engineering Professional Practice survey were aggregated into five engineering affect dimensions (Framing, Collaboration, Project management, Design, and Analysis). We calculated the means and standard deviations for each of the perceptions, attitudes, and affect dimensions, which provided a glimpse into the effects of the Arduino Mars Rover building activity on students. However, the true measure and magnitude of any effect of the intervention can only be observed by assessing the effect size of the intervention.

Effect size allows researchers and lay people to see the results from the experiment as real and tangible (Ellis, 2010). We calculated Cohen's *d* effect size (Cohen, 1988) along with the 95% confidence intervals for each of the perceptions, attitudes, and affect dimensions. We chose to calculate and report Cohen's *d* along with the 95% confidence intervals instead of performing traditional Null Hypothesis Statistical Testing because statistical significance reporting is extremely susceptible to sample size (Capraro, 2004). Additionally, the reporting of *p* values has become controversial and is increasingly being seen as an ineffective way of conveying real-world interpretations of results (Capraro & Capraro, 2002; Kline, 2004). We consider an effect size to be statistically significant if the 95% confidence interval for that effect size does not contain a zero (Nakagawa & Cuthill, 2007). We believe that the reporting of effect sizes and accompanying confidence intervals makes the interpretation of results accessible to all stakeholders.

We rejected the use of a priori benchmarks for assessing effect sizes. Contrary to Cohen's benchmarks for the magnitude of effect sizes (small, medium, and large) that were based on a priori values (0.2, 0.5, and 0.8, respectively), whose use is discouraged by the American Psychological Association and leading social scientists and statisticians (Capraro, 2004) we chose to assess the magnitude of the effects of interventions in this research study against the overall effects reported by studies in similar areas of social science and STEM education research. We found one study (i.e., Fidai et al., 2020; *d* = 0.67, SE = 0.14) that was a meta-analysis that analyzed the effects of Arduino and Scratch on students' CT skills, one conference proceeding (i.e., Fidai et al., 2019; *d = 0.70*, SE = 0.26) that was a meta-analysis of the effects of LEGO ER on students' academic skills, and one study (i.e., Ye et al., 2020; *d = 1.27*, SE = 0.22) where the effects of using 3D printed models in human anatomy courses were reported. We performed a random effects mini meta-analysis using the three effect sizes of these studies and obtained *d* = 0.86, which was used as a benchmark for the discussion of the effects of the Arduino Mars Rover activity on students in the current study. Based on this benchmark, effect sizes less than or equal to .28 are considered small, those between .28 and .57 are considered medium, and those greater than .57 are considered large. We also performed a statistical power analysis to determine if the sample size was sufficient to obtain meaningful effect sizes. Considering the previously available effect sizes, we determined that at alpha = .05 and power = 0.8, a sample size of $n = 52$ is suggested for $d = .7$ and a sample size of $n = 17$ is suggested for $d = 1.27$ (Ellis, 2010). We concluded that our sample of students ($N = 31$) would be sufficient to detect a meaningful effect between .7 and 1.27.

3.7. Results

3.7.1. Students’ STEM Perceptions and Interests

To answer our first research question, we calculated composite scores for each of the five STEM Semantics Survey subscales (Science, Mathematics, Engineering, Technology, and STEM Career). We then calculated the descriptive statistics for each dimension and the Cohen’s *d* effect size estimate. Table 3.3 presents the descriptive statistics and the effects by pretest and posttest scores for each group. The findings indicate that the Scratch coding activity had small to medium negative effects on students’ STEM perceptions. However, none of those effects were statistically significant. The effect of the Arduino Mars Rover building activity had small to medium positive effects on students’ science, mathematics, and engineering perceptions ($d =$ 0.07–0.44) *and* small negative effects on students’ perceptions towards technology and STEM careers ($d = -0.16$ and -0.18, respectively). In general, the Arduino Mars Rover group as compared to the Scratch group showed an improvement in perceptions towards STEM subjects and career interests.

To examine how the Arduino Mars Rover building activity changed perceptions towards STEM subjects and careers, we analyzed between-group data from the STEM Semantics Survey subscales (Science, Technology, Engineering, Mathematics, and STEM Career). Table 3.4 contains the posttest mean scores, effect sizes, and 95% confidence intervals of this analysis. Analysis of the between-group data revealed that the Arduino Mars Rover building activity had medium to large statistically significant positive effects on students in the Arduino Mars Rover group (d = 0.08–0.40) when compared to the students in the Scratch group. The students in the Arduino Mars Rover group showed statistically significant, medium effects on their science, technology, and STEM career perceptions. The effect on mathematics, engineering, and technology perceptions for the Arduino Mars Rover group were high when compared to the established benchmark. Overall, the Arduino Mars Rover building activity had a positive impact on improving students' perceptions towards STEM subjects and their interest in STEM careers.

3.7.1.1. Race/Ethnicity Moderated Effects

The Arduino Mars Rover activity had positive effects on the perceptions towards STEM subjects and careers for both White and non-White students (see Table 3.4). However, the positive effects on the White students were not statistically significant and ranged between d = 0.27 and 0.57. The effects on non-White students' perceptions towards STEM subjects and careers were statistically significant and positive, ranging between *d* = 0.59 and 1.51. The positive effects on non-White students' science, technology, and career dimensions were large and the effects on the mathematics and engineering dimensions were larger than the established benchmark. The Arduino Mars Rover activity had a greater positive impact on students of color than those who identified as White.

3.7.1.2. Gender Moderated Effects

The effects of the Arduino Mars Rover building activity on students' STEM subject and career perceptions were mixed for both male and female students (see Table 3.4). Both male and female students experienced positive effects on their perceptions towards the STEM subject dimensions of science, mathematics, engineering, technology, and 21st century skills. However, these positive effects were not statistically significant for female students. The statistically significant positive effects on the mathematics, engineering, and technology dimensions of STEM subjects for male students were large compared to the benchmark and ranged between *d* = 0.59 and 0.70. The findings suggest that the gender of the student had a strong moderating effect on the impact of the Arduino Mars Rover building activity on students' perceptions towards STEM subjects and career interests.

3.7.2. Students' Attitudes Towards STEM

To answer our second research question, we analyzed the data from the Upper Elementary School Student Attitude Toward STEM (S-STEM) survey. The results of within-group effects are presented in Table 3.5. The results indicated that the Scratch coding activity had non-statistically significant mixed effects on students' attitudes towards STEM. The same was the case for the Arduino Mars Rover group. The overall analysis indicated that, compared to the students in the Scratch group, students in the Arduino Mars Rover group experienced a more positive effect on their attitude towards mathematics, science, and 21st century skills.

Analyses of the posttest results for changes in students' STEM attitudes between the Scratch and Arduino Mars Rover groups are presented in Table 3.6. Results indicated that the Arduino Mars Rover building activity had a negative but not statistically significant effect on students' science attitudes; a statistically significant, large, and positive effect on students' attitudes in mathematics ($d = 0.7$); a small, positive, but not statistically significant effect on engineering ($d = 0.27$); and a statistically significant, medium, and positive effect on 21st century skills ($d = 0.48$). The overall result of the intervention on students in the experimental group was positive and statistically significant, showing the positive impact of hands-on engagement in the Arduino Mars Rover activity.

3.7.2.1. Race/Ethnicity Moderated Effects

The Arduino Mars Rover activity had positive effects on non-White students' attitudes towards STEM subjects and careers (see Table 3.6). These statistically significant positive effects ranged between $d = 0.71$ and 1.30. For students' attitudes who identified as White, the effect of the intervention was medium and positive for mathematics and negative for other dimensions. The changes in attitudes for students who identified as non-White were positive and statistically significant, except for attitudes towards science. The effects on non-White students ranged between medium and above the established benchmark. The Arduino Mars Rover activity had a more significant impact on the non-White students and thus may be important for addressing educational disparities.

3.7.2.2. Gender Moderated Effects

The gender moderated effects of the Arduino Mars Rover building activity on students' STEM attitudes are presented in Table 3.6. The effects on both male and female students were mixed. Both male and female students experienced statistically significant positive effects on their attitudes towards mathematics. Male students also experienced statistically significant positive effects on their attitudes towards 21st century skills. While male students experienced positive but not statistically significant effects on their attitudes towards engineering, this effect was negative but not statistically significant for female students. The findings indicate a link between students' gender and the changes in their attitudes towards STEM as a result of participating in the Arduino Mars Rover building activity.

3.7.3. Students' Affect Towards Engineering as a Profession

To answer our third research questions, we analyzed the data from the Affect Towards Engineering Professional Practice survey. The results of within-group effects are presented in Table 3.7. The analyses of the data indicated that students in the Scratch group experienced a small, positive improvement ($d = 0.09$) in the analysis dimension of engineering as a profession. Students in the Arduino Mars Rover group experienced a positive but not statistically significant affect development towards the collaboration, project management, design, and analysis dimensions of engineering as a profession ($d =$

0.05–0.25). The comparison of the two groups indicates that the Arduino Mars Rover activity had a positive impact on the students' affect towards engineering, whereas the Scratch activity had an overall negative impact on students' affect towards engineering as a profession.

The between-group analysis of the posttest data for all students is presented in Table 3.8. The results indicated that students in the Arduino Mars Rover group experienced small to medium but not statistically significant positive effects on four out of five dimensions of affect towards engineering. These effects ranged between $d = 0.09$ and 0.46. However, only the effect on the project management dimension was statistically significant. The positive effects on students' affect towards engineering indicates that the Arduino Mars Rover activity is a positive step in the right direction.

3.7.3.1. Race/Ethnicity Moderated Effects

Race and ethnicity moderated effects of the Arduino Mars Rover building activity on students' affect towards the engineering profession are presented in Table 3.8. Students who identified as White showed mixed results. Although none of the effects on White students were statistically significant, they did experience small positive effects on the project management ($d = 0.23$) and design ($d = 0.08$) dimensions of affect towards engineering. The effects on the engineering affect dimensions of framing, collaboration, and project management were medium, positive, and statistically significant for students who identified as non-White. These statistically significant positive effects ranged between $d = 0.51$ and 0.79. The Arduino Mars Rover building activity had a more positive and statistically significant effect on students who identified as non-White than their White counterparts.

3.7.3.2. Gender Moderated Effects

Gender moderated effects on students' affect towards engineering as a profession are presented in Table 3.8. The effects were positive but not statistically significant for the collaboration, project management, and design dimensions of affect towards engineering for male students. Female students experienced positive but not statistically significant changes in the framing, collaboration, and design dimensions of affect towards engineering. The changes in the analysis dimension were negative for both male and female students. None of the effects were statistically significant for female students; however, the positive effect on male students' project management dimension of affect towards engineering was positive. The Arduino Mars Rover building activity seemed to produce positive learning changes in male and female students' affect towards engineering as a profession.

3.8. Discussion

The purpose for this study was to investigate the effects of an Arduino Mars Rover building activity on fourth-grade students. The majority of positive effects experienced by the students in the Arduino Mars Rover group indicate that the Arduino Mars Rover building activity was successful in improving students' perceptions towards

STEM subjects and careers, their attitudes towards STEM subjects and 21st century skills, and their affect towards engineering.

Overall, there were three important outcomes. First, White students were not advantaged in either setting. Primarily, this finding differs from many other studies in that non-White students and female students tended to show greater gains. Perhaps the small sample size can account for the finding, but the intervention was a wonderful mediator of racial education inequity, nonetheless. While the intervention did not hinder White students, their gains were simply less than those of students from typically underserved populations. Specifically, White students experienced a negative effect across most dimensions of their perceptions towards STEM subjects and careers, their attitudes towards STEM, and their affect towards engineering after engaging in the Arduino Mars Rover building activity. On the other hand, students who identified as non-White showed improvements in all dimensions of their perceptions and attitudes towards STEM subjects and careers and their affect towards mathematics. We believe that non-White students may have simply had more room for score growth due to the intervention potentially being their first opportunity to see themselves in a STEM role. This disparity in exposure and preparation can be a result of socio-economic and familial factors (Parker, 2013) and is prevalent in post-secondary settings as well (Sax et al., 2001). The positive effects of the Arduino Mars Rover building activity show the potential impacts of open source educational robotics on students who have been traditionally marginalized and underrepresented in STEM coursework and professional fields.

Generally, female students experienced broad positive effects across most domains. Female students have traditionally been underrepresented in STEM fields. The effects on female students’ perceptions towards STEM subjects and careers were positive and small to medium. The effects on their attitudes towards mathematics and a majority of the dimensions of their affect towards engineering as a profession were also positive. However, female students did experience negative effects on their attitudes towards science and engineering. This leads us to believe that although the female students in this study perceived STEM subjects as important, they did not hold positive attitudes towards them. This finding should encourage instructional leaders and other stakeholders to find ways to make STEM coursework more interesting and approachable. STEM teaching and learning activities integrated with ER may help encourage greater participation of female students in STEM coursework, ultimately leading them to post-secondary STEM professional tracks.

Finally, the Arduino Mars Rover building activity had a positive effect on all dimensions of a student’s affect towards engineering as a profession. This result may indicate that there was a positive impact from engaging in hands-on STEM learning using Arduino and Scratch-based visual coding environment alongside the 3D printed Mars Rover. These findings are similar to the findings from the meta-analysis of the effects of Arduino and Scratch-enabled interventions on students’ CT skills (Fidai et al., 2020) and findings from systematic reviews on the effectiveness of educational robotics

(Anwar et al., 2019; Benitti, 2012; Jung & Won, 2018). The findings from this research study add to the literature by providing evidence of the effectiveness of educational robotics based on open source Arduino and Scratch-based visual coding environment while using 3D printed parts.

3.9. Conclusion

In this research study, we wanted to examine the effects of an open source Arduino Mars Rover building activity on students' perceptions and attitudes towards STEM subjects and careers and their affect towards engineering as a profession. Instead of using traditionally accepted a priori magnitudes of effect sizes, as suggest by Cohen (1988), we decided to conduct a mini meta-analysis of related literature and establish a relevant benchmark. We believe that the calculated benchmark effect size of $d = 0.86$ allows for a better interpretation of the results found in this study. The results indicate that the intervention had positive effects on students' perceptions and attitudes towards STEM subjects and careers. The intervention also had a positive effect on students' affect towards engineering. Students who identified as non-White seemed to benefit more positively from the intervention than White students. Finally, the intervention improved female students' perceptions and attitudes towards STEM subjects and careers and their affect towards engineering. A low-cost and open source Arduino-based ER (Mars Rover) building, coding, and testing activity was successful at producing a positive impact on students, and the findings from this study add to the literature on reforming STEM education to make it more equitable and accessible for all students.

3.10. References

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4. OPENBRICK EDUCATIONAL ROBOTICS KIT: A USABILITY STUDY

4.1. Introduction

Educational robotics (ER) can provide engaging and hands-on learning environments for students. There is empirical evidence to support the efficacy of ER in STEM classrooms. The review of ER based instruction indicates that proprietary ER kits such as LEGO were used to improve teaching and learning practices (Anwar et al., 2019; Benitti, 2012; Jung & Won, 2018). As effective as proprietary ER have been at engaging students in hands-on learning and improving their perceptions and attitudes towards STEM, the high cost attached to LEGO ER kits puts them out of reach of students and teachers from schools situated in low-SES areas that are often under resourced. The problem of the high costs attached to LEGO and other commercially available proprietary ER kits makes their use a novelty in the classroom rather than an instructional technology tool to be used in day-to-day teaching and learning. If a STEM teacher is somehow able to acquire a LEGO ER kit, they are only able to use the ER for demonstration purposes in the classroom. Students are often not able to engage in hands-on learning because of the extremely high costs (in thousands of dollars) of proprietary ER kits. And furnishing each student with an individual LEGO ER would be impossible due to budgetary constraints (Zhong & Xia, 2020). Unless each student has access to ER in everyday teaching and learning practices, the true potential of ER will stay locked.

4.2. Statement of Problem

Commercially available ER kits are expensive. The cost to equip a single classroom with ER can reach into thousands of dollars (Terranova, 2017) which often leads creative teachers to look for other solutions. Open source Arduino based ER can be that solution. Low-cost Arduino based ER encourages access for all students to quality hands on STEM education. But the difficulties in adopting and integrating an open source ER kit can become a tricky prospect for educators and school administrators who are often not well-versed in ER and especially open source ER. These open source Arduino based ER kits can cost as little as $25 (Amazon.com, n.d.) and they come with their own sets of problems. Missing or incomplete instructions and the number of electronic components along with all the wiring can easily overwhelm a teacher who is not skilled in electronics or DIY. The difficult nature of DIY open source ER kits often serves as a deterrent to the adoption of open source ER by teachers (Alsoliman, 2018; Gläsel, 2018). There is a need for an open source Arduino based device for instructors and other users that is easy to assemble, code and integrate into teaching and learning practices. The low cost of OpenBrick, makes it affordable and its Arduino based framework makes it easy to assemble, code and implement in STEM classrooms. An OpenBrick device costs less than $50 (depending on where the materials are sourced from) which is roughly one-fifth the cost of a LEGO Intelligent Brick. A complete LEGO kit is even more expensive (at around $500) (LEGO Group, n.d). For the price of one LEGO kit, a teacher can furnish their classroom with eight OpenBrick devices. There is a need to create greater access for all student to ER, OpenBrick can help to create greater access through its low cost and open architecture. But it needs to be determined if the users, especially the STEM teachers find this device useful. In this paper we discuss the development and the results of the usability testing of OpenBrick

(Figure 4.1) an open source ER kit that is easy to assemble and use device to compete with the likes of LEGO and VEX.

4.3. Background

4.3.1. ER in STEM Instruction

Researchers have indicated that ER can be useful for improving many aspects of students' academic and social skills. ER has been used to improve students' executive functions and working memory (Di Lieto et al., 2019), motor skills (Marques et al., 2017) and critical thinking skills (Atmatzidou & Demetriadis, 2016). ER has also been shown to be effective in introducing students to data acquisition through electronic sensors (Karalekas et al., 2020). Use of ER allows STEM teachers to help engage students with academic concepts in an engaging and playful environment to increase their understanding and participation (D'Amico et al., 2020; Hussain et al., 2006). ER also enhances students' social interactions by enhancing their confidence and communication skills (Melchior et al., 2005). Use of ER improves students' technology self-efficacy and positive self-perceptions (Beisser, 2005). Researchers have indicated

Figure 4.1
OpenBrick Educational Robotics Module

Source: Fidai, 2020

that engagement in hands-on ER activities improves students' STEM academic achievement (Yanış & Yürük, 2020). Recent empirical research into the use of ER has produced a plethora of evidence of the efficacy of ER in STEM education establishing ER has a viable instructional tool.

4.3.2. Disparities in ER Instructional Practices

ER is not readily available to all students. The socio-economic status of students' families, and the wealth of the neighborhood that the students reside in often determines the richness of the ER curriculum, to which, the students have access (Kepple, 2015). This fact is evident from the high cost of instructional robotic kits (Kepple, 2015). Under resourced schools that are struggling with underfunding and budget shortfalls simply cannot allocate exorbitant funds for ER materials. Disparities in ER deployment due to high costs result in lack of access for students from poor neighborhoods. Thus, they cannot participate in these innovative learning opportunities, which can have a lasting impact on their attitudes, perceptions, and interest towards STEM careers (Renninger et al., 2015). There is need for an ER kit that is effective, accessible, but most importantly, affordable so that more students can have access to the power of ER in their STEM classrooms.

4.3.3. A Push Towards Low-Cost Open Source ER

The last few decades have seen a strong push towards everything open source. STEM education research has been influenced by the open source movement as well. A quick search of the major databases reveals a plethora of recent empirical and theoretical literature dedicated to the advocacy of low-cost open source ER (see Table 4.1). The ER devices presented and discussed in current literature include solutions that are both easy to assemble by sourcing materials (e.g., Eguchi, 2014; Nel et al., 2016; Plaza et al., 2018) and those solutions which require specific high level technical skills such as soldering (e.g., Eguchi, 2014; Karahoca et al., 2011; Kerimbayev et al., 2020) or laser cutting (e.g., Katterfeldt et al., 2015; Pérula-Martínez et al., 2016; Vandevelde et al., 2016). But most ER 'recipes' prescribed in the current research literature offer single case solutions specific to specialized research questions. Devices built and tested in classroom settings for specific research purposes may help answer some specific research questions, but they completely fail to offer a low cost alternative to proprietary ER such as LEGO or VEX. Device designed to answer specific research questions also do not offer teachers solutions that they would find useful and suitable for classroom use. OpenBrick, can provide versatility and ease of use to STEM teachers while costing a fraction of the cost of proprietary ER. A detailed cost analysis of OpenBrick ER is presented in in Appendix D along with a cost comparison to LEGO ER. The low-cost and ease of use can make OpenBrick a viable alternative for adaption by STEM educators.

4.3.4. History of System Usability Scale (SUS)

System Usability Scale (SUS) is ten-question questionnaire to assess a user's perceptions of usability of a system. This scale was developed by John Brooke in 1984 and published in 1996. The SUS is one of the most widely used usability questionnaires (Lewis, 2018). Brooke's SUS scale was by no means the first questionnaire designed to assess usability. Many of these usability scales are still in use, however, the SUS is unique because it was the last of such usability scales to be published and it is also the shortest one of them (Lewis, 2018). Brooke (1996) defended the validity of SUS by suggesting that the “quick and dirty” (p. 1) survey delivers a single number which represents the extent to which the users found a system (or a device) to be usable (Brooke, 1996). He also warned that the score should be looked at as a composite and the ratings from individual items on the survey would not yield much meaning. Researchers have found SUS to be very useful for collecting reliable usability data (Bangor et al., 2008; Lucey, 1991), a fact that is evident by the wide usage of SUS since its publication.

4.4. Literature Review

4.4.1. Usability Studies in STEM Education

Usability studies allow the product developers to assess users’ perceptions of their products. Usability studies are a staple of industry (Mónica Faria et al., 2013; Tang & Webb, 2018) and medicine (Carroll et al., 2007; Landman et al., 2015), but recent years have seen an increase in usability studies concerning STEM education as well. While the number of usability studies in STEM education does not compare to the usability studies conducted in commercial and industrial areas, there are numerous studies assessing the usability of web-based STEM education (e.g., De Jong et al., 2014; Kim et al., 2019; Peters & Songer, 2013), geometry learning software (Naya et al., 2007; Yağmur & Çağıltay, 2013), mathematics learning (Hansen et al., 2010; Sánchez & Flores, 2004; Seo, Y. J. & Woo, 2010), technology education (Adiguzel et al., 2011; Carrera et al., 2018; Saleh et al., 2014) and engineering education (Bhat et al., 2018;

Martín-Gutiérrez & Contero, 2011). Usability studies in STEM education have enabled educational researchers and academicians to gain insights into products aimed at improving students' academic achievements. Usability studies in STEM education have also assisted in bringing academic and social science research up to par with industrial and medical research.

4.4.2. ER Usability Studies

The literature on ER usability is sparse. The lack of studies assessing usability of ER is evident of the still infant nature of ER despite the decades of ER availability. Current ER usability research is focused on summarizing currently available ER (Ruzzenente et al., 2012; Takacs et al., 2016), Web-based delivery of ER lesson plans (Kim et al., 2019) and single use ER (Phamduy et al., 2015). We were only able to locate two studies that used the industry standard *System Usability Scale* questionnaire to measure the usability of an ER (Barradas et al., 2019; Vandevelde, 2016). The scant empirical literature on the usability studies of ER suggests a gap in the push for greater integration of open source ER into STEM classroom and their true effects on students' academic and social outcomes.

4.5. Research Questions

This mixed methods research study is guided by the following research questions:

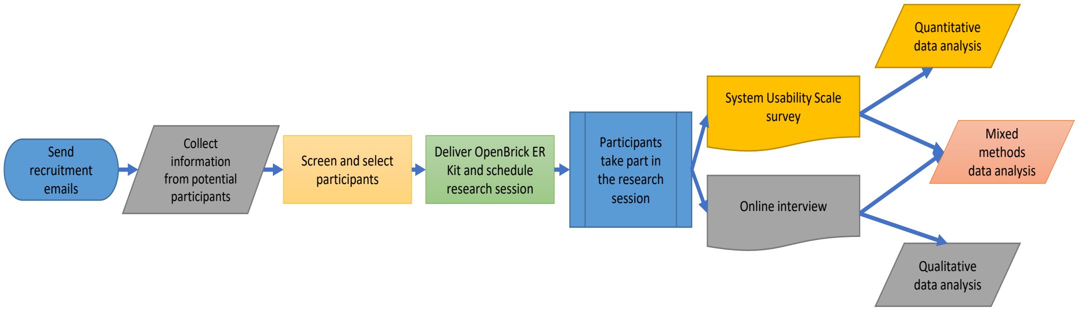
1. What was the perceived usability of the OpenBrick Robotics module for implementing the STEM ER based lesson and activities for participating user?

2. What characteristics of the OpenBrick Robotics module did users find to be effective in completing the tasks outlined in STEM ER lesson?
3. What were the concerns about the efficiency with which the participating users were able to implement STEM ER lesson using OpenBrick Robotics module?
4. What was the satisfaction level for users of OpenBrick Robotics module for implementing STEM ER lesson?
5. What connections could be observed between participants' composite SUS scores and their perceptions of usability of OpenBrick ER kit?

4.6. Methodology

In this research study we employed a mixed methods research design, combining quantitative and qualitative data collection and analyses (Creswell & Clark, 2017). This research approach allowed for an in-depth analysis of participants experiences with OpenBrick ER kit. We used a modified version of the SUS (replacement of the words "OpenBrick" with the word "system") to collect quantitative data from users. We also conducted structured interviews to collect qualitative data. Due to COVID-19 related restrictions, the interview responses were collected using Flipgrid, an online platform for sharing video responses to survey questions and prompts. Case study research design is one of the most utilized qualitative approaches in social science research and is often used in situations where interpersonal communications and interactions within group members is of importance (Suryani, 2008). Figure 4.2 shows the mixed methods research process used in this research study.

Figure 4.2
Mixed Methods Research Process



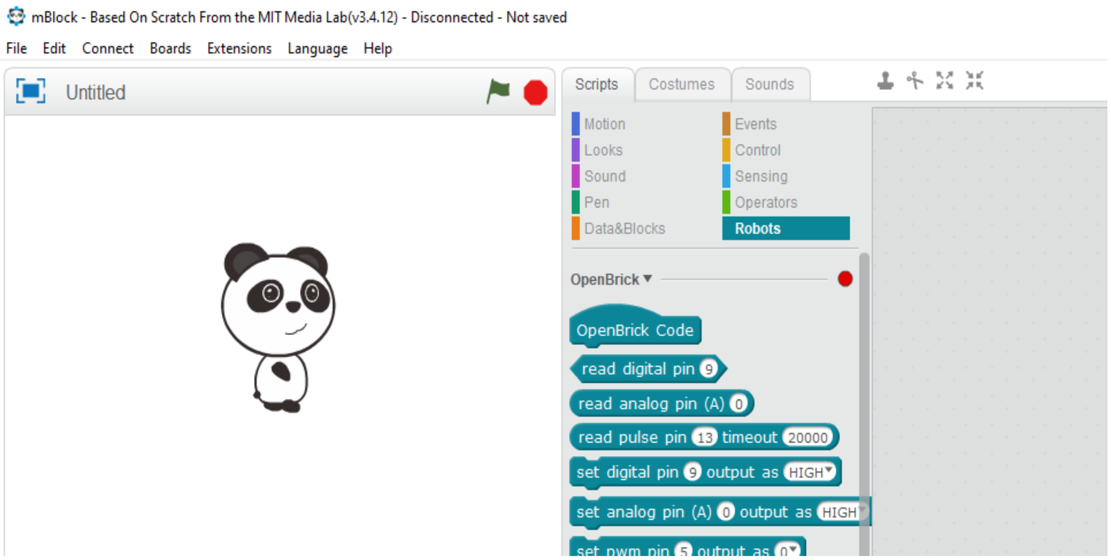
4.6.1. Participants

The participants in this study were pre-service STEM teachers, in-service STEM teachers, and undergraduate engineering students from a state in the southwestern United States. Participants were recruited using e-mail campaigns conducted at universities and school districts. Recipients were encouraged to reply to the email to receive further information. COVID-19 research restrictions ruled out face-to-face research sessions. So, the researchers decided to deliver the kits to each participant for the usability testing. Researchers replied to each interested potential participant with an information sheet describing the research along with a link to a Qualtrics registration form. Interested potential participants were asked to provide information about their role (student or teacher) and their area of study (teacher education/STEM teacher/engineering). This information was used as the inclusion/exclusion criteria later during the participant selection process. Initially 55 potential participants registered showing their interest in participating in the research study. From this initial pool, 14 registrants were deemed outside the scope for this research study because they did not meet the selection criteria or did not provide sufficient contact information. Therefore, 41 registrants were contacted using email with a video of the OpenBrick demonstration and a link to provide a delivery address for the kit. The final sample who provided a delivery address for the kits was 21, therefore, 21 participants scheduled a research session and received a kit. By the end of two weeks, 16 participants had completed the research session, provided responses to the SUS questionnaire, and participated in the online interview. Of the 16, three were pre-service STEM teachers, 11 were in-service STEM teachers, and two were undergraduate engineering students. Table 4.2 provides description of the participants along with their demographic and STEM role information.

4.6.2. Hands on Engagement with OpenBrick

In this mixed methods research study, participants engaged in implementing an ER-enabled STEM lesson plan using OpenBrick ER kit. This lesson plan was based on a freely available lesson plan that used a proprietary ER kit costing roughly $500. The modified lesson plan uses OpenBrick ER kit and is available at 4th grade - Intro to distance formula.doc. Participants were first introduced to the open source OpenBrick using a video in which they saw a LEGO EV3 rover and an OpenBrick Rover side by side performing obstacle avoidance. The video is available at (https://youtu.be/h69PRSEqbl4). During the hour-long research session, participants were introduced to the OpenBrick code blocks (see Figure 4.3). These code blocks were used to program to rover to move the rover in forward and reverse direction to conduct the experiment using a freely available visual coding software called mBlock.

Figure 4.3
Mixed Methods Research Process



Each participant first became familiar with coding blocks by using the forward blocks to make the rover move in the forward direction. Then following the lesson plan, each participant conducted an experiment multiple times changing the pulse width modulation each time. Participants were referred to the lesson plan for a description of the pulse width modulation and how different values of it related to the proportion of available power is allotted to each motor. Changing the pulse width modulation resulted in the rover covering different distances each time. Participants recorded this information in the student worksheet. Once the participant had successfully collected 5 – 8 data points, they calculated the speed of the rover using the time interval and distance covered. Finally, participants used an online graphing tool (link provided in the lesson plan) to graph the data points to produce a bar and line graph of speed vs. distance. Participants were reminded that as a teacher they could ask students probing questions at this point and use the graphs to reinforce or introduce new concepts to their students. This concluded the hands-on engagement portion of the research session.

4.6.3. Instruments

To collect quantitative data about users' perceptions of OpenBrick's usability, we administered the *System Usability Scale* questionnaire (Brooke, 1996) (Appendix C). This scale consists of 10 Likert scale type questions. Each item is measured on a 5-point scale (1 = *Strongly disagree* to 5 = *Strongly agree*). Odd numbered items are scored as is and even numbered items are reverse coded by subtracting the original score from five. Bangore et al. (2008) conducted a factor analysis of SUS and determined that all items loaded on one factor. A score between 50 and 70 is considered fair and a score above 71 is considered good (Brooke, 1996). SUS has been found to obtain reliable data about usability and has been extensively used to conduct usability since its publication.

Additionally, to collect qualitative data about participants' perceptions of usability we collected online interviews responses using Flipgrid. The interview questions are presented in Appendix C. The online interview questions were adapted from a set of questions used by Kim et al. (2019) to assess the usability of an online resource repository to promote the use of robotics in STEM classrooms. We chose to adapt 14 questions from the original set of interview questions to assess the effectiveness, efficiency, and use satisfaction of OpenBrick ER kit. We believe that these questions are suitable for assessing the usability of OpenBrick ER.

4.6.4. Data Analysis

All quantitative data were entered in STATA 16. We calculated descriptive statistics from the analysis of user responses of the *System Usability Scale* questionnaire. Brooke (1996) suggested that the score should be looked at as a composite and the ratings from individual items on the survey would not yield much meaning. Therefore, we calculated the composite score for each participant to assess their perceptions of usability of OpenBrick ER kit. We also calculated the mean score for the entire participant pool and for each subgroup based on participants' race, Hispanic origin, gender, STEM role (student or teacher), major of study (teacher education or engineering), grade taught (in case of teachers), and previous experience with ER as student, teacher, or in any other role). This subgroup analysis allowed us to make connections between the participants' demographic and ER experience information and their perceptions of the usability of OpenBrick ER kit and look for any moderating effects.

We analyzed the user responses from semi-structured interviews using thematic analysis. We looked for three themes in user's responses: effectiveness, efficiency, and satisfaction. The three themes corresponded with the three usability categories defined in the ISO 9241-11 usability standard (ISO, 2018). Based on the deductive approach to qualitative data analysis, we used DeDoose, a qualitative data analysis software to code the responses from the users. Some of the codes applied to user responses to assess effectiveness were completion, correctness design (chassis, coding, connection, upload, motors, software installation, wheels, and caster wheels), difficulties, and improvement.

To assess participants perceptions of efficiency, we applied the following codes to interview responses: productive and confident. And to assess participants' satisfaction with OpenBrick ER kit, we applied the following codes: adaptable, affordable, amazing, compact, curious, design, dislikes, effective, engaging, enjoyable, excited, fun, future use, good, great, liked, new experience, potential, etc. This allowed for a deductive analysis of users' responses to the semi-structured interview questions. Using this approach, we were able to look for themes and patterns withing the three categories of usability and assess the usability of OpenBrick.

4.7. Quantitative Results

To answer our first research question, we calculated the composite SUS scores for each individual participant, the mean SUS composite score for all participants and mean SUS composite score for participant subgroups based on their demographics, STEM role and their previous experiences with ER. The descriptive findings from the analysis of individual SUS responses are presented in Table 4.3 along with an overall composite score. The individual SUS scores ranged between 60 and 90 and the average composite SUS score was 79.88 (*SD* = 10.16). participant with the highest composite SUS score had previous experience with ER as a student, teacher and in other role, while the participant with the lowest composite SUS score had no previous experience with ER.

Subgroup analysis of the SUS composite score is presented in Table 4.4. Teachers teaching different grades had the most variations in their perceptions of the usability of the OpenBrick ER kit. The difference between teacher subgroups was 14 composite points with a minimum score of 72 (post-secondary) and a maximum score of 86 (middle school) composite points. The second largest difference between mean composite SUS scores were between the race subgroups (10 composite points) where the American Indian and Alaska Native participant had the highest score (88 composite points), and the White participants had the lowest score (78 composite points). The difference between mean female participants scores and male participants score was 9.18 composite points with male participants finding OpenBrick ER kit more usable. Similar difference was found between the mean composite scores of students who were studying engineering and those who were studying teacher education to become STEM teachers (8.67 composite points). Teacher education students found the OpenBrick ER kit more useful. Participants who had used ER as students found OpenBrick ER kit more usable than those who had not used any ER as students (3.25 composite points difference). Teachers who had previously used ER found OpenBrick ER kit more usable (5.5 composite points difference) than those teachers who had no previous ER experience.

4.8. Qualitative Results

To answer our second, third, and fourth research questions, we analyzed participants' interview responses. Using the three usability categories defined in the ISO 9241-11 and working definitions of the three constructs (Brooke, 1996; Jeng, 2005; Lin et al., 2015) we categorized the questions as probing participants' perceptions of effectiveness, efficiency, or satisfaction. Here we present our findings regarding participants' perceptions of effectiveness, efficiency and satisfaction with OpenBrick ER kit.

4.8.1. Participants Perceptions of OpenBrick ER Kit's Effectiveness

To answer our second research question, we analyzed participants' responses to interview question # 3, 8, and 12 to assess their perceptions of OpenBrick ER kit's effectiveness. Effectiveness of a device is measured by the ability of that device to allow users to complete the tasks correctly. Difficulties and distractions experienced by users can deter them from completing the desired tasks correctly. Questions 3 asked the participants, "*Are there any aspects of OpenBrick that could be improved*?" question 8 asked, "*Did you experience any distractions while using OpenBrick*?" and questions 12 inquired "*Did you experience any difficulty while using OpenBrick*?" All participants were able to complete all tasks described in the lesson plan successfully and correctly thus indicating that OpenBrick ER kit was effective in delivering the ER STEM lesson plan, however, some difficulties were experienced.

Several themes were identified about OpenBrick ER kits' effectiveness. The first theme pertained to the software aspect of the users' experiences. Overall, user experience with the software was fairly positive. The mBlock software which was used to code the OpenBrick Rover for the lesson plan is based on Scratch, a widely used visual coding environment in educational settings which meant that some participants had previous familiarity with the software. Louigina said "*Its doing Scratch as you use it on the website to do coding, so this is like more ... you graduated from just doing it on the computer*" However, in order to use the OpenBrick ER kit with mBlock software an extension needs to be installed (downloaded and then dragged and dropped onto the mBlock work area) in mBlock. Lindsey shared her apprehension about not wanting to download anther software "… *besides not wanting to download it first… it just took a little bit of time and working with it*." She also suggested that "*that's also something that can be done before class*." The mBlock software allows users to manipulate visual block which generates the C++ code in the background. Once the user connects the OpenBrick to the computer and clicks on the upload button, mBlock compiles the C++ code into machine readable code and uploads it to the OpenBrick where it is executed. This final and crucial step caused some difficulties for some users. Adriana was not able to upload the code to the OpenBrick and realized that she did not press the cable completely inside the OpenBrick USB connector. "*Yes, I had no idea that I did not push in one of the wires all the way into the slot where it had to connect to the brick from the computer and that caused us some trouble.*" The researcher who was present during her session suggested she check the connection and the problem was solved. Adriana described her experiences, "*Until we figured out that that's why we couldn't download the program into the robot I just had to make sure I do press in gently but sturdy.*" Lindsey complained about the time it took for the mBlock software to upload the code to the OpenBrick. Lindsey was concerned that "*Children could get a little rowdy or just kind of distracted by that*." But she also saw it as an opportunity for the students "*it was cool that I think they could also see the code being uploaded. So maybe that would also like pique their interest*." Diego on the other hand was concerned about the durability of the wires and connectors themselves. Diego said, "*kids usually … are not aware of how delicate those cables are so when they start plugging in or plug out [the cables] sometimes you have some issues*." Although Diego did not experience any connection issues himself, his concern was rooted in his previous experience as a robotics coach. Overall, mBlock software along with the OpenBrick extension enabled users to code the OpenBrick ER module and correctly complete all activities.

Participants experienced two types of difficulties with the OpenBrick ER kit. For the purpose of the delivery of the ER lesson, the OpenBrick ER kit was configured as an OpenBrick Rover. In this configuration the OpenBrick ER module sits on a chassis that has two motors with wheels and a caster ball or caster wheel attached to it for balance. On two units the caster wheel caused friction and pulling of the rover to one side or the other. Brianna and Jason had some issues with the caster ball attached to their OpenBrick rover. Brianna complained, "*I feel like finding a way to keep the caster ball straight [would help and] be probably the best way [so that] everything is already fixed as soon as the bot is handed to the kid that way they don't have to worry*." For Jason "*the little caster wheel also caused a lot of problems*" The two motor configuration allows for forward/reverse movement along with turning right and left. Some users did not like the way OpenBrick ER module was connected to the chassis with connection pins. Adriana was concerned about the module falling off the chassis and said, "*the biggest concern that I have is that the brick is not completely attached to the platform and in the hands of young kids… they don't have the best skills*." She expressed that OpenBrick module "*could easily get damaged and can easily be pulled from the platform and wires*." Victor also called for a "*better platform.*" Washley echoed the concern and asked for the module to be "*a little bit more secure*". Cheneka suggested "*adding more holders [pins]*" to make the module sit more securely on the chassis. The chassis and specially the caster wheel caused some problems for a few participants but with the help of researchers' suggestions and problem solving all participants were able to overcome the chassis and caster wheel issues and complete the tasks.

The second issue that almost all participants had with the OpenBrick Rover was that it did not want to go straight. Kristin complained that "*the only difficulty we experienced was the constant pulling to the left*" Washley provided a reason for why this was happening "*we had a slight difficulty with the wheel motors. One giving a little bit more power than the other and so we had to adjust the power levels being given so that way it would drive straight*." Jason's reasoning of why the rover was pulling to one side was similar to Washley but he also blamed the caster wheel. Adriana looked at this as an opportunity to engage students in problem solving and said "*[this] could trigger them to think about cars and how cars are built and slowly getting them into an engineering mind[set]*." All participants were able to make the rover go in a straight line by adjusting the power levels to the individual motor but only a few of them included a discussion of this difficulty in their interview responses.

4.8.2. Participants Perceptions of OpenBrick ER Kit's Efficiency

To answer our third research question, we assessed participants' perceptions of OpenBrick ER kit's efficiency from their responses to interview question 1, 5, 6, 9, and 11. Efficiency of a device describes how easy a device or system is to use based on numerous things including the number of resources required to use the device to complete a task (Brooke, 1996). Efficient devices are considered to more productive than less efficient devices (Park, 2020; Shaik et al., 2018). Question 1 and 11 were aimed at determining if the participants found the provided resources to be adequate and enough. Question 1 asked "*What do you think of OpenBrick for delivering ER lesson*?" and question 11 asked "*Did you feel uncertain or unsure while using OpenBrick*?" Question 5, 6, and 9 were aimed at determining if the participant found the OpenBrick ER kit productive and suitable to teaching another lesson. These questions asked, "*Did you try any other activities with OpenBrick that were not described in the provided ER lesson plan*?" "*What benefits do you think OpenBrick will provide to teachers and other users*?" and "*How would you use OpenBrick in your own classroom*?" For the OpenBrick ER kit to be considered efficient, it must enable a participant to successfully implement the lesson plan correctly and completely without a need for additional parts and within a reasonable amount of time. Participants' discussion of extending the OpenBrick ER kit's usage to teach additional lessons with same configuration also indicates that the kit is productive in addition to being efficient in delivering ER based STEM lessons.

All participants were able to correctly complete all lesson plan activities with the OpenBrick ER kit. Louigina found the kit sufficient for delivering the ER STEM lesson and said, "*it was just straight to the point, and I think that's what I love, and it doesn't require too many plugins into many things to be connected to make it work*." Victor found the OpenBrick ER kit "*great for ER lesson*" and Kristin said, "*it was easy for me*". Cheneka commented on the kit and said, "*everything that was given to me in the experience was kind of user friendly*". Washley agreed and found the OpenBrick ER kit to be "*a really good resource for delivering ER lessons*". Participants' discussions of extending the lesson to include other learning activities as well as using the ER kit to teach other lessons indicated that participants found the OpenBrick ER kit to be productive. Lindsey commented on OpenBrick ER kit's ability to deliver integrated STEM lesson: "*I think [it] is really cool that OpenBrick will give teachers such an easy way to bring in basically all aspects of STEM to their classroom*". Nicole said, "*I think that open Brick provides teachers as an opportunity to enhance their curriculum and to incorporate learning objectives in a unique and unorthodox ways*". Diego suggested using OpenBrick ER kit in helping students learn about the scientific process and said, "*They can develop their own like hypothesis … then they can test their hypothesis.*" Christina suggested that "*it [OpenBrick ER kit] may serve as foundation for learning programming languages*". The findings from the analysis of participants' responses indicate that they found OpenBrick ER kit to be efficient in delivering the. ER STEM lesson.

4.8.3. Participants Satisfaction with OpenBrick ER Kit

Our fourth research question was aimed at assessing participants' perceptions of satisfaction with OpenBrick ER kit. Brooke (1996) referred to satisfaction as a user's subjective reaction to using the system (or device). To assess participants' overall satisfaction with the OpenBrick ER kit, we analyzed their responses to interview questions numbered 2, 4, 7, 13 and 14. The numbered questions probed participants' satisfaction by asking "*How would you summarize your overall experience with OpenBrick for delivering ER lessons*?" "*Would you like to share any more information* *about your experience with OpenBrick for delivering ER lessons*?" "*Do you think that OpenBrick could be useful for you*?" "*How did you feel when using OpenBrick*?" and "*What did you like and dislike about OpenBrick*?" We chose to look at participants' perceptions of satisfaction with OpenBrick ER kit from three perspectives. What were their positive feelings towards the OpenBrick kit (their likes)? what were their negative feelings towards the OpenBrick (their dislikes)? And what future use they envisioned for the OpenBrick kit? Identifying what worked, what did not work and how the participants planned to use the kit in the future provided a measure of how satisfied participants felt with the OpenBrick ER kit.

All participants found the device user friendly. Concerning the physical aspects of the OpenBrick, Adriana said, "*I like it, the robot is simple*." Antonio also liked the "*easy setup*" and "*easy going*" nature of the OpenBrick rover and considered it "*student and teacher friendly*". Cashley liked that the "*instructions for building it and being able to code it were pretty much straight forward*". She also felt satisfied with the overall design "*Putting together the equipment went fairly quickly and I didn't have any issues and was very simple to put together*." Cheneka found that OpenBrick "*did what you told it to do, and you didn't have to do a whole lot of trial and error with it*" and called the system "*user friendly*". Christina found OpenBrick "*simple to put together, mechanically*". Diego expressed that putting together the kit was "*intuitive*" and felt "*very comfortable*". Adriana noticed that "*… [OpenBrick ER module] is created with 3D printer, and that's exciting*". Diego liked the "*modularity and simplicity*" of the OpenBrick ER kit. The connection of the OpenBrick ER module to the chassis and the caster wheel/ball were the only two aspects identified as dislikes by the participants. Washley said, "*securing of the of the brick to the base of the robot I think that could be improved a little bit. Getting it to sit on, well, a little bit more securely*". Cheneka said, "*Main thing I disliked about it, I was afraid that the brick was gonna fall off its platform*". Jason and Brianna disliked the caster wheel and how it disrupted the motion of the OpenBrick rover. Overall, participants had an easy time putting together the kit and were pleased by the physical aspects of the OpenBrick ER kit.

Participants also found the coding OpenBrick very easy. Antonio also admired the simplicity of coding "*I really enjoy[ed] this program because it has simple code*." Washley also liked the easy programming and called the process simple. Brianna "*loved the fact that it [OpenBrick] was very easy to use and very easy to understand. You don't have to download as much as you would for other systems*." Cheneka found OpenBrick "*easy to program*" and "*easy to connect*". Christina had trouble setting up the software but reflecting on her experience she said, "*once we have this primary screen setup where we would input changes in the PWM and stop times, I liked how easy it was to manipulate those variables*." Jason found the OpenBrick to be "… *easy to program and just point and click to tell it what to do. There's not a whole lot of options in the code so that it's really easy and it was fairly easy to figure out what to do*." Kristine, looking at coding from students' perspectives found that the repetitive nature of coding "*became a comfort*". Lindsey summed up her experience with coding OpenBrick as "*It's super easy once you know you [what to] upload and or download*." Participants also found the OpenBrick ER kit to be easy to learn. Christina suggested that "*anyone trying to use this* *system just needs to be guided through it once or twice and after that it's just a simple procedure*". Christine felt confident about OpenBrick's learnability and said, "*I could definitely see a young student completing this lesson and learning a lot from it*". Lindsey liked that OpenBrick kit was "*supe easy to use*" and "*there's not too much going on with it, so there's not like a billion ports for students to get confused on where to plug things in*." Participants found the mBlock visual coding environment and the OpenBrick code blocks very easy to use and were able to successfully implement them to complete all lesson activities.

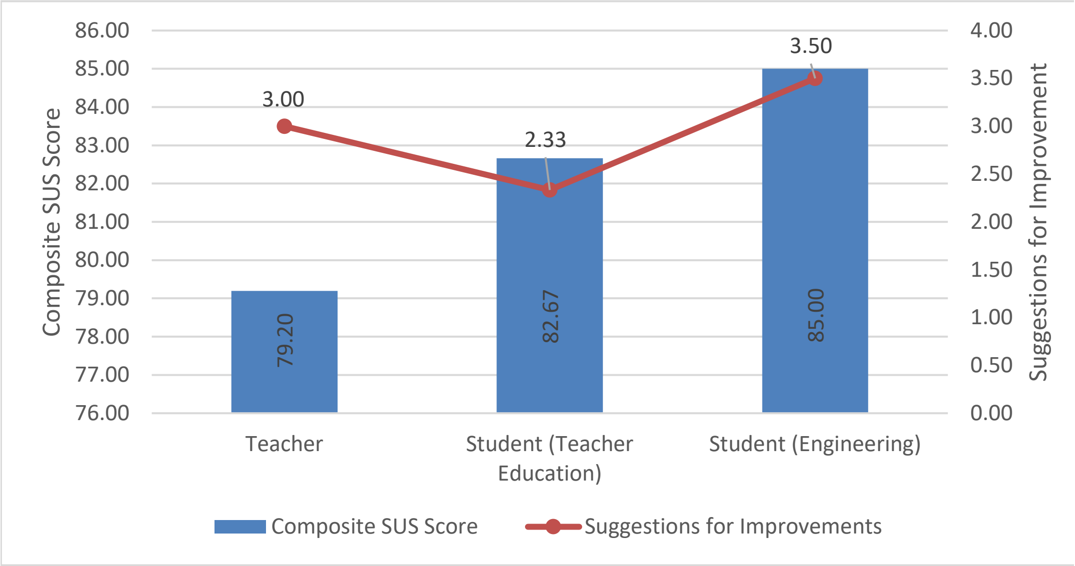
Participants used many adjectives to describe their satisfaction with OpenBrick ER kit. Participants used terms such as curious, excited, and fun to describe their experience with OpenBrick ER kit and considered their experience a rewarding one. Participants' discussion of how they would use the OpenBrick ER kit in the future is also an indication of their satisfaction. Several participants discussed how they would use the OpenBrick ER kit in the future. Jason commented "… *(OpenBrick is) definitely different from the LEGO ones I think they were like sealed up tight, so it's not just that it's (OpenBrick) not expensive it's also very accessible*." Adriana looking forward to her physics class said, "*I do have an idea on how to adjust that to my classroom already*" and Washley suggested that she would use it her younger students, "*with younger grades, I thought about how I could do logic puzzles and have them program the robot to like go certain distances and certain directions for certain number of times or even to go through a maze*." Victor saw the use of OpenBrick in "…*all grade levels starting from kinder all the way to high school*". In addition, in Table 4.5 we present a sample of additional adjectives with excerpts. Participants’ intentions for using OpenBrick in the future coupled with an abundance of discussion concerning their positive experiences with OpenBrick indicates that participants felt satisfied with OpenBrick ER kit and its capabilities in delivering ER STEM lessons.

4.9. Mixed Methods Results

To answer our fifth research question, we combined our quantitative and qualitative findings. We compared participant’s composite SUS scores to the frequency of suggestions for improving the device and their STEM role. This analysis allowed for a deeper insight into participants’ perceptions of OpenBrick’s effectiveness. The findings are presented in Figure 4.4. STEM teachers had the lowest mean composite SUS score compared to the participants who identified as teacher education or engineering students. However, STEM teachers provided more suggestions for improvements on average, than teacher education students. Engineering students on the other hand had the highest average composite SUS score and provided the most suggestions for improving the OpenBrick ER kit. This indicated that engineering students found the OpenBrick ER kit most usable and also saw a potential for more improvement.

Figure 4.4

Participants' STEM Role and Suggestions for Improvements

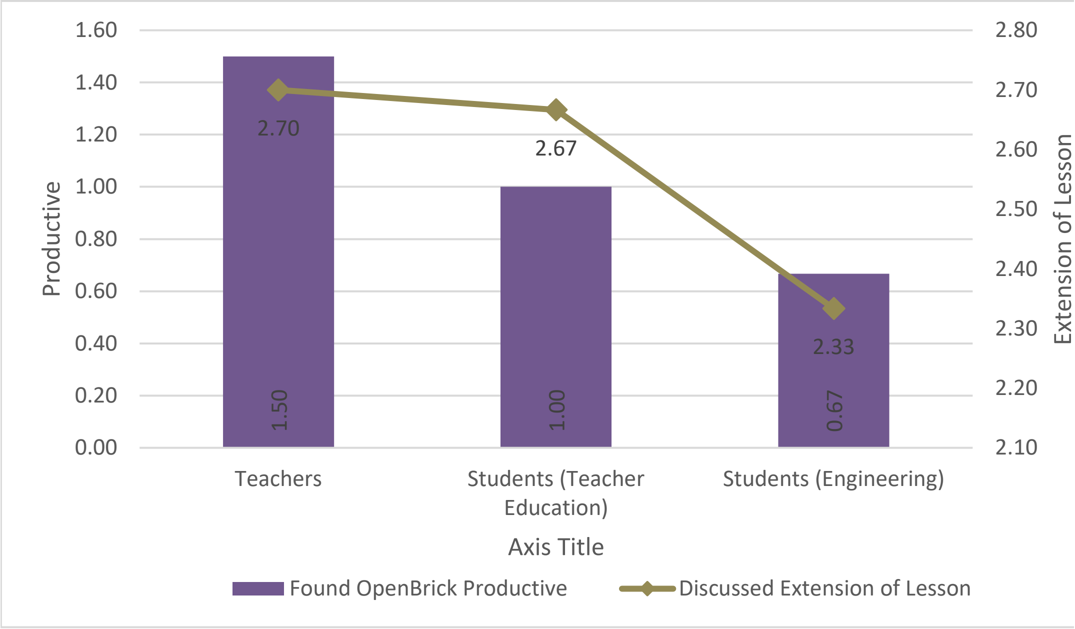


We analyzed responses about OpenBrick's efficiency for participants from different STEM roles. We compared average positive remarks indicating OpenBrick's productivity and its ability to extend to different teaching and learning situations between teachers, teacher education students, and engineering students. The findings from this mixed methods analysis are presented in Figure 4.5. Mixed methods findings indicate that STEM teachers found OpenBrick to be most productive and they were also more likely to believe that they could extend the use of OpenBrick ER kit beyond the current lesson plan to other STEM concepts. Teacher education students ranked second when talking about the productivity of OpenBrick ER kit and its use in extending the current STEM lesson. However, engineering students found OpenBrick ER kit to be less productive than STEM teachers and teacher education students. Their belief in

OpenBrick's ability to be useful in teaching other STEM concepts was also lower than their counterparts. Findings indicate that STEM teachers and teacher education students found OpenBrick more efficient in delivering ER based STEM lesson than engineering students.

Figure 4.5

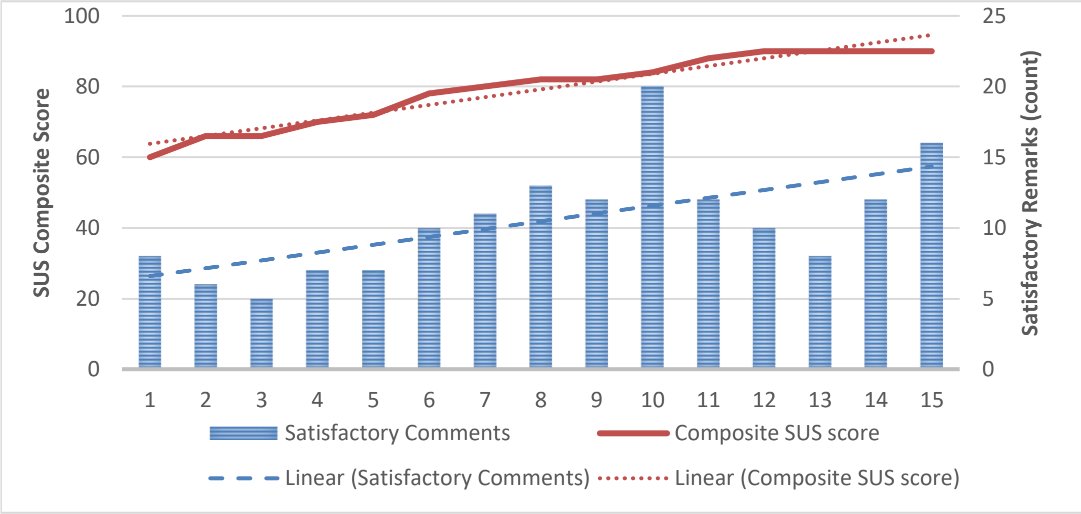
Participants' STEM Role and OpenBrick's Productivity and Efficiency



Finally, to assess mixed methods results for participants' overall satisfaction with the OpenBrick ER kit, we compared each participants' composite SUS score with the number of satisfactory remarks they expressed during the interview about their positive experiences with the OpenBrick ER kit. Figure 4.6 shows the participants' SUS scores (sorted from lowest to highest) displayed as a connected line and the count of participant’s satisfactory remarks as bars. The fitted dashed line represents the trend for participants’ level of satisfaction with the OpenBrick ER kit. Similarly, the fitted dotted line represents the trend for participants’ composite score. Both fitted lines have a positive trend and display similar slopes. The comparison of participants’ composite SUS scores and their satisfactory remarks suggest that there was a strong relationship between the two and that participants’ perceptions of usability was driven by their satisfaction with the OpenBrick ER kit.

Figure 4.6

Participants’ Composite SUS Scores and Their Satisfaction with OpenBrick ER Kit



4.10. Discussion

All students do not have access to ER in their STEM classrooms. This disparity is mainly caused by the high cost of ER. The problem of access is further complicated by STEM teachers’ incorrect perceptions ER. Open source ER holds the potential promise of leveling the playing field for all students, but implementation is often complicated by the level of DIY and technical expertise needed by the STEM instructor who takes on the task of putting such ER kits together for their students. OpenBrick ER kit can help solve the problem of disparities in access with its low cost and ease of use.

Analysis of quantitative, qualitative, and mixed methods results from this usability study provide us with some very interesting observations. The descriptive analysis of the SUS composite scores demonstrates notably that the participant with the highest SUS score also had previous experience with ER as a student, teacher, or in another role. On the other hand, the participants with the lowest SUS score had no previous experience in using ER. This may just have been a random co-incidence, but the third highest SUS score also belongs to a participant who had no previous experience with ER. The two contradicting observations indicate that there may be more at play here than just previous ER experiences. One possible explanation of these observations comes from the subgroup analysis of the SUS composite score (see Table 4.4). Participants who identified themselves as White had the lowest mean SUS score compared to participants who identified as American Indian and Alaska Native, Black, or African American, or Two or more races. Also, participants who identified as having Hispanic origin also had a higher SUS score than their counterparts. It is a well-established fact that minority students and students from under underrepresented and marginalized groups experience a much lower level of exposure to ER (Anwar et al., 2019). It is possible that SUS score for those participants who belonged to minority or underrepresented groups were influenced by their own personal experiences as students.

It is likely that as children in not so distant past, they themselves lacked access to ER and found OpenBrick ER kits more usable than their White counterparts simply because of the open source and accessible nature of the OpenBrick ER kit. This interesting observation calls for further investigation into what factors shape users' perceptions of effectiveness, efficiency, satisfaction, and ultimately the usability of a device such as OpenBrick ER kit.

Participants' gender seemed to play a role in their perceptions of usability of OpenBrick ER kit. Female participants found OpenBrick ER kit less usable than their male counterparts. This finding aligns with other findings about male users developing greater positive attitudes and perceptions of ER than female users (Atmatzidou & Demetriadis, 2016; Kucuk & Sisman, 2020; Milto et al., 2002 etc.). However, research also suggests that innovative teaching and learning activities have been shown to improve female students' engagement with and perceptions towards ER (Beisser, 2005). The findings from this usability study suggest that there is a need for exposing female students to ER at a young age so that they can develop positive perceptions towards ER.

Participants' STEM role did not seem to have an effect on their perceptions of usability. However, participants' previous experience with ER seemed to influence their perceptions of usability. STEM teachers who had previous experience with ER found OpenBrick more usable than any other subgroup of participants, even those with previous experience with ER as students and in other roles. Exposure to other ER (proprietary or open source) allowed these users to assess OpenBrick ER kit more critically and their higher SUS score suggests that OpenBrick ER kit is truly effective, efficient, and satisfactory.

All participants were able to successfully complete the ER lesson plan activities using the OpenBrick ER kit. This fact coupled with participants' responses to the interview questions suggest that OpenBrick ER kit was effective in achieving its goal of ER STEM lesson delivery. Participants did have issues with the caster ball/wheel, chassis, and the motors but those problems were not severe enough to hinder completion of the lesson activities. As a matter of fact, some participants welcomed those challenges and suggested that the minor issues with the kit could be used as an opportunity for engaging students in problem solving. Participants however enjoyed the OpenBrick ER kit's simple design and straight forward manner in which the OpenBrick ER module connected to the computer and how the module was coded. The Scratch-based mBlock visual coding software was a big hit with those who had never coded before. Additionally, those who had used Scratch before, found it interesting to use the same block-based coding environment to program a robot. Some users found the process of code being uploaded to the rover very interesting and saw it as an opportunity to engage their student with physical computing concepts. Overall, findings suggest that OpenBrick ER kit was effective at helping participants implement an ER STEM lesson plan.

Engineering students provided the most suggestions for improving OpenBrick ER kit. They also had the lowest SUS score among the three groups of participants (teachers, teacher education students, and engineering students). Looking at OpenBrick from an engineering students' perspective, they did not seem to find the kit as usable as teacher education students or even the STEM teachers. However, based on their training as engineers, engineering students were able to provide valuable suggestions for improving the ER kit. Suggestions to improve the chassis, caster wheel/ball, wires, software, upload process, and other aspects of OpenBrick ER kit are certain to make the OpenBrick a more effective, efficient, and user-friendly device capable of delivering ER STEM lessons to students in STEM classrooms.

An interesting theme can be identified regarding the efficiency of OpenBrick. Teachers as a group found OpenBrick most productive and they also imagined themselves using OpenBrick for delivering additional STEM lessons. On the other hand, engineering students did not find OpenBrick as productive and did not envision themselves using OpenBrick beyond their experience during the research session. Teacher education student's perception of productivity and their desire to use OpenBrick was situated in the middle when compared to teachers and engineering students. We believe that this is a positive finding. Current STEM teachers can influence how much their students are exposed to innovative new educational technology. The fact that STEM teachers find OpenBrick ER kit productive and envision themselves using it to engage their students in hands-on STEM learning is a testament to the potential of OpenBrick ER kit. This finding also suggests that more current and future STEM teachers need to be exposed to OpenBrick ER kit and its potential for engaging their students in hands on STEM lessons.

This is not a surprise finding and reflects the users' desire to feel fulfilled and satisfied by a desire to find that device usable. The adjectives used by the participants (see Table 4.5) paint a very clear picture of how satisfied users were with OpenBrick ER kit. Users described their experiences as amazing, they found OpenBrick cool and useful. But perhaps the best compliment given to OpenBrick was by Jason who suggested that "*It (OpenBrick ER kit) could be as a replacement for the for some of the things that the LEGO Mindstorm kits have done*". This comment is a very important because OpenBrick was conceived by a teacher who as a STEM club sponsor could not afford to acquire robotic kits for his students. The developer of OpenBrick wanted to level the playing field for his students and all those students who did not have access to ER due to lack of resources. So, for a teacher with previous experience with ER to suggest OpenBrick as a replacement for LEGO, an expensive, proprietary ER is an enthusiastic vote of confidence. Overall, all participants were satisfied with their experience with OpenBrick and found it usable.

4.11. Conclusion

All students do not have access to the power and promise of ER in their STEM classrooms. The findings from this usability study suggest that OpenBrick is a step in the right direction. All participants were able to completely and correctly implement the activities associated with the ER STEM lesson plan. There were some difficulties with the physical aspects of the ER kit but none of those difficulties were associated with the OpenBrick ER module (the brain of the kit) nor were those difficulties severe enough to deter the completion of the lesson plan implementation. We also found that participants deemed OpenBrick productive, and teachers and teacher education students (future teachers) envisioned themselves using OpenBrick ER kit in the future. All participants were satisfied with the OpenBrick ER kit and had an engaging experience with it as they implemented the ER STEM lesson plan. Overall, participants found OpenBrick ER kit effective, efficient, and satisfactory and usable for delivering ER-based STEM lessons.

4.12. **References**

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5. BROADER IMPACTS AND INTELLECTUAL MERIT

Research provides overwhelming evidence for the potential for ER in STEM classrooms. But all students do not have access to ER in their STEM classrooms. There are three major factors that serve to propagate the disparities in access to hands-on ER based STEM education for all students. First factor is the high cost of proprietary ER, second factor is the teachers' incorrect and sometimes negative perceptions about day-to-day teaching with ER in STEM classrooms. Open source ER have the potential to increase access for all students to high quality hands-on STEM education. however, implementing open source ER solutions can become a tricky and often complex endeavor. The difficulties in adapting open source ER solutions serves as the third and finally factor adding to the unequal access for all students to ER. The research undertaken in this dissertation sought to advocate greater integration of low cost ER that are based on open source Arduino hardware and Scratch software. Using a three-article dissertation design, I provide empirical evidence of the efficacy of Arduino and Scratch through a meta-analytic study and an experimental study. I also conducted usability testing of OpenBrick, an easy to use ER kit that is based on open source Arduino and Scratch. In this chapter, I will restate the research questions that guided this dissertation, discuss the major findings from the three individual research studies undertaken in this dissertation, the broader impacts, and implications of those findings, provide recommendations for future studies, and offer a summary conclusion.

5.1. Research Questions

My research was guided by the following three sets of questions.

1. To what extent do Arduino- and Scratch-enabled interventions effect students' overall computational thinking (CT) skills?

a. What are the effects of Arduino- and Scratch-enabled interventions on each dimension (concepts, practices, and perspectives) of students' CT skills?

b. What are the moderating effects of students' grade level and the duration of intervention on the effectiveness of Arduino- and Scratch-enabled interventions on students' CT skills?

2. What are the effects of participation in an Arduino Rover building activity on students' interest and attitudes towards STEM subjects and career fields?

a. What are the moderating effects of race/ethnicity and gender on these changes?

b. To what extent have students' affects towards engineering as a profession changed as a result of participating in the Arduino Rover activity?

3. What was the perceived usability of the OpenBrick Robotics module for implementing the STEM ER based lesson and activities for participating user?

a. What characteristics of the OpenBrick Robotics module did users find to be helpful in completing the tasks outlined in STEM ER lesson?

b. What were the concerns about the efficiency with which the participating users were able to implement STEM ER lesson using OpenBrick Robotics module?

c. What was the satisfaction level for users of OpenBrick Robotics module for implementing STEM ER lesson?

5.2. Major Findings

The first article in this dissertation meta-analyzed the effects of open source Arduino- and Scratch-based interventions on students' CT skills. I found that these interventions had a positive effect *d* = 1.03 (*CI* = [0.63, 1.42]) on students' CT skills. The study meta analyzed 19 effect size, out of which 12 effects sizes were statistically significant. The findings also suggested that within the framework of CT skills suggested by Brennan and Resnick (2012), the Arduino- and Scratch-based interventions had a positive effect on students' CT concepts skills (*d* = 1.16, *CI* = [0.41, 1.91]), CT practices skills (*d* = 0.72, *CI* = [0.42, 1.02]), and CT perspective skills (*d* = 1.68, *CI* = [0.08, 3.27]). I also found that these results were moderated by students' grade level and the duration of the study. The findings from the meta-analysis suggested that teaching and learning activities based in open source Arduino and Scratch had a positive impact on students' CT skills.

Purpose of the second research study in this dissertation was to assess the changes in student's perceptions and attitudes towards STEM subjects and careers after engaging in a hand on ER activity. I also analyzed the changes in students' affect towards the engineering profession. The results indicate that the intervention had positive effects on students' perceptions and attitudes towards STEM subjects and careers. The intervention also had a positive effect on students' affect towards engineering. Students who identified as non-White seemed to benefit more positively from the intervention than White students. Finally, the intervention improved female students' perceptions and attitudes towards STEM subjects and careers and their affect towards engineering. A low-cost and open source Arduino-based ER (Mars Rover) building, coding, and testing activity was successful at producing a positive impact on students, and the findings from this study add to the literature on reforming STEM education to make it more equitable and accessible for all students.

Finally, the third article presented the results of the usability study of OpenBrick ER kit. OpenBrick is based on open source Arduino and Scratch and is extremely low cost when compared to commercially available proprietary ER kits. The participants in this usability study were eleven STEM teachers, three teacher education students, and two engineering students. Participant engaged in an ER based STEM lesson using OpenBrick ER kit, then participated in a SUS survey and an online interview session. The individual SUS scores ranged between 60 and 90 and the average composite SUS score was 79.88 (*SD* = 10.16). participant with the highest composite SUS score had previous experience with ER as a student, teacher and in other role, while the participant with the lowest composite SUS score had no previous experience with ER. The qualitative analysis of the interview responses suggested that participants were extremely satisfied with the usability of OpenBrick ER kit for delivering ER based STEM lessons. And the mixed methods analysis of the participants' demographics, SUS scores, and interview responses suggested that participants previous experiences with ER had a positive effect on their perceptions of OpenBrick ER kit's usability. STEM teachers and engineering students provided the most suggestions for improving OpenBrick ER kit and participants' satisfaction was directly related to their composite SUS score. Overall, participants found OpenBrick ER kit to be very usable.

5.3. Broader Impacts and Implications

The research findings from the three articles in this dissertation have many broad implications for current and future STEM teachers. The findings from this dissertation add to the knowledge base of STEM education, impacting curriculum aspects as well as the pedagogical training of future STEM teachers. The first implication of the findings from this dissertation is the aggregation of an overall effect size for the efficacy of Arduino and Scratch in STEM classrooms. The review of quantitative research provides a window into teaching and learning practices based in open source Arduino hardware and Scratch software. Over the course of last four years, I have collected much anecdotal evidence of the effectiveness of Arduino and Scratch and there were unique pieces of evidence in the literature suggesting that the combination of open source Arduino and Scratch is effective for improving students' CT skills. But the meta-analysis and the resulting effect size provides empirical evidence of the effectiveness of open source Arduino and Scratch. Hence, the determination of an overall effect size adds to the knowledge base and impacts the policies governing the training of future STEM teachers.

Another implication of the findings from this dissertation is development of practices towards innovative use of 3D printed material use in STEM classrooms. Our STEM classrooms need a transformation. This transformation can be achieved using hands-on learning that encourages real-world problem solving. However, hands-on learning requires physical materials that the students could manipulate and engage with. These materials are often expensive or inaccessible for students and teachers for a variety of reasons, mainly their cost. The use of 3D printed Mars rover in the second research study should impact the way we look at and feel about the physical parts of the STEM curriculum. The successful use of 3D printed curriculum pieces (the Mars rover) should help STEM instructors see innovative new technologies as their friend in classrooms. The findings from the second research study suggest that future STEM teachers should be familiar with the basic concepts of 3D printing and should be able to use 3D printed curriculum components as STEM teaching tools. The implications of the findings from the second study are very far reaching and these findings reiterate the need for a reform in teacher education programs.

The findings also have implications for how our future teachers are being exposed to innovative new open source technologies. Findings from the second article in this dissertation suggest that low cost Arduino based ER can be just as effective in improving students' perceptions and attitudes towards STEM subjects and careers. Implementing open source Arduino based Mars rover also helped improve students' affect towards engineering as a profession. But the same level of similar implementations cannot be expected without teachers who are knowledgeable about open source hardware and software. And are able and willing to implement such open source solutions in their classrooms to create more access for all students to quality hands-on STEM education. The need for knowledgeable STEM teachers points to the need for reform in teacher education. Teacher education programs need to ensure that they are exposing future teachers to open source technology and ensuring that the future STEM teachers are able to fully take advantage of the wealth of open source ER resources. Ensuring that our future teachers are aware of open source hardware devices such as Arduino and software platforms such as Scratch will help encourage greater access for all students to ER in their STEM classrooms.

Another major implication of this research is the validation of a low cost open source ER kit as a useful replacement for proprietary and expensive ER kits. LEGO and VEX have dominated the ER market for the three decades and for good reason. These proprietary ER kits simply work. They are easy to use and allow teachers to implement ER based STEM lessons with ease. Compared to LEGO and VEX ER kits, open source Arduino based ER kits require the instructors to possess DIY and technical skills. Participants found the OpenBrick ER module to be simple and user friendly. Participants who had previously used LEGO ER went as far as to say that OpenBrick could be used as a replacement for LEGO ER kit. This implication should impact policies and practices that govern who teaches our future teachers. Teacher education programs must ask this question, are the people who are preparing our future teachers themselves open to innovative new open source technologies and are adapt at exposing the future teachers to effective open source tools, or are they firmly situated in the previous decades unwilling to accept the promise of open source instructional tools. Open source Arduino based ER can provide an effective alternative to proprietary LEGO and VEX ER. It is about time that our teacher trainers receive much needed training in implementing open source Arduino based ER lessons with low cost ER kits such us OpenBrick.

I believe that the usability study achieved its intended goal of assessing the usability of the OpenBrick ER kit, but the study also provided a window into how the perceptions of the usability were being shaped by participants STEM role and their previous experiences with ER. Participants who had used ER before as a student, teacher or in any other role found the kit more usable than those for whom working with OpenBrick ER kit was their first exposure to ER. This finding seems very anecdotal but has profound implications for policy impact. The finding is akin to the situation where the more one performs an act, the better one is able to perform that act. And not just that, the experience of performing that act also allows one to assess how someone else is performing the same act. It should be no surprise that the people who had experience with ER found OpenBrick ER kit more usable than those who had no previous experience with ER. This finding has many policy implications relating not just to how we are training our future teachers, but who is training them and what kind of training do these teacher trainers have themselves.

Finally, I feel that the research findings have great personal implication for myself as an advocate for equity within the role of an educational researcher as well. The beginning of my work with Arduino and the advocacy for integration of Arduino based teaching and learning practices did not coincide with my Ph.D. I had been first exposed to Arduino when I was teaching mathematics as a high school teacher. The many years of collected anecdotal evidence was a driving force behind my decision to take a leave from K-12 classroom teaching and pursue a Ph.D. The research findings contained in this dissertation along with the lived experiences I amassed while conducting this research have impacted me in many profound ways. My belief in open source Arduino hardware's power to encourage has only strengthened as a result of my research activities and the research findings. I also believe that there is plenty of room for future research on the diverse roles open source Arduino can play in encouraging equity and access for all students to hands-on quality STEM education. These roles are not limited to K-12 STEM classrooms but can and should easily extend to post-secondary STEM course work. But most importantly, the greatest personal implication of the findings from this dissertation is that I have been set on a path to work for encouraging access to ER for all students, regardless of their race, ethnicity, their SES, or their school's zip code.

5.4. Recommendations for Future Studies

The focus of this three-article dissertation was open source Arduino hardware. But the three research studies contained in this dissertation by no means provide all the answers to the questions about the efficacy of open source Arduino in STEM classrooms. As a matter of fact, this dissertation hardly begins to ask some relevant questions about the promise of open source educational technologies in general and Arduino and Scratch in particular. Future research may focus on meta-analyzing the effects of Arduino on other thinking and problem solving skills, especially, within the context of mathematical thinking and problem solving processes. Other meta-analytic studies focused on aggregating the effects of Arduino based interventions on students' engagement in post-secondary engineering classrooms are warranted as well. Future meta-analyses can certainly extend the meta-analytic results presented in this dissertation.

The effects of Arduino based Mars rover was assessed in this dissertation. The results were positive; however, the sample size was small due to attrition. Future studies may replicate the same experimental and control conditions using a large (classroom or school level) participant pool. The same can be said for the usability study. Future usability study could be conducted using a large sample of pre-service teachers or in-service STEM teachers from many different schools within a school district. The large participant pool would make the findings statistically more powerful and generalizable. Also, a larger participant pool would allow for regression analysis to develop linear or multi-level models that could explain the roles of participant demographics and their previous ER use as moderators on their perceptions of OpenBrick ER kit's usability.

Finally, the usability study engaged participants in implementing one ER STEM lesson plan. Future studies could vary the lesson plans among STEM teachers who teach different STEM subjects or who teach different grades. The varying lessons would allow for an in-depth assessment of the usability of the OpenBrick ER kit in diverse STEM classroom conditions. Also, researchers may also consider assessing students' perceptions of OpenBrick ER kits' usability. I believe that looking at OpenBrick's usability from students' point of view would lead to some interesting findings. Future research on usability of OpenBrick ER kit will help make OpenBrick ER kit more effective and user friendly in STEM classrooms.

6. APPENDIX A

Table 6.1
Summary of Studies Included in the Meta-Analysis

#	*Author, Year*	*Publication Type*	*Grade Level*	*Duration (weeks)*	*Experimental Curriculum*	***N***
1	Blancas et al., 2020	C	E	10	Robotics and Programming	10
2	Booth & Stumpf, 2013	C	F	1	Robotics and Programming	11
3	Felicia, Sha'rif, Wong, & Mariappan, 2017	J	M	10	Computer science through programming	69
4	Hsiao, Lin, Lin, Lin, Chen, & Chen, 2019	J	M	18	6E Model	67
5	Jaithavil & Kuptasthien, 2019	C	M	16	Microcontroller based programming	77
6	Karaahmetoğlu, & Korkmaz, 2019	J	E	11	Physical computing	33
7	Kuan, Tseng, Chen, & Wong, 2016	C	F	17	Computer Assisted instrumentation curriculum	14
8	Merkouris, Chorianopoulos, & Kameas, 2017	C	M	17	Embodied Computing Platform	12
9	Plaza et al., 2019	C	E	18	Robotics and Programming	16
10	Psycharis, S., & Kotzampasaki, E. (2019	J	M	7	STEM inquiry game learning	115
11	Sáez-López, Sevillano-García, & Vazquez-Cano, 2019	J	M	17	Robotics and Programming	129
12	Tsarava et al., 2019	C	E	10	plugged in programming	31

Table 6.2

Effect Sizes and CI of Arduino- and Scratch-Based Interventions CT Skills and Dimensions

CT Dimensions	*# Of Effect Sizes*	*Mean Effect Size*	*SE*	*95% CI Interval*
Concepts	7	1.16	0.38	(0.41, 1.91)
Practices	9	0.72	0.15	(0.42, 1.02)
Perspectives	3	1.68	0.81	(0.08, 3.30)
Overall	19	1.03	0.20	(0.63, 1.42)

Figure 6.1

Literature Search Flowchart

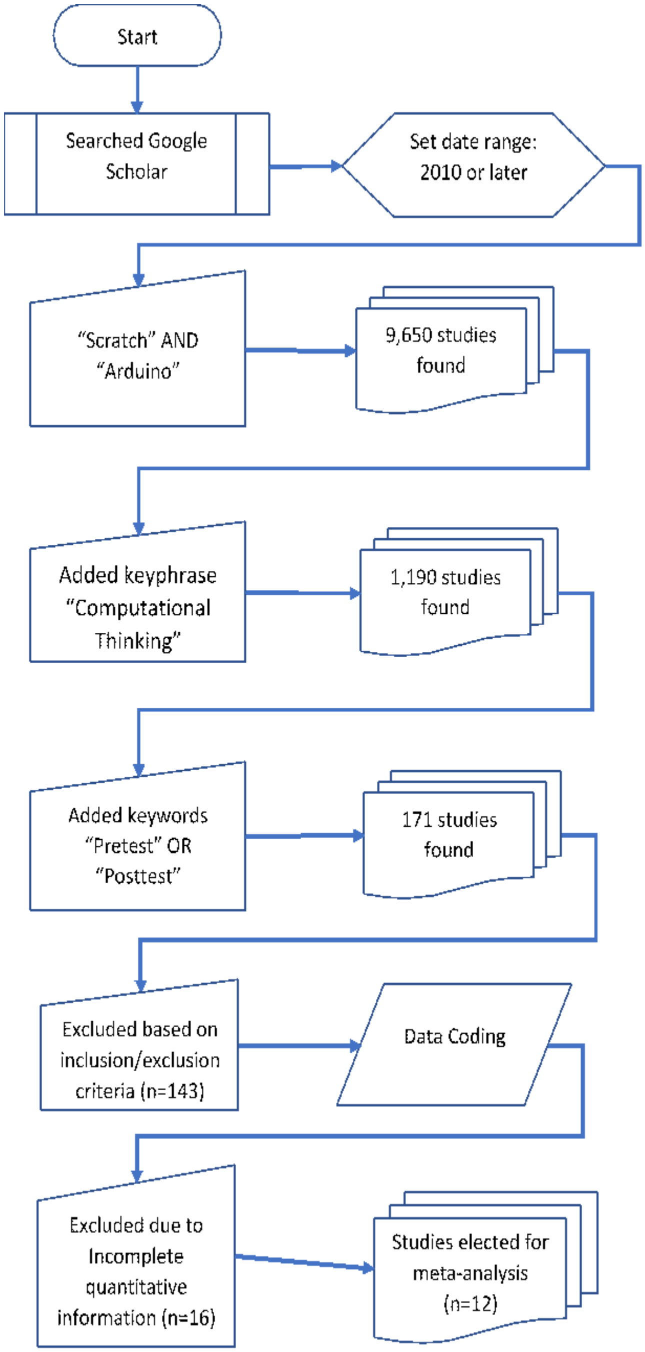
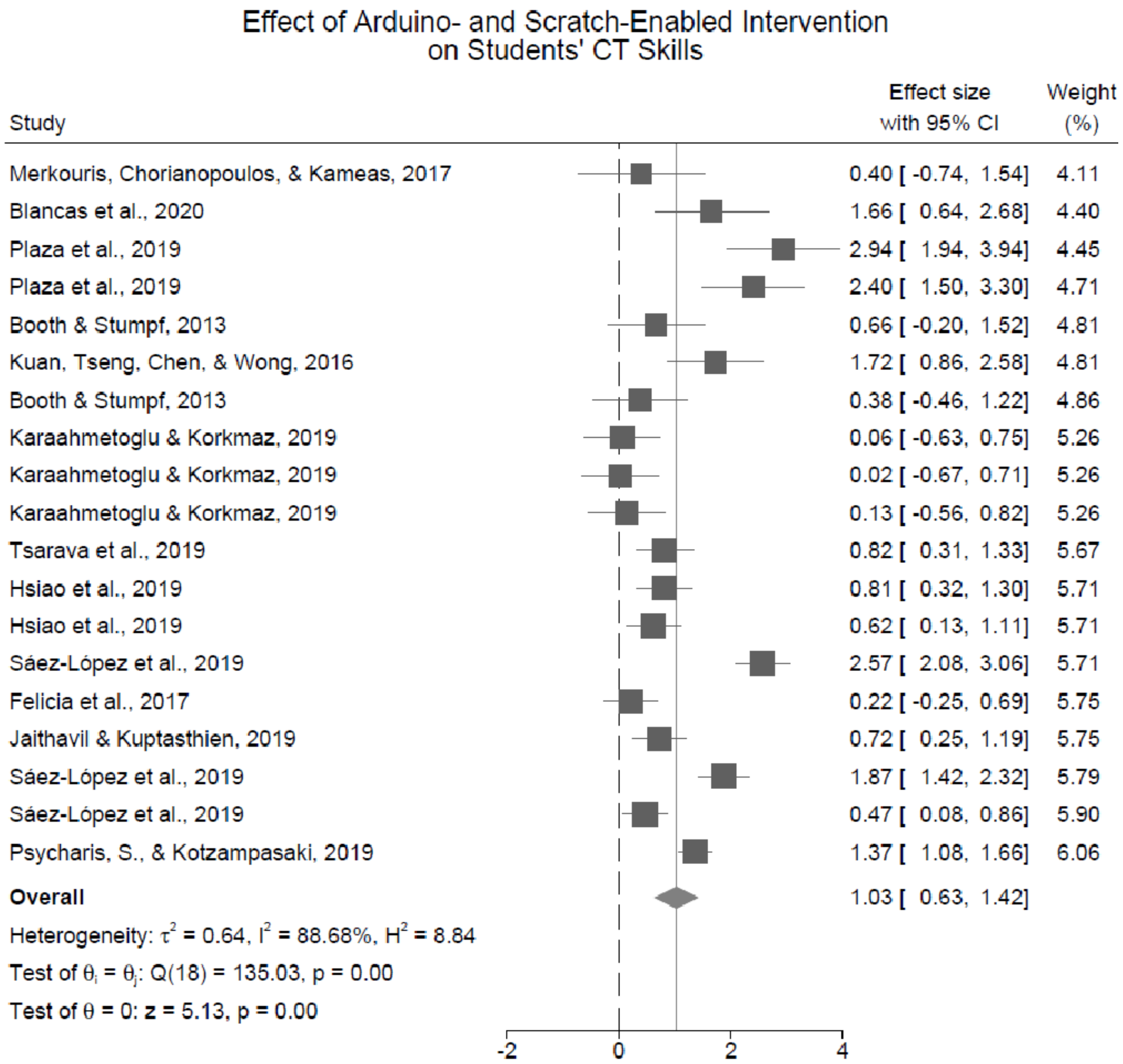


Figure 6.2

Forest Plot of Overall Effects of Arduino- and Scratch on CT Skills



Effect of Arduino- and Scratch-Enabled Intervention on Students' CT Skills

Study	Effect size with 95% CI	Weight (%)
Merkouris, Chorianopoulos, & Kameas, 2017	0.40 [-0.74, 1.54]	4.11
Blancas et al., 2020	1.66 [0.64, 2.68]	4.40
Plaza et al., 2019	2.94 [1.94, 3.94]	4.45
Plaza et al., 2019	2.40 [1.50, 3.30]	4.71
Booth & Stumpf, 2013	0.66 [-0.20, 1.52]	4.81
Kuan, Tseng, Chen, & Wong, 2016	1.72 [0.86, 2.58]	4.81
Booth & Stumpf, 2013	0.38 [-0.46, 1.22]	4.86
Karaahmetoglu & Korkmaz, 2019	0.06 [-0.63, 0.75]	5.26
Karaahmetoglu & Korkmaz, 2019	0.02 [-0.67, 0.71]	5.26
Karaahmetoglu & Korkmaz, 2019	0.13 [-0.56, 0.82]	5.26
Tsarava et al., 2019	0.82 [0.31, 1.33]	5.67
Hsiao et al., 2019	0.81 [0.32, 1.30]	5.71
Hsiao et al., 2019	0.62 [0.13, 1.11]	5.71
Sáez-López et al., 2019	2.57 [2.08, 3.06]	5.71
Felicia et al., 2017	0.22 [-0.25, 0.69]	5.75
Jaithavil & Kuptasthien, 2019	0.72 [0.25, 1.19]	5.75
Sáez-López et al., 2019	1.87 [1.42, 2.32]	5.79
Sáez-López et al., 2019	0.47 [0.08, 0.86]	5.90
Psycharis, S., & Kotzampasaki, 2019	1.37 [1.08, 1.66]	6.06
Overall	1.03 [0.63, 1.42]	

Heterogeneity: $\tau^2 = 0.64$, $I^2 = 88.68\%$, $H^2 = 8.84$

Test of $\theta_i = \theta_j$: $Q(18) = 135.03$, $p = 0.00$

Test of $\theta = 0$: $z = 5.13$, $p = 0.00$

Figure 6.3

Forest Plot of Effects of Arduino- and Scratch on CT Concepts Skills

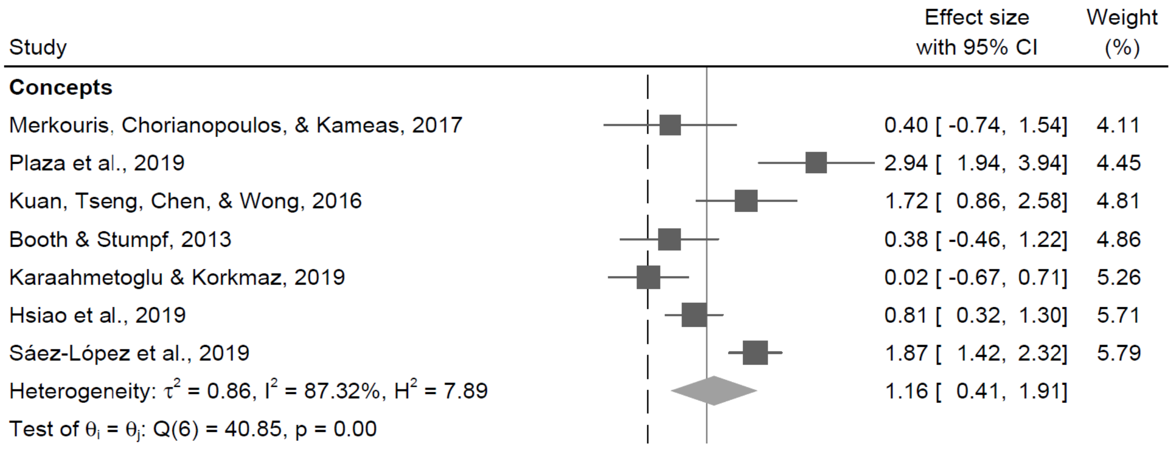


Figure 6.4

Forest Plot of Effects of Arduino- and Scratch on CT Practices Skills

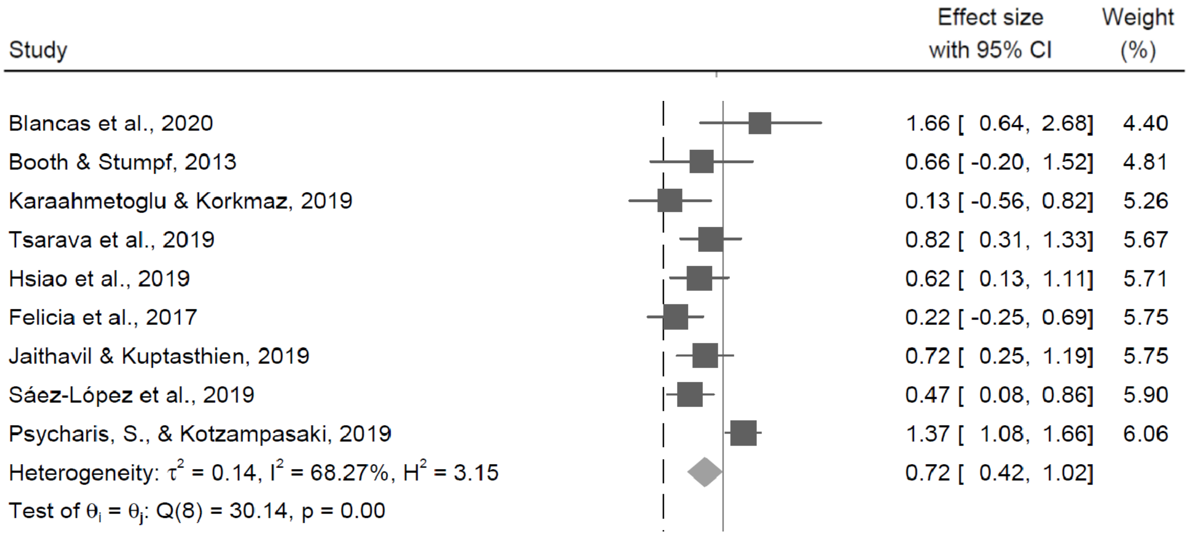
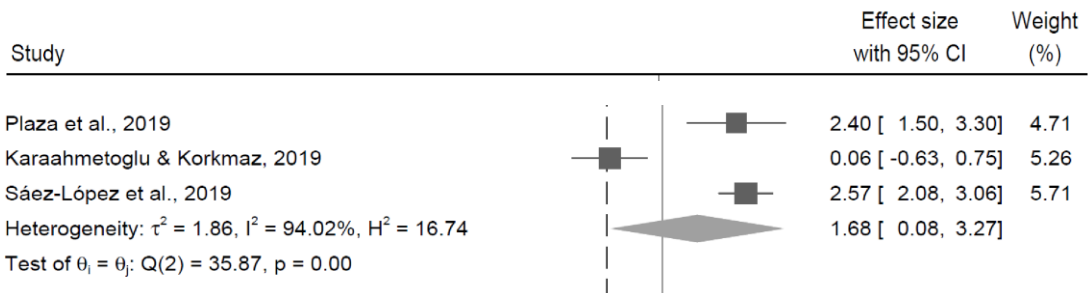


Figure 6.5

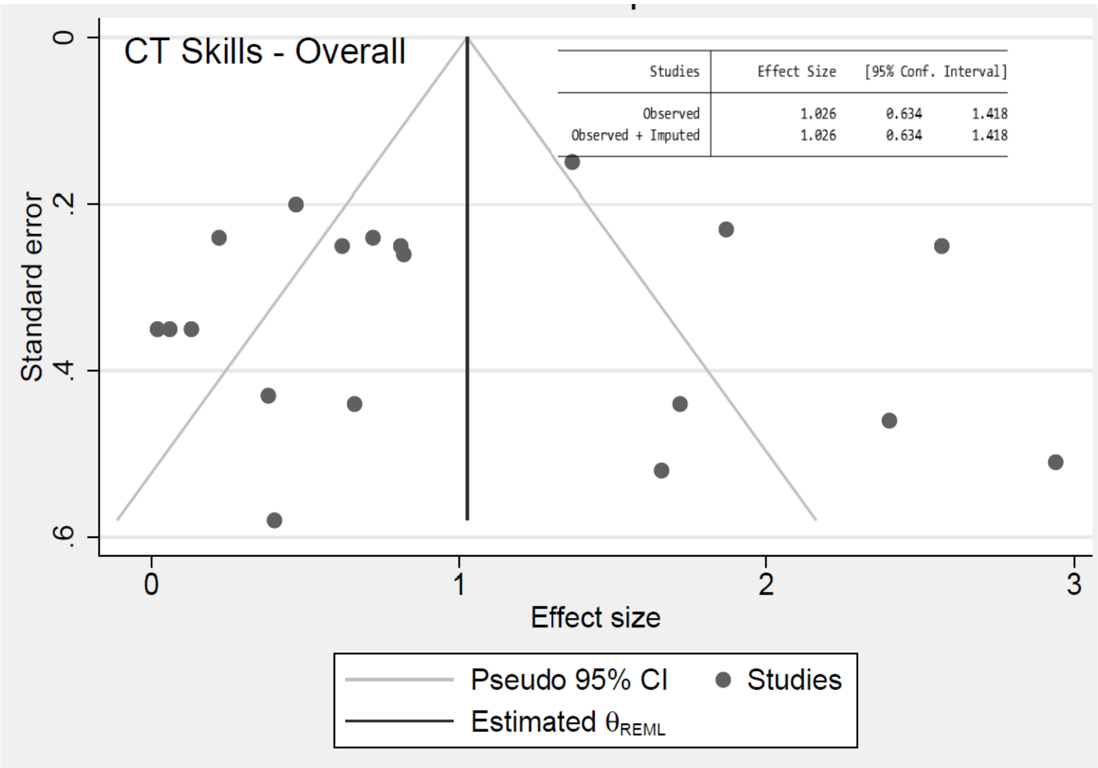
Forest Plot of Effects of Arduino- and Scratch on CT Perspectives Skills



Study	Effect size with 95% CI	Weight (%)
Plaza et al., 2019	2.40 [1.50, 3.30]	4.71
Karaahmetoglu & Korkmaz, 2019	0.06 [-0.63, 0.75]	5.26
Sáez-López et al., 2019	2.57 [2.08, 3.06]	5.71
Heterogeneity: $\tau^2 = 1.86$, $I^2 = 94.02\%$, $H^2 = 16.74$	1.68 [0.08, 3.27]	
Test of $\theta_i = \theta_j$: $Q(2) = 35.87$, $p = 0.00$		

Figure 6.6

Trim and Fill Funnel Plot of Effects of Arduino and Scratch on CT Skills



Studies	Effect Size	[95% Conf.	Interval]
Observed	1.026	0.634	1.418
Observed + Imputed	1.026	0.634	1.418

7. APPENDIX B

Table 7.1
Descriptive Statistics of Participants

	Scratch			Arduino Rover			Total
Race/Ethnicity	Female	Male	Total	Female	Male	Total	
Asian	0	0	0	1	0	1	1
Black/African American	1	1	2	2	0	2	4
Hispanic	1	1	2	0	0	0	2
Other	0	2	2	0	0	0	2
Two or more races	0	3	3	1	0	1	4
White	1	0	1	2	5	7	8
Total	3	7	10	6	5	11	21

Table 7.2
STEM Club Format

Session	Minimum	Maximum
Pretest, Project Overview, Basics of Coding (Flowcharts), and Hour of Code	60 min.	90 min.
Introduction to Scratch Coding	60 min.	90 min.
Introduction to Electrical and Electronic Components Using Arduino	60 min.	90 min.
Problem Identification, Research, Ideation, and Idea Analyzation	60 min.	90 min.
Build	60 min.	90 min.
Test and Refine	60 min.	90 min.
Communicate, Reflect, and Posttest	60 min.	90 min.

Source: Fidai, Jarvis et al., 2019

Table 7.3
Pre-Post Changes in Students' Perceptions Towards STEM Subjects and Careers Interests

	Scratch			95% Confidence Interval		Arduino Mars Rover			95% Confidence Interval	
	Pre	Post	Cohen's *d*	Lower	Upper	Pre	Post	Cohen's *d*	Lower	Upper
Science	6.12	5.74	-0.22	-0.60	0.15	6.38	6.44	0.44	-0.35	0.44
Mathematics	5.96	5.52	-0.22	-0.60	0.16	6.60	6.67	0.07	-0.32	0.46
Engineering	5.98	5.56	-0.24	-0.61	0.14	6.28	6.70	0.34	-0.06	0.73
Technology	6.12	5.59	-0.33	-0.70	0.05	6.56	6.38	-0.16	-0.55	0.23
STEM Career	5.91	5.85	-0.03	-0.41	0.34	6.70	6.52	-0.18	-0.57	0.22

Note. The effect is based on the 95% confidence interval around Cohen's *d*.

Table 7.4

Effects on Students' Perceptions Towards STEM Subjects and Careers Interests

		Scratch		Arduino Mars Rover			95% Confidence Interval	
		Mean	SD	Mean	SD	Cohen's *d*	Lower	Upper
All students								
	Science	5.75	1.80	6.44	1.31	0.44	0.05	0.82
	Mathematics	5.58	1.77	6.66	0.82	0.77	0.37	1.16
	Engineering	5.56	1.80	6.70	0.79	0.80	0.40	1.20
	Technology	5.58	1.88	6.38	1.29	0.49	0.10	0.88
	Career	5.85	1.63	6.52	1.13	0.47	0.08	0.86
White								
	Science	5.94	1.98	6.47	1.30	0.31	-0.30	0.92
	Mathematics	5.94	1.84	6.73	0.80	0.49	-0.13	1.10
	Engineering	5.71	1.87	6.53	1.06	0.49	-0.13	1.10
	Technology	5.74	1.90	6.67	0.62	0.57	-0.05	1.17
	Career	6.20	1.67	6.60	0.91	0.27	-0.34	0.87
Non-White students								
	Science	5.40	1.79	6.42	1.33	0.68	0.11	1.24
	Mathematics	4.95	1.47	6.63	0.84	1.51	0.89	2.12
	Engineering	5.30	1.69	6.77	0.65	1.30	0.69	1.89
	Technology	5.30	1.87	6.25	1.48	0.59	0.02	1.14
	Career	5.25	1.37	6.48	1.22	0.97	0.38	1.54
Male								
	Science	5.92	1.75	6.53	1.40	0.39	-0.15	0.92
	Mathematics	6.04	1.70	6.87	0.57	0.68	0.13	1.22
	Engineering	5.80	1.87	6.77	0.77	0.70	0.15	1.24
	Technology	5.72	1.90	6.63	1.16	0.59	0.05	1.13
	Career	6.24	1.64	6.60	1.25	0.25	-0.28	0.78
Female								
	Science	5.96	1.59	6.07	1.28	0.07	-0.57	0.71
	Mathematics	5.56	1.66	6.27	1.10	0.48	-0.17	1.12
	Engineering	5.76	1.54	6.47	0.92	0.53	-0.13	1.17
	Technology	5.80	1.80	5.87	1.45	0.04	-0.60	0.68
	Career	5.88	1.45	6.20	1.01	0.24	-0.40	0.89

Note. Mean comparison using posttest scores between Arduino Mars Rover and Scratch groups.

Table 7.5

Pre-Post Changes in Students' Attitudes Towards STEM

	Scratch			95% Confidence Interval		Arduino Mars Rover			95% Confidence Interval	
	Pre	Post	Cohen's *d*	Lower	Upper	Pre	Post	Cohen's *d*	Lower	Upper
Mathematics	3.29	3.63	0.09	-0.21	0.39	4.33	4.41	0.25	-0.06	0.56
Science	4.08	3.75	-0.30	-0.61	0.01	3.38	3.67	0.26	-0.04	0.56
Engineering	4.00	3.77	-0.22	-0.51	0.07	4.04	4.03	-0.01	-0.29	0.27
21st Century Skills	3.80	3.85	0.05	-0.21	0.32	4.13	4.25	0.15	-0.10	0.40

Table 7.6
Effects on Students' Attitudes Towards STEM

		Scratch		Arduino Mars Rover			95% Confidence Interval	
		Mean	SD	Mean	SD	Cohen's *d*	Lower	Upper
All students								
	Mathematics	3.63	1.16	4.41	1.07	0.70	0.39	1.01
	Science	3.75	1.11	3.67	1.20	-0.07	-0.37	0.23
	Engineering	3.77	1.01	4.03	0.96	0.27	-0.02	0.55
	21st Century Skills	3.85	0.84	4.26	0.82	0.48	0.22	0.74
White								
	Mathematics	3.38	1.14	4.38	1.14	0.38	-0.04	0.81
	Science	3.98	1.18	3.58	1.15	-0.35	-0.77	0.08
	Engineering	4.02	1.00	3.98	0.92	-0.04	-0.44	0.35
	21st Century Skills	4.02	0.85	4.00	1.00	-0.02	-0.37	0.34
Non-White								
	Mathematics	3.16	1.05	4.44	1.01	1.25	0.76	1.73
	Science	3.41	0.91	3.75	1.25	0.31	-0.15	0.75
	Engineering	3.39	0.90	4.07	1.01	0.71	0.27	1.14
	21st Century Skills	3.61	0.78	4.47	0.56	1.30	0.88	1.72
Male								
	Mathematics	4.06	1.11	4.55	1.13	0.43	0.00	0.86
	Science	4.06	1.24	3.81	1.31	-0.19	-0.62	0.23
	Engineering	4.11	1.04	4.17	0.99	0.06	-0.35	0.46
	21st Century Skills	43.05	0.78	4.36	0.83	0.39	0.02	0.75
Female								
	Mathematics	3.40	1.22	4.04	0.75	0.60	0.08	1.12
	Science	3.65	1.03	3.29	0.75	-0.38	-0.89	0.13
	Engineering	3.71	0.82	3.67	0.78	-0.06	-0.53	0.42
	21st Century Skills	3.87	0.79	3.97	0.73	0.13	-0.31	0.55

Note. Mean comparison using posttest scores between Arduino Mars Rover and Scratch groups.

Table 7.7

Pre-Post Changes in Students' Affect Towards Engineering

	Scratch			95% Confidence Interval		Arduino Mars Rover			95% Confidence Interval	
	Pre	Post	Cohen's *d*	Lower	Upper	Pre	Post	Cohen's *d*	Lower	Upper
Framing	4.28	3.85	-0.37	-0.73	-0.01	4.06	4.00	-0.05	-0.39	0.29
Collaboration	3.72	3.62	-0.08	-0.44	0.28	3.56	3.88	0.25	-0.09	0.59
Project Management	3.80	3.25	-0.39	-0.84	0.05	3.75	3.89	0.11	-0.31	0.53
Design	4.20	3.78	-0.36	-0.69	-0.02	3.84	3.91	0.05	-0.26	0.37
Analysis	3.60	3.73	0.09	-0.42	0.59	3.76	3.85	0.07	-0.41	0.55

Table 7.8

Effects on Students' Affect Towards Engineering

		Scratch		Arduino Mars Rover			95% Confidence Interval	
		Mean	SD	Mean	SD	Cohen's *d*	Lower	Upper
All students								
	Framing	3.85	1.34	4.00	1.15	0.12	-0.23	0.47
	Collaboration	3.62	1.15	3.88	1.04	0.24	-0.11	0.58
	Project Management	3.33	1.21	3.89	1.22	0.46	0.03	0.89
	Design	3.79	1.17	3.91	1.00	0.11	-0.21	0.44
	Analysis	3.73	1.44	3.85	1.09	0.09	-0.40	0.59
White								
	Framing	4.13	1.33	3.75	0.99	-0.21	-0.94	0.53
	Collaboration	3.72	1.16	3.58	0.72	-0.14	-0.65	0.38
	Project Management	3.63	1.13	3.88	1.02	0.23	-0.41	0.86
	Design	3.83	1.29	3.93	1.02	0.08	-0.40	0.56
	Analysis	4.17	1.34	3.92	1.00	-0.21	-0.94	0.52
Non-White								
	Framing	3.42	1.25	4.14	1.22	0.59	0.08	1.10
	Collaboration	3.46	1.14	4.04	1.17	0.51	0.00	1.02
	Project Management	2.88	1.20	3.89	1.34	0.79	0.14	1.42
	Design	3.71	0.98	3.90	1.01	0.18	-0.28	0.65
	Analysis	3.08	1.38	3.80	1.16	0.58	-0.15	1.30
Male								
	Framing	4.43	1.07	4.13	1.21	-0.27	-0.72	0.19
	Collaboration	3.90	1.12	3.92	1.08	0.02	-0.44	0.47
	Project Management	3.50	1.19	4.34	0.97	0.80	0.21	1.37
	Design	3.94	1.14	4.04	1.08	0.08	-0.34	0.51
	Analysis	4.27	1.16	4.04	1.12	-0.20	-0.84	0.45
Female								
	Framing	3.46	1.41	3.67	0.91	0.17	-0.44	0.78
	Collaboration	3.42	1.17	3.78	0.94	0.33	-0.28	0.95
	Project Management	3.31	1.30	2.66	0.98	-0.55	-1.31	0.22
	Design	3.50	1.23	3.57	0.68	0.07	-0.50	0.63
	Analysis	3.41	1.56	3.33	0.87	-0.63	-0.93	0.80

Note. Mean comparison using posttest scores between Arduino Mars Rover and Scratch groups.

8. APPENDIX C

A) *System Usability Scale* questionnaire (Brooke, 1996)

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
2. I found the system unnecessarily complex	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
3. I thought the system was easy to use	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
4. I think that I would need the support of a technical person to be able to use this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
5. I found the various functions in this system were well integrated	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
6. I thought there was too much inconsistency in this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
7. I would imagine that most people would learn to use this system very quickly	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
8. I found the system very cumbersome to use	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
9. I felt very confident using the system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
10. I needed to learn a lot of things before I could get going with this system	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

B) Questions for semi-structured interview (Adapted from Kim et al., 2019)

1) What do you think of OpenBrick for delivering ER lessons? (Satisfaction)

2) How would you summarize your overall experience with OpenBrick for delivering ER lessons? (Satisfaction)

3) Are there any aspects of OpenBrick that could be improved? (Effectiveness)

4) Would you like to share any more information about your experience with OpenBrick for delivering ER lessons? (Satisfaction)

5) Did you try any other activities with OpenBrick that were not described in the provided ER lesson plan? (Efficiency)

6) What benefits do you think OpenBrick will provide to teachers and other users? (Satisfaction)

7) Do you think that OpenBrick could be useful for you? (Satisfaction)

8) Did you experience any distractions while using OpenBrick? (Effectiveness)

9) How would you use OpenBrick in your own classroom? (Satisfaction)

10) What resources would you like to be provided along with OpenBrick to you as a teacher? (Satisfaction)

11) Did you feel uncertain or unsure while using OpenBrick? (Satisfaction)

12) Did you experience any difficulty while using OpenBrick? (Effectiveness)

13) How did you feel when using OpenBrick? (Satisfaction)

14) What did you like and dislike about OpenBrick? (Satisfaction)

9. APPENDIX D

A) Cost analysis for OpenBrick with links to off-the-shelf parts.

#	Part Description	Link	Bulk Quantity	Bulk Price	Price Per Unit	Units per OpenBrick	Price per OpenBrick
1	Arduino UNO R3 (or compatible microcontroller)	Link	3	$13.99	$ 4.66	1	$ 4.66
2	L298N motor controller	Link	4	$ 9.88	$ 2.47	1	$ 2.47
3	28BYJ-48 Stepper motor with controller	Link	5	$10.99	$ 2.20	2	$ 4.40
4	2 pin JST connector 28 AWG (male/female pair)	Link	10	$10.99	$ 1.10	2	$ 2.20
5	NodeMCU ESP8266 12E WiFi module	Link	3	$13.99	$ 4.66	1	$ 4.66
6	Jumper wires	Link	120	$ 6.98	$ 0.06	20	$ 1.16
7	On/off switch	Link	5	$ 5.49	$ 1.10	1	$ 1.10
8	4XAA battery holder	Link	2	$ 5.98	$ 2.99	1	$ 2.99
	Total component cost per OpenBrick without batteries						$ 23.64
Optional							
	4XAA battery charger with 8 batteries	Link	1	$22.99	$ 22.99	1	$ 22.99
	Total component cost per OpenBrick with batteries						$ 46.63
3D printed shell							$ 3.70
Shipping							$ 0.99
Total							$ 51.32

Note. Shipping from Amazon is included in the yearly prime membership ($99/year) and the shipping cost per unit is estimated at 100 units produced during the first year.

B) Cost comparison between OpenBrick and LEGO Intelligent Brick ER.

	Link	Cost	Cost Compared to OpenBrick
LEGO Intelligent Brick	Link	$ 214.99	809% more
LEGO Battery	Link	$ 94.99	313% more
Total		$ 309.98	565% more

Note. Shipping to the customer is dependent upon the shipping method chosen and is not included in the per unit cost.

10. APPENDIX E

Table 10.1
An Enumeration of Research on Low-Cost Education Robotics

Source	Number of Articles
Peer Reviewed Journal Articles	
PsycINFO	6
Eric	4
Science and Technology Collection	11
JSTOR	4
Web of Science	28
IEEE Xplore	13
LearnTechLib	11
Conference Proceedings	
Web of Science	59
IEEE Xplore	166
LearnTechLib	9
ACM Digital Library	25
IEEE Computer Society	153

Table 10.2
Participant Demographics and Their STEM Role

Participant	Race	Hispanic Origin	Gender	STEM Role	Major (Student)	Grade (Teacher)
Brianna	Black or African American	No	Female	Student	Teacher Education (pre-service STEM)	-
Christine	White	No	Female	Student	Teacher Education (pre-service STEM)	-
Diego	Two or more races	Yes	Male	Student	Engineering	-
Lindsey	White	No	Female	Student	Teacher Education (pre-service STEM)	-
Nicole	White	No	Female	Student	Engineering	-
Adriana	White	No	Female	Teacher	-	Middle school
Antonio	White	Yes	Male	Teacher	-	Elementary school
Cashley	American Indian and Alaska Native	Yes	Female	Teacher	-	Elementary school
Washley	White	No	Female	Teacher	-	High school
Cheneka	Black or African American	No	Female	Teacher	-	Elementary school
Christina	White	Yes	Female	Teacher	-	Elementary school
Jason	White			Teacher	-	College/University
Kristin	White	No	Female	Teacher	-	Elementary school
Louigina	White	Yes	Female	Teacher	-	Elementary school
Pamela	Black or African American	No	Female	Teacher	-	Middle school
Victor	Two or more races	Yes	Male	Teacher	-	Elementary school

Table 10.3
Participant SUS Scores and Their Previous ER Experience

		Previous Educational Robotics Experiences as			
Participant	STEM Role	Student	Teacher	Other	SUS Score
Louigina	Teacher	Yes	Yes	Yes	90
Victor	Teacher	No	Yes	No	90
Antonio	Teacher	No	No	No	90
Pamela	Teacher	Yes	Yes	Yes	90
Brianna	Student	Yes	No	Yes	90
Cashley	Teacher	No	No	No	88
Washley	Teacher	No	Yes	No	84
Adriana	Teacher	No	Yes	Yes	82
Diego	Student	Yes	Yes	Yes	82
Lindsey	Student	Yes	No	No	80
Christine	Student	Yes	No	No	78
Jason	Teacher	Yes	Yes	Yes	72
Cheneka	Teacher	Yes	Yes	Yes	70
Kristin	Teacher	No	No	No	66
Nicole	Student	No	No	Yes	66
Christina	Teacher	No	No	No	60
		Average Composite SUS Score			79.88

Table 10.4

Subgroup Analysis of SUS Scores by Demographics, STEM Role, and Previous Experience with ER

Group	Number of Participants	Mean	SD	Min	Max
Race					
American Indian and Alaska Native	1	88.00	-	88.00	88.00
Black or African American	2	80.00	14.14	70.00	90.00
Two or more races	2	86.00	5.66	82.00	90.00
White	11	78.00	10.66	60.00	90.00
Hispanic origin					
No	9	78.44	9.32	66.00	90.00
Yes	7	80.71	11.63	60.00	90.00
Gender					
Female	13	78.15	10.40	60.00	90.00
Male	3	87.33	4.62	82.00	90.00
STEM role					
Student	5	79.20	8.67	66.00	90.00
Teacher	11	80.18	11.15	60.00	90.00
Major (Students)					
Engineering	2	74.00	11.31	66.00	82.00
Teacher Education	3	82.67	6.43	78.00	90.00
Grade taught (Teachers)					
Post-secondary	1	72.00	-	72.00	72.00
Elementary	7	79.14	13.26	60.00	90.00
High	1	84.00	-	84.00	84.00
Middle	2	86.00	5.66	82.00	90.00
Previous experience with ER - Student					
No	8	78.25	12.26	60.00	90.00
Yes	8	81.50	8.05	70.00	90.00
Previous experience with ER - Teacher					
No	8	77.25	11.95	60.00	90.00
Yes	8	82.50	7.91	70.00	90.00
Previous experience with ER - Other					
No	8	79.50	11.20	60.00	90.00
Yes	8	80.25	9.77	66.00	90.00

Table 10.5
Adjectives Describing Participants' Satisfaction with OpenBrick

Adjective	Participant	Sentiment
Adaptable	Jason	*OpenBrick could be a replacement for some of the things that the LEGO Mindstorm kits can do.*
	Washley	*OpenBrick ER kit could be adapted for my high school students as where they could work on more complex tasks.*
	Washley	*I think OpenBrick ER kit has a lot of potential and room for growth.*
	Louigina	*My fourth and fifth grade students can use OpenBrick ER Kit for learning mathematics and sixth grade students can use it for learning physics.*
	Diego	*OpenBrick ER kit is simple and modular.*
Affordable	Kristin	*I think the best benefit of OpenBrick ER kit is its low cost. This way we can get more ER kits in more students' hands.*
	Christine	*OpenBrick ER kit is very low cost and would be of great help to teachers.*
Amazing	Louigina	*My overall experience was amazing.*
	Victor	*Everything was amazing.*
Compact	Lindsey	*Everything was kind of condensed inside the 3D printed box. This is great because keeping things simple for students is very important. Specially in the beginning when they are first learning how to work with robotics.*
Cool	Jason	*OpenBrick ER kit looks cool. It looks like a brick, but it has that lab equipment kind of look to it.*
	Lindsey	*OpenBrick ER kit was really cool.*
Engaging	Cashley	*The ER lesson was engaging.*
	Nicole	*The ER lesson was engaging.*
Useful	Louigina	*OpenBrick ER kit is very useful for me.*
	Christine	*I do think that the OpenBrick would be useful.*
	Victor	*I agree that OpenBrick ER kit would be very useful for my class.*
	Diego	*I am an engineering student, so these kinds of platforms are very useful.*
	Lindsey	*I definitely think OpenBrick would be useful for me as a student and as a teacher.*