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VOLUME 5 ISSUE 1, 2020

# TABLE OF CONTENTS

## Research Articles

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# Robotics and Early-years STEM Education: The botSTEM Framework and Activities

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## ABSTRACT

botSTEM is an ERASMUS+ project aiming to raise the utilisation of inquiry-based collaborative learning and robots-enhanced education. The project outputs are specifically aimed to provide in- and pre-service teachers in Childhood and Primary Education and children four-eight years old, with research-based materials and practices that use integrated Science Technology Engineering Mathematics (STEM) and robot-based approaches, including code-learning, for enhancing scientific literacy in young children. This article presents the outputs from the botSTEM project; the didactical framework underpinning the teaching material, addressing pedagogy and content. It is a gender inclusive pedagogy that makes use of inquiry, engineering design methodology, collaborative work and robotics. The article starts with a presentation of the botSTEM toolkit with assorted teaching practices and finishes with examples of preliminary results from a qualitative analysis of implemented activities during science teaching in preschools. It turns out that despite perceived obstacles that teachers initially expressed, the analysis of the implementations indicates that the proposed STEM integrated framework, including inquiry teaching and engineering design methodologies, can be used with children as young as four years old.

**Keywords:** STEM, robotics, preschool

## INTRODUCTION

STEM programmes are receiving increasing attention in the research literature, and decision makers are becoming interested in incorporating STEM approaches in formal education. This is because these approaches are considered efficient for developing scientific literacy for citizens and for increasing the number of young people choosing to study scientific-technological disciplines at the end of their compulsory schooling (EU, 2015; NRC, 2012, 2014). However, what can be understood as an integrated STEM approach is not clear. Nowadays, many different conceptions of curriculum integration for STEM coexist (Bybee, 2010) but only a few theoretical frameworks for teaching exist (Ortiz-Revilla et al., 2018), and the didactical guidelines are often not specific enough for teachers' implementation (Chu, Martin, and Park, 2019). Furthermore, most initiatives are addressed to teenagers, but recent research (Tytler and Osborne, 2012) points out that early childhood intervention could be very efficient. What is more, while children at elementary school often have an intrinsic interest in STEM content areas, a declining pattern in attitudes towards science has been found as the age of the students increase (Ali et al., 2013; Denessen et al., 2015; DeWitt and Archer, 2015; Said et al., 2016). Moreover, students from upper elementary and middle school grades show negative attitudes towards the enjoyment of science lessons (Ali et al., 2013; DeWitt and Archer, 2015). Therefore, pre-primary and primary education stages constitute great opportunity for smoothing the way, and help generate positive attitudes to STEM.

The ERASMUS+ project *Robotics and STEM education for children and primary schools* (botSTEM) with partners in Spain (coordinators), Sweden, Italy and Cyprus that is reported on here, has developed a didactical framework for integrated STEM activities involving robotics for preschool and primary schools (children four-eight years old.). The project outputs are specifically aimed to provide in- and pre-service teachers in Childhood and Primary Education with a didactical framework and research-based and tested robotics activities designed to scaffold STEM-teaching. This article aims to present the project output and starts of by presenting the developed theoretical framework for the botSTEM integrative STEM approach. Then the process of searching for and collecting tested robotics practices, which have been, together with the developed framework, the basis for the development of new robotics activities is described. One example of the practices developed within botSTEM is presented in Appendix A. Finally, the research framework for ongoing implementation of botSTEM activities is described with some preliminary results given from qualitative analysis of implemented activities during STEM teaching scaffolded by robotics in preschools.

## DIDACTICAL FRAMEWORK OF STEM AND ROBOTICS

### STEM and Science

Two main themes are prominent in the botSTEM partners' stance on the goals of science education: science as an institution of liberal democracy, and science as a discipline composed of principles and processes that need to be mastered. There is often a tension between science education aimed at producing the next generation of professional scientists (Vision I), and science education aimed at equipping citizens with the knowledge and understanding of science that they need to participate in democratic decision making (Vision II) (Roberts, 2007). Countries, school districts, schools and even individual teachers differ in the relative weight that they give to each aspect, although it seems that many standards-based movements and organizations, such as EU, OECD and NRC support a combination of the two, which is also the main goal of the botSTEM project.

botSTEM is focusing on integrative STEM (Science - Technology - Engineering - Mathematics), which is a comprehensive approach merging the different content areas through active and participative methodology involving problem-based learning and collaborative projects. The objective of this approach, considered useful for all ages, is to achieve a STEM literacy that can be summarized as

> "the ability to adapt to and accept changes driven by new technology work, to anticipate the multilevel impacts of their actions, to communicate complex ideas effectively to a variety of audiences, and perhaps most importantly, to find measured, yet creative, solutions to problems that are today unimaginable" (Lederman, 1998).

STEM education implies a higher level of integration than the treatment of the four content areas in the acronym defined separately. STEM can be considered a new discipline uniting all the included content areas in what has been called integrated STEM education (Zollman, 2012) - a form of crosscutting educational instruction that can develop competencies among students in an integrated and humanist manner (Ortiz-Revilla et al., 2018). It is worth stressing that even though practices from all content areas are required to support STEM learning, there is often one STEM area that plays a dominant role (Honey et al., 2014). Since education in early childhood should be preferably holistic, child centred, project- and problem-based, the integration of science, technology, engineering and mathematics fields creates valuable STEM experiences for children (Kermani and Aldemir, 2015; Toma and Greca, 2017).

Integrated STEM approaches imply several challenges for teachers. Making crosscutting STEM connections is not an easy task, requiring that teachers prepare lessons that allow students to understand how STEM knowledge is applied to real-world problems. To make these connections, teachers need to address both content and pedagogy. However, identifying exactly what content and pedagogy are is often complex and difficult (Dare et al., 2019). Even in the USA, where STEM approaches have been advocated since the nineties, few teachers have operationalized STEM education (Kelley and Knowles, 2016). Perhaps, many teachers consider designing and delivering interdisciplinary and multidisciplinary lessons require too much time and effort (Chu et al., 2019).

The framework proposed by botSTEM attempts to help teachers overcome these challenges, based on five ideas presented in the following. First, it is considered that integrative STEM education is more pertinent and viable for elementary school, because teachers teach most of the subjects to the same class. In goal-directed preschool, an integrated STEM approach fits well with the didactics of early childhood education that is at present applied in the classroom. Teachers need to be carriers of both knowledge of the content and updated skills on how to generate situations that support the learning of their children (Fleer and Pramling, 2015; Thulin and Redfors, 2016). In the words of Fleer, "The challenge goes beyond content knowledge to teacher beliefs and pedagogy practices" (Fleer, 2009: 1074). Teachers' attitudes to the content area is important and Fleer et al. (2014) have shown that teachers have unique possibilities by implementing a 'sciencing attitude', which fits in well with integrated STEM.

Second, in terms of methodologies, although several methodologies can be useful within this approach, the framework proposed is based on inquiry and engineering design methodology. Inquiry helps intertwine the different fields in STEM through real world problems. Working with inquiry-based STEM activities provides children with opportunities to practice skills such as reasoning, reflection, questioning, modelling, justifying decisions and communicating. In this framework, guided inquiry is used, (Bevins and Price, 2016; NRC, 2012) because it seems to be the best for four-eight years old children as well as it is the model that seems to provide the best learning results (Minner, Levy, and Century, 2010). Nevertheless, in many integrated STEM education programs, engineering design practices are increasingly emphasized (Kang, 2019), since design problems are all strongly related to the everyday world. Engineering often plays a central role as an 'integrator' that helps to contextualize student learning, providing rich contexts in which learning and the application of science and mathematics concepts and practices happen when students are actively looking for solutions (Kelley and Knowles, 2016).

Both methodologies imply collaboration, an essential part of an integrative STEM approach to teaching and learning. Collaboration emphasizes joint participation in the task, intellectual interdependence, and the co-construction of knowledge, making it difficult, and at times impossible, to identify the individual contributions in the final products. Collaboration demands careful preparation, because some students may not view peer-interaction or group work as a form of viable learning at all, but as a game. Effective communication in peer interaction also involves shared norms regarding turn taking; shared perceptions of the appropriate amount of overlap in verbal contributions and shared norms for the acceptance of different point of views, to reach consensus and make the process continue onwards. It is worth stressing that integrative STEM approaches require collaboration not only between children but also with teachers, who support the process by creating a "bridge" between the child's previous experiences and the new focus of knowledge (Thulin and Redfors, 2016).

Third, in terms of contents, it is considered that the relation between theoretical scientific models and reality is central for the scientific processes. Observations and experiments are embedded in theory and therefore "Theory laden" (Hanson, 1958). Empirical and theoretical work is connected leading to construction and refinement of theories and theoretical models in an interactive process of discussions, experiments and observations in the science community (Adúriz-Bravo, 2012; Giere, 1988; Koponen, 2007). Communicating this in science class is part of making the nature of science (Erduran and Dagher, 2014; Lederman, 2007) explicit, which has been found central for the teaching of science. botSTEM activities focus on versatile theoretical models for talking about, predicting and explaining science phenomena pertinent to the selected age group (four-eight years old). Therefore, focus in the botSTEM project is on theoretical models connected to Big Ideas (Harlen, 2015), and to the everyday lives of the selected age group. Also related with contents, the approach adopted in this project, in consonance with the definition of technological literacy, refers to learning among children of the use of the tools that scientific professionals, mathematicians and engineers, employ. In this sense, children must learn to take data with appropriate tools (scales, tape measures, dynamometers, thermometers, chronometers, microscopes, test tubes, etc.) as well as the necessary tools to analyse such data (spreadsheets) and to present them (word processors). Through these activities, children should understand how technology shapes and is shaped by society.

The fourth idea is about how computational thinking (by means of robotics and/or code learning), an aspect discussed below, is regarded as valuable for its potential to teach logical thinking, problem solving and digital competence, and should be introduced at early childhood.

The fifth and final idea builds on that, given that girls in general are more negative towards technology and its development (Bøe et al., 2011; Henriksen et al., 2016), botSTEM pursues to establish gender inclusive teaching and learning activities for early childhood. Evidence suggests that gender-balanced curricula should strive to be contextualized in line with the interests of girls, linking abstract concepts to real-life situations, and use hands-on activities (UNESCO, 2017). Hence, inquiry and engineering design methodology are potentially useful methodologies, since they emphasize the use of scientific concepts in finding solutions to real-life problems. Also, complementary strategies should be adopted by the teachers, such as encouraging the participation of girls in the communication and reviewing group work to encourage girls to adopt an active role (Scutt et al., 2013).

**Robotics, Computational Thinking and Coding**

Since there are few articles that address principle-based framework for teaching educational robotics concepts for early childhood (Misirli and Komis, 2014), this aspect of the proposed framework will be dealt with more extensively. botSTEM concurs with the definition found in Wikipedia for robots and robotics:

> A robot is a machine, especially one programmable by a computer, capable of carrying out a complex series of actions automatically. Robotics is an interdisciplinary branch of engineering and science that includes mechanical engineering, electrical engineering, computer science, and others. Robotics involves design, construction, operation, and use of robots, as well as computer systems for their perception, control, sensory feedback, and information processing. (Wikipedia, 2020)

Hence, integrated STEM education can be formulated in terms of robotics activities focusing on several, if not all, of the four content areas in STEM, and pertinent theoretical models of science. Robots are increasingly finding their way into classrooms, and Educational Robotics (Eguchi, 2017) is discussed as a transformational tool for learning computational thinking, coding, and engineering. According to Eguchi (2017) educational robotics is an effective learning tool for project-based learning where STEM, coding, computer thinking, and engineering skills can all be integrated in one project. Robotics provides opportunities for students to explore how technology works in real life, while giving them the opportunity to find new ways to work together to foster collaboration skills, express themselves using the technological tool, problem-solve, and think critically and innovatively. Most importantly, educational robotics provides a fun and exciting learning environment because of its hands-on nature and the integration of technology. The engaging learning environment motivates students to learn whatever skills and knowledge needed for them to accomplish their goals in order to complete the projects of their interest (Eguchi, 2017).

According to Wing (2006) computational thinking is a problem-solving skill-set rooted in computer science. The skill-set comprises solving problems, designing systems and understanding human behaviour. Computational thinking represents a type of analytical thinking, which is, according to Wing (2006), applicable to everybody, not just computer scientists. Generic skills like identifying patterns, breaking apart complex problems into smaller steps, organizing series of steps to provide solutions, etc, are put forward.

Coding is the action of putting together sequences of instructions and debugging, or problem solving and is often described as the new language of the digital society, needed to be understood by everyone in order to be able to interact in a culture and society heavily influenced by computer systems. Coding with robots shows children what they can create with technology, engaging children as producers and not merely consumers of technology (Bers, 2018). Bers (2018) suggests seven powerful ideas for early childhood computational thinking.

- Algorithms - a series of ordered steps taken in a sequence to solve a problem sequencing, such as for instance tying shoelaces. Understanding abstraction is central to understanding algorithms and its practice goes beyond computational thinking. Identifying what constitutes a step in the sequence is a matter of abstraction.
- Modularity - breaking down tasks or procedures into simpler units, engaging in decomposition. This can be practiced without computers, for instance when analysing the task of having a birthday party. What different tasks are involved? How detailed should the tasks be described? Inviting guests could for example be broken down further.
- Control structures - the order in which instructions are followed or executed. More advanced examples of control structures are repeat functions, loops, conditional events and nested structures. However, in the early childhood the key issue is familiarizing with patterns and realizing the relationship between cause and effect e.g. when you click the mouse and x does y, or when the robot detects light through its light sensor and the robot should beep.
- Representation - sort and manipulate data and values in different ways. Concepts can be represented by symbols, e.g letters can represent sounds, numbers represent quantities, programming instructions represent behaviours. Different types of things have different types of attributes, e.g cats have whiskers. In addition, data types have different functionalities, e.g numbers can be added, letters can string together. To code, children need to understand that programming languages use symbols to represent actions.
- Hardware/software - computing systems need hardware and software to operate, where the software provides instructions to the hardware. Robots are mainly visible hardware but some components might be hidden, e.g. circuit boards. Children need to understand that hardware is programmed to perform a task and many devices can be programmed, not just computers.

These five powerful ideas have their origin in computer science and are all strongly linked to foundational concepts in early childhood education. However, Bers (2018) puts forward two more powerful ideas concerning processes and habits of mind; debugging and the design process.

- Design process - an iterative process used to develop programs and tangible artefacts. Bers (2018) suggests a series of steps defining a design process adapted for children, where the design process is a cycle: there is no official starting or ending point. The steps are; ask, imagine, plan, create, test and improve, share.
- Debugging - allows us to fix our programs using testing, logical thinking and problem solving. Once children understand how to debug their systems, they start to develop common troubleshooting strategies that can

 

be used on a variety of computing systems. Things do not just happen to work on the first try, but many iterations are usually necessary to get it right.

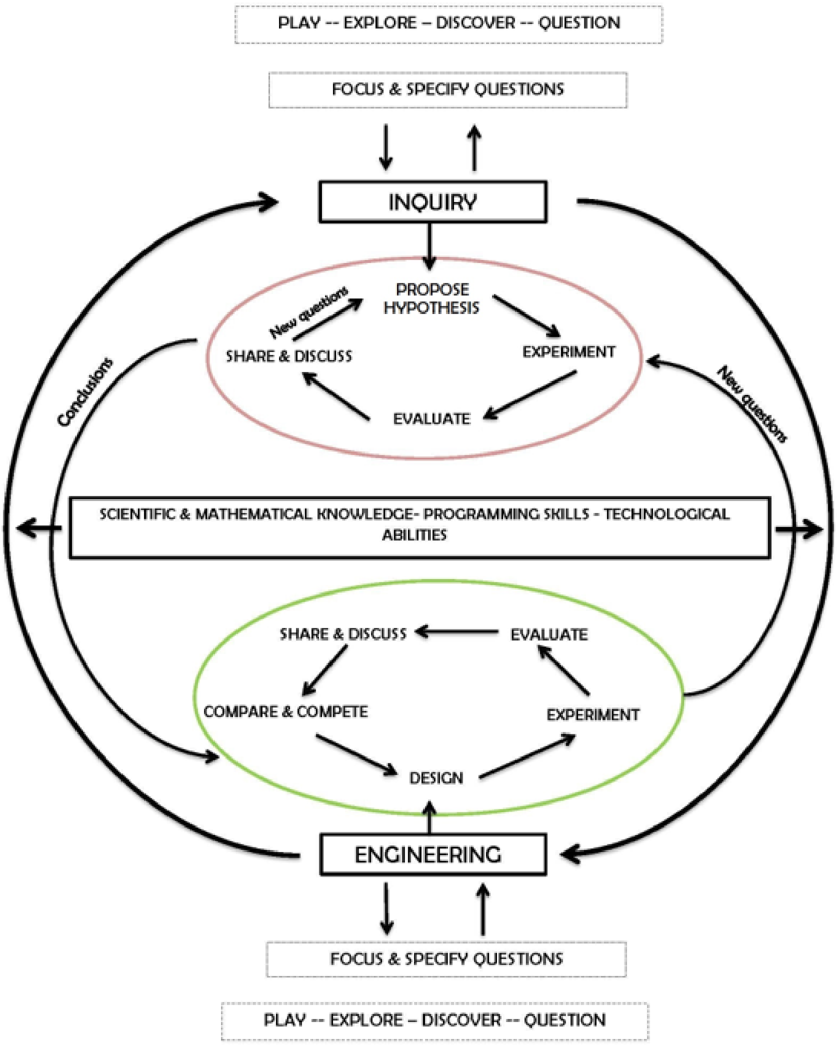


**Figure 1.** botSTEM didactical model developed for introducing integrated STEM education at elementary grades. Inspired by Chalufour & Worth (2004)'s cycle of inquiry.

Summing up, the didactical framework for underpinning the didactical material addresses pedagogy and content within an integrated STEM education: a gender inclusive pedagogy that makes use of inquiry, engineering design methodology, collaborative work, robotics and a scientific content that relates to Harlen's science big ideas and coding.

### The Didactical Model Proposed in the botSTEM Project

The ideas shaping the botSTEM framework have been organized in a didactical model, shown schematically in **Figure 1**, that makes use of inquiry teaching and engineering-design methodologies. Both methodologies imply a certain number of steps and research suggests that young children can follow both, although some adjustments must be made. Inquiry teaching and engineering design are about questions, but, as Chalufour and Worth (2004) note, it is difficult for children to ask questions about something they have neither seen, nor touched, nor experienced. These authors propose that it is very important for young children first to engage, notice, wonder and question. That is, to be given time to play in a scientifically stimulating environment. It is therefore considered necessary to create these rich environments to stimulate children's questions, as can be seen in **Figure 1**. These environments can be created bringing to class objects, toys or through playful activities related with the topic that is going to be addressed for children that interact with them. As many of the emergent questions may not be investigated, the role of the teacher is to focus observation and to clarify questions.

Next, our STEM model consists of three phases, each designed to encompass more than one STEM discipline. Thus, in the first phase, teachers propose an engineering-based real-world problem, based on children's observations and questions that serves as a context to teach science-related content matter. During the second phase students perform a guided inquiry (Martin-Hansen, 2002) in which, among other tasks, the students conduct different experiments using scientific practices and technology, in order to apprehend the knowledge necessary to solve the initial problem. The third and final phase (the problem resolution) requires the design or implementation of a technological solution for the initial problem. In this way, students begin to explore engineering design, linking engineering and science, as proposed in NRC (2012). It is worth stressing that the teacher can begin a cycle through a guided inquiry, for example, if children are curious about why oil and water do not mixture, a lava lamp can be proposed as a challenge. As appears in **Figure 1**, simplified steps are proposed in both methodologies. In the case of inquiry, propose hypothesis, experiment, evaluate, share and discuss. Since teachers are proposed to work with both methodologies, the conclusion step from the inquiry phase is an input of the engineering design methodology. The steps of the engineering design methodology are similar, including a compare and complete step is needed, since a relevant aspect of the engineering design methodology is to compare the different solutions achieved (in terms of efficiency, sustainability, beauty, etc). Nevertheless, the teacher can make these steps more complex, depending on the children's responsiveness. Collaboration among children and with the teachers should be actively promoted during the use of both methodologies.

Maths concepts (such as classification, order, units, symmetries, graphics) are used explicitly in all the phases. Similarly for technology, where besides the use of tools to take data, to analyse it and to present results, technology can be utilised to express children's scientific explanation models, for example by means of 'stop-motion' technique (Fridberg et al., 2017).

Related to computational thinking, a scaffolding process is proposed: begin with simple robots (that can be programmed physically), followed by the introduction to block-based coding (like *Scratch*© , that can be used for presentations, simple modelling, etc.) and ending with physical computing (like BBC microbit, that children can programme to be used as different measuring devices). Also, robotics and programming are integrated in two different ways: as auxiliary to a science real-world problem that guides the activities, or central when the problem is directly related with robotics. In the first case, for example, robots can be used to consolidate the new knowledge, letting children program a robot to "find" answers or using simple programming tools for modelling the phenomena. In the second case, activities such as the design of a domotic garden (or 'smart garden') where robotics and programming are directly integrated with the STEM content. See appendix A for the example activity 'Domotic garden.'

**Figure 1** outlines this didactical model. This combined use of both methodologies, framed in a rich environment, fosters the development of scientific and mathematical knowledge, programming skills and technological abilities.

## OUTPUT FROM THE botSTEM-PROJECT

The output from the botSTEM-project presented here involves the above discussed didactical framework and a downloadable interactive Toolkit, freely available at botstem.eu. The toolkit includes practices for collaborative inquiry teaching and learning concerning robotics and STEM with methodological guidelines. The activities in the toolkit are partly from a search for successfully implemented robotics practices that pay special attention to STEM and gender perspectives, and newly developed practices by botSTEM partners. The activities have been tested and improved by teachers and results from the implementations of selected activities are presented below.

### The Search for Tested Practices

Main criteria for the search for successfully implemented practices addressing four-eight years old children were:

- Pedagogical innovative strategies in education with robotics
- Generic and versatile in relation to robotics and robots
- Specific learning goals for several of the four content areas S, T, E, M
- Learning goals related to big ideas in science
- Gender inclusive
- Including collaborative work
- Involvement of a wide educational community (parents, stakeholders)
- Extended in time

A search for existing robotics practices matching the criteria listed above has been completed. The search was made through use of databases at ERIC, Springer, Routledge and Wiley and Google (Google scholar), as well as Scientix database. In addition, science education researchers and experienced 'expert' teachers were interviewed. The search gave a limited number of educational practices (47) involving more than one of the content areas in

STEM, coupled to robotics and programming for our target ages. Most of the practices found were extracurricular practices, being developed in non-formal environments. Also, activities focusing gender inclusion and described from a gender perspective proved difficult to find for young children. However, so far discussions with experienced teachers and researchers has rendered a view among the teachers that activities involving robotics have proven to be by nature gender inclusive, and it has not been seen as a major issue, especially not for the early-years age group (four-five years old). Another discovery, also confirmed by the experienced teachers, was that, prior to botSTEM, teachers working with digitalization tended to use activities that was readily available and easy to buy and use, rather than theoretically-based teaching activities accompanied by didactical frameworks supporting the teaching.

### The Use of the Didactic Model for Developing New Teaching Material

STEM integrated activities were designed based on the didactical model described above. Among the activities, issues related with magnets, changes of matter, simple machines, solutions and mixtures, plants, heat transfer and gravity, can be found, all of them addressing at least one big scientific idea and robotics/programming. These activities, along with the theoretical framework and other on-line resources constitutes the project toolkit, available through the interactive web-site of the project (www.botstem.eu). The guidelines provided in the activities have to be adapted to their specific contexts by teachers, and the site includes forums for teachers in a Moodle platform, where they can discuss experiences during implementations and share advices for future teaching.

An example of the activities developed following the didactical model, that also appears in the botSTEM toolkit, is presented in Appendix A. The activity, intended for children seven-eight years old, spins around the design of a domotic garden (or 'smart garden'), that is, the design of a garden with an automation system for irrigation. This is an example of how a "robotic" problem serves as anchor to learn about a key idea in science (in the example: organisms require a supply of energy and matter for which they often depend on, or compete with, other organisms) and to apply mathematical knowledge on measurement systems, representation of data and graphs. At the same time, children learn to programme and design an automating device. Furthermore, a possible extension of the activity - named 'how to care for plants on Mars' - allows for the introduction of astronomical concepts. The teacher initiates the activity by creation of a stimulating environment through distribution of plants with very different needs in classroom, and through videos of existing 'smart gardens.' In this way, children get the opportunity to identify and analyse advantages and disadvantages of how 'smart gardens' work, and pose questions about the different needs of the living plants. The definition of the variables that must be controlled in a 'smart garden' allows the introduction of BBC microbit and programming in order to construct a measuring tool, i.e. measuring temperature, humidity, light and so on. It is worth noting that in this part of the activity, the children are working and learning about current technology. Once the children programme the instrument, an inquiry cycle can begin, focused on the needs of the plants. For example, they can use two different plants (basil and cactus) and propose experiments to determine their optimal living conditions, such as following their development for a couple of weeks varying temperature, humidity or lightening. After sharing the results obtained, children can enter the engineering design cycle, designing a watering system for each type of plant, using the knowledge obtained through the inquiry cycle.

As can be seen in Appendix A, the outline of the activity, following the different phases of the didactical model, is given to the teachers, as well as some suggestions and hints (derived from its use with children) that might be useful for the implementation.

### Implementation of the Teaching Activities in Preschools

The botSTEM activities are being implemented, evaluated and refined in preschools in Spain and Sweden during 2018-2020. A design-based implementation (Barab and Squire, 2004) of the activities, guided by variation theory (Marton and Booth, 1997; Marton, 2014) is followed. One of the basic ideas of variation theory (Marton and Booth, 1997) is that learning is always directed at something (phenomenon, object, skill, aspect of reality). This something is called the object of learning and 'learning' entails a qualitative change in the way of experiencing the object of learning - ways of acting originate from ways of experiencing (Marton, Runesson, and Tsui, 2004). There is a dynamic nature to the object of learning. The 'intended object of learning' planned by the teacher will not be the same as the 'enacted object of learning' that the teacher implements in complex classroom situations, and what the students actually experience (the 'lived object of learning') is again not the same as the enacted object of learning (Marton et al., 2004). In planning the teaching of each activity, teachers were asked to discuss with colleagues, and formulate answers about the intended object of learning (What knowledge are the children expected to develop?; What does it mean to understand this?; What differs between different ways of understanding this?; How are they expected to understand and use the knowledge afterwards?) about both STEM and robotics. Through both participative and non-participative observation, several teachers have been observed during activities, in order to determine the enacted and the lived object of learning. Video data of implemented activities have been collected and interviews of teachers pre and post their experience with the activities have been performed.

Preliminary results from the teaching of young children (four-six years old) in Swedish preschools (Cronquist, Fridberg, and Redfors, 2019; Fridberg and Redfors, 2020) indicate that robotics may function as a motivation factor for exploring scientific concepts. In the data, teachers and children discuss, cooperate and physically try out skills in computational thinking with the focus of helping robots to overcome obstacles. These obstacles could be created by the teacher with a specific aim, such as giving the children a task to help the robot up an inclining plane, or by the children themselves in spontaneous inquiry and play situations. Programming the robots is indicated to be a complex task for children in itself, especially when they have to program the robots to turn around. The robot activities make the children reflect about their own role in the programming. In a situation where a robot was programmed to walk up an inclined plane but failed and took another route then that intended by the programming child, the child uttered: "I would like to be in his brain to see what he thinks!". The teacher answered "It's you that program him." and this made the child reflect "But then I am his brain!". The play with robots thus gives opportunities for the children to metareflect and learn about important aspects of programming and their possibilities to affect the outcome of it. Before the implementations of botSTEM activities, not all teachers and children had had experience with robots, but teachers could adapt the activities and the didactical model to the realities of their classrooms, despite perceived obstacles that the teachers initially expressed.

In the case of an activity about magnets in Spanish schools for children four-five years old (Greca, García Terceño, Cronquist, Fridberg, and Redfors, 2019), the involved teachers did not have any knowledge about how to introduce robots in their classrooms, at the outset. However, when the teachers started the activity, they felt more and more confident to introduce new ways to use robotics with the children. The activity also includes addressing laterality, spatial orientation, sequence of movements, working memory and counting. In spite the fact that the teachers that implemented this particular activity did not consider the understanding of the proposed methodologies as an object of learning, they implemented an inquiry methodology during the process. However, engineering design methodology described in the toolkit was not part of the intended object of learning - it was not addressed in an explicit or reflective way. Nevertheless, in practice, the teachers implemented an integrated STEM approach, integrating the STEM along with robotics. The reason for this could be their holistic view of education, i.e. that teachers usually work with extended teaching projects. Additionally, all Spanish teachers, without exception, agreed that an integrated STEM approach is an exceptional way to teach STEM because it encourages children to learn and it boosts their curiosity. However, after these first implementations, the teachers are still reluctant to integrate this approach in their regular teaching practice. They perceive it as isolated occurrence, even though they note that the children's competences improved significantly.

## CONCLUSIONS

Even though integrated STEM education from kindergarten to high school is being promoted by national and international stakeholders, it was difficult to find teaching material for four-eight years old children, upheld by research in science education and involving robotics. Moreover, the existing frameworks did not seem to be very useful for helping teachers to develop integrated STEM activities (Chu et al., 2019), especially for the first schooling years (Ortiz-Revilla et al., 2018). Given this scenario, the Erasmus+ project botSTEM developed a research based didactical framework for integrated STEM education and robotics for early years, with a gender inclusive pedagogy that makes use of inquiry, engineering design methodology, collaborative work and robotics focusing on STEM content that relates to big ideas in science. The didactical model was used to develop teaching material in the form of integrated STEM activities, including robotics. The botSTEM-activities, as well as the theoretical framework, the didactical model, have been translated and are available in the project-partners' languages as part of the published toolkits at the project website botstem.eu. Hence, all activities are available through the interactive web-site of the project. Active teachers in the partner countries also have forums in a Moodle© platform to discuss experiences made during implementations and future teaching.

The preliminary results of the use of the didactical model and the activities in preschool indicate that, despite the fact that many preschool teachers are not used to or trained to teach STEM content areas, integrated, by experimental means and using robotics, the teachers that are working within the botSTEM-activities seem to have adopted key aspects of the framework and successfully applied them. This shows that inquiry teaching and engineering design methodologies can be used with children as young as four years old. So, the activities developed within the didactical framework, associated with the design-based implementation seem promising and potentially useful to improve integrated STEM and robotics teaching and learning at pre and primary school. More detailed analysis of implementations is ongoing and results from the final development of the activities during 2020 will be presented via botstem.eu.

 

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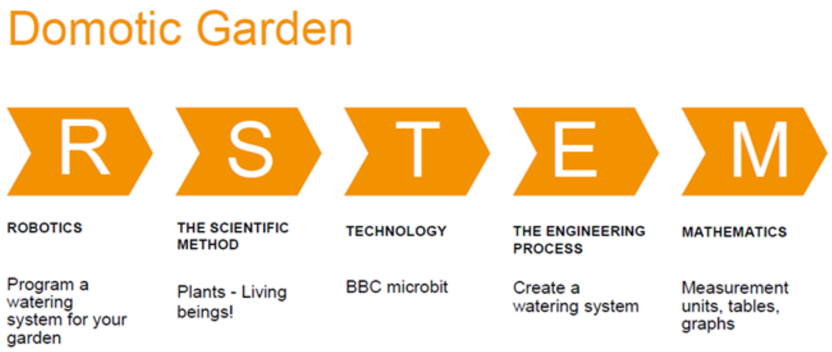
## APPENDIX A: AN EXAMPLE OF A DEVELOPED ACTIVITY




### Concise Description

Nowadays, robots are part of our daily lives. Not only are they in industry but they are also in our houses and schools and they make our life easier. In this unit, kids are called to design and build a 'domotic garden' to grow plants in a more effectively and efficiently way. For that reason, they have to learn about what a domotic system is; how it works and how it can be programmed. In addition, they have to generate their own knowledge about plants following the Scientific Method and how to create a system capable of taking care of our garden. In order to achieve these goals, kids have to apply mathematical knowledge about measurement instruments and units, tables and graphs.

### Observe & Question

At the beginning of the class it is important to encourage a collaborative environment where kids can share their opinions and doubts, where they can work together and where they can generate their own knowledge. For that, it would be a good idea to introduce the concept of 'smart garden' through a piece of news or a video where they can analyze how it works and identify which are the advantages and disadvantages of its use. Boost a dialogue among the members of the class, what do you think about smart gardens? Is it useful? What for? What things/variables can be controlled in your garden with this system? How does it work? Is it related to robots?

Inspire children to talk and discuss more deeply about the variables which must be controlled in a garden such as temperature, humidity, insects, soil, etc. and focus their attention on two of them: temperature and humidity. Help them relate these concepts to their experiences through the evaporation process. What happens to the puddles after raining when the sun shines and the temperature is high? And if there is no sun and the temperature is low?

Introduce a discussion about their experiences and ideas about temperature and evaporation, and talk about how temperature and humidity can be measured. Make sure that the students have understood these concepts properly and then show them a BBC microbit.

### Play & Discover about BBC microbit

Let pupils investigate in groups about what a BBC microbit is, discover how it works and test it. After that, design some activities/challenges to work with this gadget having in mind their previous experiences with programming and specifically with BBC microbit. You can get ideas at: https://microbit.org/

When children feel comfortable working with BBC microbit, guide them in programming a temperature and a humidity gadget. If you consider it appropriate every group can be responsible of only one of them in order to explain to the other groups how they have managed to program it afterwards. Letting the pupils become a "teacher" helps them to consolidate their knowledge and improve their reasoning skills through giving and receiving instructions with peers.

### Design, Experiment & Programme

Once the BBC microbits are programmed it is time to test them. Create bigger groups getting together one which was responsible for a temperature gadget and other for a humidity one and give them two plants with very different needs, such as a cactus and basil.

Encourage children to identify what the plants need to live and use the Scientific Method for it. Firstly, provide them with resources that they can use to find out information about this topic that allows them to define the hypothesis, how much water does the cactus need to live? And the basil? Are high temperatures appropriate for the basil? And for the cactus?

After that, with your support, they must design an experiment to check what conditions of temperature and humidity that these two plants need. They must decide how much water they will use for the plants and where they will be located (both plants of each group must be under the same conditions and these conditions must be different from the rest of the groups in order to compare the results afterwards). One more option to consider is to introduce the concept of sunshine, a new variable which can be measured after programming a BBC microbit as a light sensor.

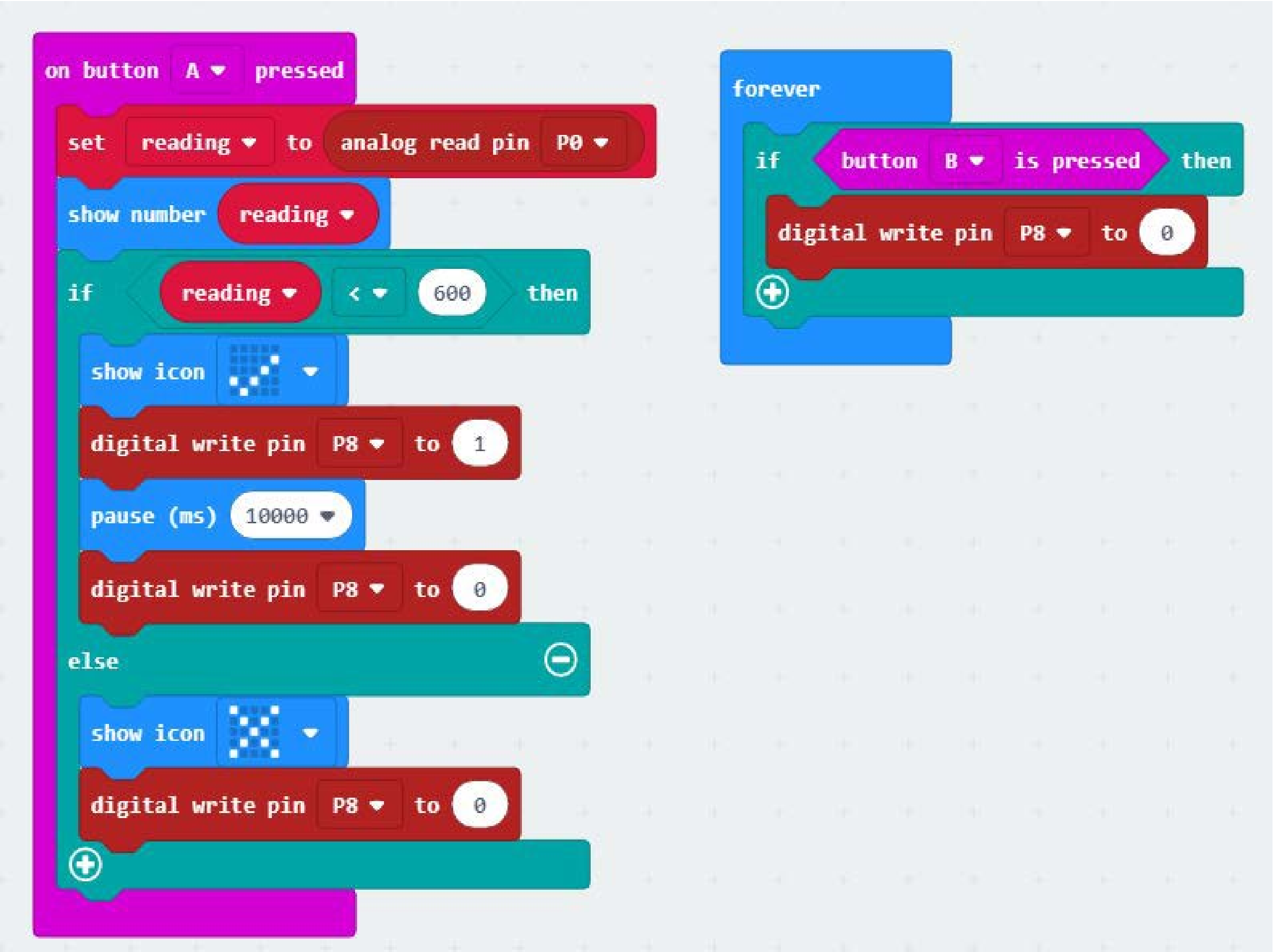
During a week they have to measure the temperature and the humidity of the plants and describe how they are (students can also take photos or draw pictures), have the plants changed their colour or their size? If it has leaves, are they fresh or dry? If it has prickles, are they sharp? Does it have any shrunken part? If you consider it appropriate you can create a poster where kids can write down their results or draw graphics and tables. This will help them compare more easily the results gathered from every group.

After a week the groups must explain their findings to the rest of the class and discuss all together the analyses, the results and draw conclusions. Do both plants need the same quantity of water? Do both plants withstand cold temperatures? What happens to basils when the temperature is high?

A wide range of options can be also included in this inquiry sequence if you consider it applicable for your pupils, such as deciduous and evergreen plants, sunshine and photosynthesis or even the evolution of the plants.

**Engineering Design Process**

When they have defined the best conditions of temperature and humidity for the plants, each group has to choose one to take care of and design a watering system using the Engineering Design Process. Support kids to imagine possible solutions having in mind the knowledge acquired and the gadgets used before and they can analyse the ideas and suggestions proposed so as to choose the most promising one. Provide them the appropriate support to plan how they are going to create the watering system using the plants, the BBC microbit, the water sensors, the pumps and the bowls with water supply and taking into account children coding skills, help them to think and reason how to create the code asking them questions and explaining them each step. Here you have a code for your BBC microbit, but remember: there are a lot of possibilities; this is just an option.




You can find some videos at: https://www.youtube.com/watch?v=jcc5Qae2Cfs

**Evaluate & Share**

Once the watering system is ready it is time to test it and make the suitable improvements. After sharing their knowledge and the key of their prototypes, a discussion can be held, is an irrigation system useful? How it can facilitate people's life? Which other applications does it have? Do these watering systems help preserve natural resources such as water? They can also create a poster, a stop motion video or a slide-presentation that shows with photos, pictures, etc., what are the best conditions for the plant they chose, what happens to the plant when the circumstances are not the right ones and how a watering system can be created.

As a complementary activity you can explore and search what are the cares that the plants would need if they were on Mars and think about how they can grow and take care of them using robots.

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# A Mixed-Methods Approach to Understanding PBL Experiences in Inclusive STEM High Schools

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## ABSTRACT

**Background:** Inclusive STEM high schools employ a variety of instructional strategies, including PBL (problem and/or project-based learning) experiences, with the goals of building students' 21st century skills, facilitating long-term academic success, and encouraging pursuit of STEM careers. PBL approaches are central to the goals of inclusive STEM schools; however, at this writing, no description of the implementation of PBL at these schools exists.

**Material and Methods:** The current study draws on classroom observations and teacher interviews to describe PBL implementation across schools and classrooms. We describe specific instructional practices and classroom behaviors that teachers and students engage in during PBL.

**Results:** Results highlight the multifaceted and multidimensional nature of PBL implementation, and that consistencies in practice do exist across inclusive STEM schools. Additionally, quantitative results show increased use of particular strategies in PBL experiences, as compared with non-PBL classes.

**Conclusions:** This paper provides an in-depth look at instructional practices used in PBL approaches at inclusive STEM schools across the country, and findings have implications for how researchers and practitioners understand and use PBL going forward.

**Keywords:** STEM, PBL, mixed-methods

## INTRODUCTION

The growing emphasis on cultivating students' science, technology, engineering, and mathematics (STEM) skills reflects both societal and workplace evolution in the United States. In addition to needing proficiency in the skills required to carry out their jobs, workers now also need to be technologically competent and able to adapt to changes in work processes and the workplace environment. These changes may require workers to possess skills needed to complete more cognitively-demanding tasks, apply the skills and knowledge to solve complex problems, and work successfully in interdisciplinary and multidisciplinary teams (Heerwagen, Kelly, and Kampschroer, 2016; National Academies of Sciences, Engineering, and Medicine [NASEM], 2017). As such, traditional methods of education, which often rely on rote memorization and recitation of information, are not sufficient to prepare today's students for work (Barron and Darling-Hammond, 2008). Instead, approaches that build 21st century skills, such as communication, collaboration, critical thinking, and creativity, are critical to students' long-term academic success and career pursuits. This is particularly true for preparing students to fill jobs in STEM fields, which are predicted to increase more rapidly over the next decade than jobs in any other sector (Klobuchar, 2014; Committee on STEM Education National Science and Technology Council, 2013; Economics and Statistics Administration, 2017). Changes in education that both provide well-rounded academic experiences and bolster interest in STEM subjects are necessary to create equal opportunities for students of all backgrounds to develop the skills that will help them be qualified to pursue careers in STEM fields.

Policymakers, industry professionals, educators, and researchers have all recognized this need, and inclusive STEM high schools, which aim to increase and expand participation in STEM careers to diverse populations of students, have emerged as one response. Such schools also strive to prepare students for 21st century workplaces more broadly, and are becoming increasingly popular across the U.S. Leaders, teachers, and staff in these schools employ a variety of strategies to enhance students' educational experiences and to prepare students for real-world careers, including PBL, which STEM schools use to refer to either problem- or project-based learning. PBL approaches are an essential component of inclusive STEM school models; however, PBL is a multidimensional and multifaceted construct with no singular definition or method of implementation existing across STEM schools (LaForce et al., 2016). As such, before we can understand whether PBL approaches used in these schools are associated with improved STEM attitudes, academic achievement, participation, or workforce preparedness, it is essential to first describe what PBL looks like in inclusive STEM schools. To that end, the current study uses data from classroom observations and teacher interviews to understand how inclusive STEM schools describe PBL, how PBL is used, and how it differs from traditional instructional approaches in classrooms.

## Inclusive STEM High Schools

STEM-focused high schools have existed in the U.S. for over 70 years (Almarode et al., 2014). These include selective enrollment math- and science-focused schools, which admit students based on prior academic achievement, as well as more recent *inclusive* STEM high schools, which do not impose academic or achievement-related admissions criteria for students. Inclusive STEM schools typically serve a more diverse population of students (Means et al., 2008; National Research Council, 2011), and often focus specifically on increasing underrepresented students' exposure to STEM and preparedness for future STEM careers (Peters-Burton, Lynch, Behrend, and Means, 2014). Recent research also indicates that inclusive STEM high schools strive to prepare students more broadly for life after high school (e.g., careers, or two- or four-year colleges) by focusing on the development of workplace and 21st century skills and engaging students in real-world applications of the content they are learning (LaForce et al., 2016; Means, Confrey, House, and Bhanot, 2008; Young, House, Wang, Singleton, and Klopfenstein, 2011). Providing students with learning opportunities through PBL represents one approach to holistic learning and application of learned skills, and has become so integral that PBL is oftentimes described as synonymous with STEM education (Gorman, 2013; Laboy-Rush, 2011; Miller, 2017) and a trademark of inclusive STEM schools (LaForce et al., 2016; Peters-Burton et al., 2014).

## What is PBL?

Researchers and educators define PBL as either problem- or project-based learning, however, there is no agreed upon definition or operationalization; this is, in part, the motivation for the current study. At a high level, these approaches share underlying principles including learner-centered experiences, inquiry, authentic scenarios, group work, and application of skills. Many of these are echoed in other strategies associated with STEM practices and learning, including, for example, discovery- and design-based approaches, and the Next Generation Science Standards science and engineering practices (Alfieri, Brooks, Aldrich, and Tenenbaum, 2011; English and King, 2015; NASEM, 2018). Teachers in inclusive STEM high schools may employ a range of these in their classrooms, sometimes combining or overlaying strategies in order to best fit the needs of their students as well as their own beliefs about effective teaching—this again points to the need for clear descriptions of what is happening in schools before attributing positive (or negative) outcomes to a singular approach.

Here we highlight foundational project- and problem-based learning literature, although in practice, we find that inclusive STEM high schools often use these terms interchangeably, or that some schools indicate they are doing "project-based learning" that closely aligns more to some definitions of "problem-based learning," and vice versa. . Given the shared emphasis on student autonomy, connections to real life, and teamwork, we operationally define "PBL" as having components rooted in both well-known project- and problem-based learning definitions.

*Project*-based learning is often considered to be derived from Kilpatrick's Project Method (1921), which has been a cornerstone of institutions such as the Buck Institute for over 25 years (Buck Institute for Education, n.d.). Scholars agree that project-based learning is student-centered, connected to the real world, and framed around meaningful and authentic questions or problems, which involves students engaging in inquiry processes over an extended period of time (Brassler and Dettmers, 2017; Buck Institute for Education, n.d.; Holm, 2011). However, researchers and educators are not in complete agreement regarding the implementation of project based learning.

 

For instance, some scholars believe that projects culminate in a final product (e.g. Holm, 2011; Savery, 2006), and in some cases, a *public* product or presentation [Buck Institute for Education, n.d.]), whereas others specify that projects should not end in a predetermined outcome (Thomas, 2000). Moreover, the Buck Institute (n.d.) specifies that project-based learning experiences should include goals related to learning content *and* specific skills, such as critical thinking, problem solving, communication, collaboration, and self-management, and that students and teachers should engage in reflection on their learning experience throughout the project; these criteria are not necessarily specified as mandatory by other researchers and educators engaging in project-based learning.

The concept of *problem*-based learning is first found in medical education models originating in the mid-20th century. The approach was developed to provide students with student-centered and multi-disciplinary curriculum that would facilitate application of knowledge in clinical settings (Boud and Feletti, 1997; Savery, 2006). Despite arguments about its effectiveness, problem-based learning approaches grew in popularity in medical schools in the US, Canada, and Europe during 1980's and 90's, followed by their adoption in universities and expansion into the K-12 educational space more recently (Savery, 2006). Problem-based learning posits that learning experiences should be learner-centered, integrate theory and practice, and require students to conduct research and apply knowledge to solve ill-structured problems (e.g., Brassler and Dettmers, 2017; Savery, 2006). Implementations of problem-based learning typically require students to solve an existing or plausible real-world problem (Torp and Sage, 2002). Some PBLs use problems that have a single finite solution, whereas others indicate that the problem at hand should be complex and without a single, correct solution (e.g., Hmelo-Silver, 2004). In addition, some scholars list the integration of disciplines or subjects as a necessary characteristic of problem-based learning (Barrows, n.d., in Savery, 2006), whereas for others, and in practice, this criterion is not always present. Problem-based learning experiences vary in time-frame (one day, three weeks, or five to six problems per semester), but are often shorter than project-based learning experiences (Brassler and Dettmers, 2017; Mergendoller, Maxwell, and Bellisimo, 2006).

Research examining the effectiveness of PBL approaches for improving student outcomes indicates similar positive outcomes, whether defined as project- or problem-based. Specifically, both have been found to result in improved skills related to communication and collaboration among students (Allen, Duch, and Groh, 1996; Bell, 2010; Baumgartner and Zabin, 2008; Cheng, Lam, and Chan, 2008; Lou, Shih, Diez, and Tseng, 2010; Mergendoller et al., 2006; Mioduser and Betzer, 2007), critical thinking and problem solving skills (Albanese and Mitchell, 1993; Ertmer, Schlosser, Clase, and Adedokun, 2014), students' ability to self-direct (Albanese and Mitchell, 1993; Bell, 2010; Norman and Schmidt, 1992), and student engagement and enjoyment (Albanese and Mitchell, 1993; Baran and Maskan, 2011; Baumgartner and Zabin, 2008; Faris, 2008; Hmelo-Silver, Duncan, and Chinn, 2007; Vernon and Blake, 1993). Furthermore, project and problem-based literature has identified benefits for low- and middle-achieving students, and for students from ethnically- and racially-diverse backgrounds (LaForce et al., 2019; Han, Capraro, and Capraro, 2014, Mergendoller et al., 2006; Tal, Krajcik, and Blumenfeld, 2006).

Despite the benefits that PBL seems to provide for diverse populations of students, it is difficult to draw conclusions from the extant research investigating "PBL," as implementations of vary widely. Savery (2006) noted that "misapplications and misconceptions" (p. 11) of problem- and project-based learning have occurred as their use has expanded across disciplines and levels of education. Because this is the case, it is not only important but necessary to investigate implementations of PBL in practice, and within specific contexts, to better understand if, when, and how PBL contributes to desired student outcomes.

## Current Study

In the current study, we sought to examine the specific practices involved in PBL experiences in inclusive STEM high schools to gain a deeper, more-contextualized understanding of how teachers engage their students in PBL in the classroom. We were interested in describing PBL implementation in practice, and the specific instructional practices that teachers and students engage in during PBL experiences. As such, the current study investigated the following research questions:

1. How do teachers describe PBL? Are there common instructional practices described across teachers?
    a. How do teachers describe the goals, benefits, and challenges of these instructional practices in the context of PBL?
2. Are there differences in the frequency of these instructional practices in PBL and non-PBL class sessions?

To answer these research questions, we investigated instructional practices identified across the literature and by interviewed teachers in the current study as central to PBL experiences; these included teacher facilitation of cognitively demanding work, student autonomy and risk-taking, student cooperation and teamwork, and making connections across disciplines and to real-world content. As teachers are the primary facilitators of PBL-based curricula and learning opportunities for students, their first-hand perspectives provide rich descriptions of these instructional practices. These were explored through semi-structured teacher interviews which elucidate interindividual differences and variations in teachers' descriptions of PBL instructional practices in inclusive STEM high schools. Additionally, differences in the presence of such practices between observed PBL and non-PBL classroom experiences (classified by researchers) were quantitatively examined. In these ways, this study can help understand and differentiate PBL implementation in a way that may be underestimated in large-scale, group-level analyses (Molenaar and Nesselroade, 2015).

## METHOD

### Participants

Interview and observation samples were drawn from 12 inclusive STEM schools located across the U.S. enrolled in a larger National Science Foundation-funded study (see LaForce et al., 2016 for a summary). Schools were selected as a representative sample of schools to participate in on-site data collection, which consisted of a four day visit by two researchers to each school.

**Interview sample.** The interview sample of 64 teachers was created by randomly selecting three to five teachers from each school. Forty-four of the teachers that participated in an interview were also observed (27.7% of the total number of classrooms observed). Teachers were not asked to provide demographic data during interviews; as a result, demographic information is not known and not reported.

**Classroom observation sample.** The sample was composed of 129 classroom observations conducted at the same 12 inclusive STEM schools. Approximately half of the observations were of classrooms composed of a relatively equal number of males and females (54.8%) and mostly white students (48.8%). All grades ($n$ = 35; 28.9% only-10$^{th}$ grade student classes) and achievement ($n$ = 105; 81.4% "regular-level" classes) levels were observed. Observations ranged in length from 25 to 180 minutes ($M$ = 72.67, $SD$ = 28.79 minutes) and included classrooms of 6 to 70 students ($M$ = 20.90, $SD$ = 9.21 students). The majority of observed classes were STEM discipline courses ($n$ = 85, 72.6%). Researchers were instructed to classify an observation as a PBL experience if a) the teacher or students vocally articulated it as such (i.e., the teacher categorized the lesson as PBL), b) the lesson/activity included a tangible problem (as solving problems is a key feature in definitions of PBL in literature, as cited above), or c) the lesson/activity was comprised of several tasks that built upon each other over time (again a feature of PBL cited in literature, this also served to distinguish PBL lessons from those than asked students to solve, for example, a single applied or real-life math word problem); researchers coded 37 (28.7%) observations as PBL projects/experiences.

### Procedure

**Teacher interviews.** During the on-site data collection period, teachers were invited to participate in interviews investigating experiences with STEM school instructional practices, including, but not limited to, PBL. Participating teachers were selected by schools points-of-contact (a school leader, teacher leader, or teacher identified during school recruitment to assist with data collection), who were asked to recruit at least one teacher from each grade level, with three to four teachers having their primary teaching duties in STEM subjects. Points-of-contact were instructed to select teachers randomly within these parameters. Interviews were, on average, 60 minutes in length, with all interviews audio-recorded and transcribed by the research team. Teachers were incentivized $50 (as Amazon.com cards) for their participation.

**Classroom observations.** Seven coders completed classroom observations at the 12 schools. Classrooms were selected by the schools' points-of-contact to represent a cross-section of grade-levels and disciplines; each point-of-contact was asked to schedule 10 classroom observations, with at least 2 per grade level (9-12), spanning all disciplines but with a focus on STEM, and including relevant non-academic but core classes (such as advisory) as appropriate for each school. All classroom observations in the current sample were academic classes (core classes and academic electives). Seven classroom observations were double-coded (5.3%) and adequate inter-rater reliability was established across coders (.75-.84; ICC 95% CI: .07-.97, $p$ = .02). Teachers were not incentivized for classroom observations, as these were part of the typical teacher work day.

### Measures

**Teacher interviews.** A semi-structured interview protocol was used to collect data on instructional practices and teacher experiences at inclusive STEM schools. The protocol largely focused on PBL and how teachers think about and incorporate PBL experiences into their instruction. For instance, teachers were asked to describe what PBL looks like (e.g., *Could you describe PBL in your experience at your school?*; *What makes PBL "good" or successful?*), how PBL projects are carried out in the classroom (e.g., *How do you plan PBL projects? Do you work with other teachers or teachers of different subjects?*), and how they impact students' learning (e.g., *How can you tell whether PBL is successful?; How are students graded or scored on PBL?*).

 

**Classroom observations.** All items were scored using a three-point Likert-type scale with values ranging from 1 (*behavior not present*) to 3 (*behavior is present*); these same items were used for both PBL and non-PBL lessons. Each construct represents a category of classroom behaviors identified as central to inclusive STEM high school models (LaForce et al., 2016) and focused on by teachers as elements of their PBL approaches. Average scale scores were computed across items measuring each construct to represent the extent to which each behavior was present during the classroom observation.

***Cognitive demand.*** Eleven items were used to assess the level of cognitive demand and challenge present (e.g., *Teacher asks students to reason and support their conclusions with evidence;* $\alpha = .79$).

***Student autonomy.*** Five items were used to assess the degree of student autonomy and independent learning present (e.g., *Teacher gives students opportunities to make choices that significantly shape their learning experiences;* $\alpha = .76$).

***Student risk-taking.*** Four items were used to assess the degree of student risk taking present (e.g., *Teacher encourages students to answer questions when they are unsure;* $\alpha = .70$).

***Integration of concepts.*** Four items were used to assess interdisciplinary connections that were made (e.g., *Teacher points out connections between the content of the lesson and other disciplines;* $\alpha = .82$).

***Real world connections.*** Four items were used to assess the extent which connections to real-world scenarios in the students' lives were made by both teachers and students (e.g., *The teacher connects activities to the students' lives;* $\alpha = .79$).

***Student cooperation and teamwork.*** Six items were used to assess the presence of student cooperation and teamwork (e.g., *Teacher encourages students to collaborate;* $\alpha = .86$).

### Analytic Strategy

**Teacher interviews.** Teacher interviews were subject to inductive and deductive qualitative analysis in HyperResearch software to identify salient PBL instructional practices described by teachers. Qualitative coding began with a directed (deductive) content coding analysis. The first and second authors developed a list of content codes relevant to PBL instructional practices (e.g., cognitively demanding lessons, student autonomy, interdisciplinary content, connections to real-world scenarios) and a codebook outlining definitions for each. Thirteen interviews (20% of the overall sample) were double-coded, after which the first and second authors met to discuss the application of the codebook and areas of disagreement. Adjustments to the codebook were made, and all discrepancies were resolved so that 100% agreement was achieved. The first and second authors divided remaining interviews and coded them using the updated version of the codebook. During this coding, conventional content coding (inductive) was also used to identify emergent sub-themes. Since teacher interviews included discussions of both PBL and instruction more generally, researchers coded *only where it was clear that the teacher was referencing PBL.* Throughout the coding process, the first and second authors wrote detailed memos of their reflection on how codes were related and should be synthesized into broader categories (DeCuir-Ginby, Marshall, and McCulloch, 2011).

**Classroom observations.** A series of independent samples t-tests were used to examine mean differences in the presence of classroom behaviors central to the success of STEM schools across classroom observations classified as PBL versus non-PBL projects/experiences.[1]

## RESULTS

### Teacher Interviews

In their descriptions of PBL, a wide variety of approaches and implementations were discussed by teachers. However, a number of instructional practices emerged as most prominent across schools and academic subjects: student autonomy, student cooperation and teamwork, integration of subjects, real-world connections, and cognitive demand. Each of these and associated themes and findings are discussed below.

**Student Autonomy.** Of the 64 teachers interviewed, 43 (67.2%) discussed student autonomy in the context of PBL, with 114 references in total. Their responses can be organized into three sub-themes, discussed below.

***Student independence.*** Teachers valued students' development of independence, and they reported that PBL experiences served as a mechanism by which students could become 'more independent.' Teachers also noted that over time, through using PBL, students became more autonomous in their learning and teachers were able to shift from a role of information provider to facilitator. As one teacher described it,

[1] This approach was chosen instead of conducting a series of one-way analysis of covariance (ANCOVA) tests or a multivariate analysis of variance (MANOVA) due to the overall sample size of classroom observations ($N = 129$) and because of the relatively small sample size of classroom observations labeled as PBL project/experiences ($n = 37$).

 

> "that's basically how it looks [in PBL], a lot of independent learning, at the same time with the guidance and the support [of the teacher] in the classroom."

***Student-led learning.*** As students' autonomy increases over the course of their high school years, teachers described giving students more responsibilities for leading. This was reported to happen in a number of ways. One teacher discussed how she '…get[s] the students to where they're running the class' whereas others references involving students in the selection and design of projects themselves. Another teacher echoed these comments,

> "So it's kind of shifting who's developing our objectives for the day. That's a major shift from like, 'I'm telling you the objectives, you're going to learn it', to, you have questions, you tell me what you want to learn, and we'll see if we can come together to provide an experience for you."

Student-led learning allows students to 'figure it out,' which was noted as critical in PBL. Teachers reported that they strive to have

> "every single [project] always [be] student-centered, student-driven, [where] they get to brainstorm, they get to plan. And they have to solve the problem."

***Students make choices.*** Both processes (i.e., student independence and student-led learning) require students to make choices about what they want to learn and how they will learn. Having the ability to make choices allows students to drive their own instruction, which teachers noted as central to successful PBL. One teacher mentioned that he has

> "a list of projects and [I] let the students choose so that I don't have everybody doing the same project [because] that's boring. Boring for me, boring for them."

Though teachers reported that stepping back to take on the 'facilitator' role can be difficult at first, they also said that they

> "never having a problem with letting them [the students] choose. The moment I started letting the students choose what they like and what's personal to them, the projects got way better."

Overall, findings reflect teachers' belief in the importance of developing students' confidence to direct and manage their own learning, and that PBL serves as an avenue in which they can foster these behaviors.

**Student Cooperation and Teamwork.** Teachers also often discussed the importance of group work and having students work together collaboratively (140 responses by 48 teachers; 75% of the sample). Two major emergent sub-themes are discussed.

***Helping students learn to collaborate.*** Teachers were largely in favor of students working together in groups or pairs, often noting that this was a major feature of their PBL projects. However, teachers also described a type of 'true' collaboration—not just being in groups where the work gets completed separately and then pieced back together into a final product—that was seen as a skill in and of itself, and one that must be built over time:

> "That's part of the maturity going from a 9th grader to working collaboratively. What they see as collaboration is not really what we want it to be (…) So we're teaching and trying to show them a skill. It's a process that's really ongoing."

Another teacher echoed this point:

> "[our principal] loves to say the freshmen love to be together, but not *work* together. So we're helping them learn to work together."

As one example of this, many teachers reported choosing groups for students, rather than letting them select their own groups, at least initially. Teachers did this often based on students' interests, but also stressed the importance of students learning to work with others who were not their friends or students who they did not necessarily choose to work with. This was discussed as a way to encourage collaboration skills like 'the ability to collaborate with people that you don't necessarily choose to work with.' Over time, when students had more practice with PBL and peer collaboration, more flexibility was built in. Teachers similarly described scaffolding students' learning in this area by having groups write contracts, again particularly with students early on in their high school careers:

> "They articulate the leadership style they're going to use, the decision-making model they're going to use, the norms on the team, how they're going to resolve conflict on the team. Everybody signs the contract in the group, they get it checked by me, and then they start the design process."

Part of the need for this type of scaffolding came from teachers' conception that collaboration not only encompasses a set of skills necessary for successfully completing PBL projects from start to finish, but also for students to have generally. One teacher noted that

> "collaboration has many subskills like how to make decisions, clear communication, specific, precise, conflict mediation and negotiation, document[ation]. So there's all these subskills that go with project management and collaboration."

These skills, teachers noted, are 'almost equally important' to the content being learned. As a whole, these findings highlight that group work and collaboration with classmates is not only an existing skillset that can be *applied* in PBL projects, but one that can be learned *through* PBL.

***Students teaching each other through group work.*** One particular skill related to collaboration and group work that teachers often discussed was students' ability to mentor, provide guidance, and/or teach fellow group members. These were noted as components central to successful PBL. As one teacher stated,

> "With the PBL projects you can, for some of the content workshops, you can break the students up, they don't always have to be in their teams. But then they're in their teams so the stronger students can help the more struggling students."

Several teachers referenced Vygotsky's Zone of Proximal Development (Vygotsky, 1978), saying that they try to group students so that 'everybody raises up' in some way. "I… set it up in teams," one teacher said, so that

> "all my kids who need the extra help are sitting with someone who can provide it, and that really helps a lot. Then the person providing the help is going to an even higher level."

In these scenarios, support of student collaboration helps students take shared responsibility for the task or PBL project, and their overall learning as well, rather than relying on their teachers for help or as the one authority. Another teacher underscored this point, saying

> "There's a saying that there's no better way to learn than to teach it. That's definitely the case here, and that's one of the beauties of the way we do PBL. With the kids working in groups, they do teach each other all the time and they're a lot more willing to listen to each other as opposed to the teacher standing up in front of the class and lecturing all the time."

**Integration of Subjects.** Many teachers (46 teachers; 71.9% of the sample; 110 responses total) noted that PBL provides a good way to incorporate interdisciplinary instruction and the integration of content across subject areas. When disciplinary content is integrated, students are able to make connections to understand how such subject areas reinforce and complement each other. Teachers described integrating disciplinary content in three ways, described below.

***PBL across multiple classes.*** Teachers at a number of schools described PBL projects which included content from multiple classes. A number of teachers at different schools described doing this by looking at the standards for commonalities across disciplines, and building out a central question or project from there. In some cases, these types of projects happened at the same time in all subject areas, while in others, teachers described projects that "moved" from class to class over the course of a semester:

> "The manuscript project was between myself and the chemistry teacher and the math teacher. In chemistry, they [the students] came up with the study they were going to do - they did it in their class - and they analyzed it in math, and then they brought all of that information into my class and put it into manuscript form to try to submit to a journal."

Certain structural elements of the school contribute largely to the feasibility of a multi-class approach to integrating disciplinary content in PBL. For instance, structuring PBL so that students are able to work on the same project in multiple classes throughout the academic day is possible only when teachers share the same group of students. As one teacher noted,

> "When we started STEM, we were in a full-year long class. Everyone had me for biology and [another teacher] for social studies. There was an entire team that shared the same kids… Now we are double-block. We don't share the same kids. Something we are struggling with here is to keep the STEM identity,

what STEM is, cross-disciplinary units, modules, whatever… [because] we don't share the same kids at the same time."

***Co-teaching for subject integration.*** Teacher collaboration, co-teaching, or team teaching allows teachers to collaborate in order to deliver interdisciplinary content to students. This was sometimes described as being done through hybrid classes (e.g., biotechnology or environmental science classes combining social studies and science). One teacher highlighted how subject integration contributes to students' learning of real-world content in PBL, stating,

> "Both of my classes are co-taught across disciplines, which is important because in the real world disciplines aren't silo-ed. So with a collaborating teacher we look at where our standards overlap and come up with a curriculum map of usually eight to ten projects per year."

A second teacher supported this idea:

> "In bio and tech, the technology is really skills and a means to communicate or means to solve a problem. So the content is almost all biology, but then the students are maybe designing or building a microscope or building a gel electrophoresis or they're creating a Mixonium [presentation]. So there's a way that technology kind of serves the content."

***Integrating content within classes/disciplines.*** PBL project experiences may also be structured to encourage students to incorporate knowledge and skills from multiple disciplines within a single class. Teachers felt that 'it's better to integrate than to not,' and that it's important to 'just [bring] that emphasis out for them [students].' When describing PBL projects that focused on a single discipline or occurred within a single class, teachers often noted trying to be explicit about and draw students' attention to the connections to other content areas, and working to help students make these connections themselves.

***Challenges with integrating content.*** While even teachers who reported *not* integrating content into their PBL projects considered integrated projects to be ideal, a number of challenges to doing so were noted. Teachers discussed how time constraints and limited opportunities to enact collaborative teacher planning adversely impacts their ability to incorporate interdisciplinary instruction during PBL. For example, one teacher said,

> "[W]ith the time available to us to schedule that kind of stuff [PBL] and the way that kids are scheduled with the blocks, there's no other teacher that I share all the same kids with now. So it [subject integration in PBL] just doesn't work out well."

Teachers also noted how subject integration is ultimately tied to successful cross-department collaboration amongst one's colleagues, which can be a challenge generally. Another teacher highlighted this point when discussing how, at his school, the teachers 'usually can do [a] really good connection with four out of the five [subject areas];' however, without collaboration from all teachers, they do not feel '…like they have a really good piece of that project.'

Thus, even when there is opportunity and time for collaborative teacher planning, creating interdisciplinary PBL projects can be challenging. These teacher responses indicate that subject integration in the context of PBL projects is largely dependent on having time and structures in place to support cross-discipline collaboration.

**Real-world Connections.** Making connections between the real world and the work being done in PBL projects was the instructional practice most frequently referenced by teachers (62 teachers; 96.9% of the sample; 278 responses total). Teachers' responses can be categorized into two broad themes: 1) strategies by which real-world connections can be made, and 2) differentiating between making *content* connections in projects and making connections to the real world via skills/processes that students will use in the real world.

***Strategies to make real-world connections.*** Teachers primarily discussed three important strategies that can help students make connections to the real world during PBL projects.

*Involvement of external partners.* Cultivating relationships with external partners is a central feature of inclusive STEM high schools (LaForce et al., 2016). Schools work with partners to create a presence in their communities, and to provide opportunities for students to apply skills learned in the classroom to real-world settings. Teachers talked about a number of ways in which local community members support their implementation of PBL; for example, one teacher said that

> "community members judge my mock congressional hearings. We also have community members come in and judge the debates."

This role of partners as an external audience for students' final PBL products or presentations was described by a number of teachers across STEM schools. Teachers also referenced how outside partners can support students' ability to make real world connections by visiting classrooms and 'speaking about their particular field or just how to be successful.'

Other teachers described more in-depth involvement in PBL projects by partners, from providing the context for a project to co-design and high levels of collaboration with teachers throughout. Partnerships were not limited to interactions with local businesses, but also extended to partnerships with individuals and groups in higher educational settings, including community colleges and state universities located in the greater community. One teacher discussed a successful partnership with a biology professor from a local university, and how the partnership is continuing to the benefit of his students:

> "He [contact at the university] said, 'I think we should talk about micelles because one of my projects is, I work on drug delivery systems using these things called micelles. There's a polar and non-polar piece and you can talk about hydrogen bonding and covalent bonding, everything you wanted to talk about, in a very authentic context'. And he [contact at the university] said, 'I can supply you with all the polymers and some grad students, and they can come out, and they can work with your kids". It was just beautiful so we've been doing it like every year."

Another teacher referenced the importance of such partnerships for his students' college readiness and exposure to STEM-related careers prior to selecting a college major:

> "[W]e have huge partnerships with places in and out of Columbus, [Ohio]. They helped us create the curriculum, so we want to keep them involved. You [the partnering organization] have problems, can these kids help work on these problems? Is there an internship opportunity? Students can see things they like and don't like prior to heading off to college."

A major benefit of such partnerships noted by teachers was that they can 'help kids get internships, [which is] a big thing.' Connections to the real world in PBL through external partnerships have tangible benefits to students not only during the course of a given project or even their high school careers, but also as they move forward through their lives and academic careers.

*Real-world needs in the community or school.* A number of teachers indicated that PBL experiences which engage students in projects or problems that are tied to actual events or problems happening around them—in their schools, their communities, or in the world—while often the most difficult to plan and execute, are the pinnacle of PBL projects. One teacher talked about the importance of

> "making it relevant to a real-world problem that is occurring today. It is not just a textbook problem. A lot of the things we have done previously in the 10 years I have been teaching, they are just synthetic. You make up, here's a scenario, but it doesn't have a real-world connection. Here's a scenario I make up, I know it's fake; the kids know it's fake. But they will work through it, but it doesn't have the same sense to them."

Relationships with external partners often helped to facilitate these types of projects, particularly when they centered on problems or needs outside of the schools themselves. For example, one teacher described a project in which

> "We're collaborating with farmers in Léogâne, Haiti to try to do sustainability projects. They're [the 9th grade students] designing solar fruit dryers that we go and implement and will actually happen… I take students to Haiti every year and we go do these projects with our sister school in [the] little community [there]."

While many schools may not have the resources to send students to another country, other teachers described similar real-world PBL projects taking place within the school. One described a project that arose out of a simple classroom need:

> "I have a 3D printer in my classroom. It's just sitting on a table, a very unsteady table. There's a spot in the back corner of my classroom where it would fit, but there's no table there. My students are designing a table. So basic ideas like, 'Hey, I need that designed.' The kids can do it."

Teachers also discussed engaging students in outside academic competitions as part of their PBL experiences as an authentic and motivating way to connect to the real world. One teacher described how his students participated in

> "a national competition, called CyberPatriot …out of the Air Force, and what they [students] do is they can go in and take out malicious code. So we're on the good side of hacking."

In all of these examples, there exists common theme of students not only connecting content they are learning *to* the real world, but producing meaningful work products that are *actually being used* or applied, whether in their classroom, their community, or across the world.

*Theoretical real-world problems or projects.* Realistically, not all PBL projects can be directly connected to a problem faced in the school or community; some projects are better represented as hypothetical scenarios to be investigated in greater depth. Teachers referenced the importance of hypothetical scenarios in that they help shift students' mindset regarding their academic purpose and potential. For instance, one teacher believed that posing hypothetical problems to students in PBL

> "gets them to step out of the 'I'm a STEM student' [and, instead gets] them to think 'I'm a researcher called in by the CDC' or 'I'm an inventor' or 'I'm a game designer' or building robotics. We don't want them to think they're just a student, and 'my presentation is just for my teachers.'"

Another teacher similarly discussed a scenario he presented to his students in which he told them,

> "You're a member of an engineering firm who's been tasked with designing x, y, z for this customer. Here are the requirements. Here are the materials that you have available."

In this type of PBL, students have to apply the skills they have learned when presented with a hypothetical situation that they may one day encounter in actuality.

***Skill/process connections versus content connections*.** When discussing how PBL experiences connect to the real-world, teachers highlighted two different ways that those links are made: first, through content that is rooted in real world scenarios, and second, through connecting skills that students will need in the real world. The first category includes projects like those mentioned above, where students are solving problems that are actually occurring. Many teachers described making these types of connections, and the importance of 'authenticity' of the content they include in PBL projects. However, teachers also noted that

> "so much of [what they learn from PBL] is not even content based, it's just the actual real-life experience. Preparing them to actually be productive outside of school and in the future."

This preparation included skills that teachers felt would be important for students in the workplace in particular, such as communication and collaboration (as discussed above), work processes, relationship building, and working to meet expectations. For example, one teacher described changing the structure of his rubrics to better align with how performance expectations are communicated in jobs:

> "For the overall project I have done away with the category of 'emerging'. I don't think that's useful at all (…) My argument for that is that we strive for authenticity. I've never had a job [where my boss said], 'Here's your rubric. Look, it's your emerging column. If you do this you're only going to get three quarters of your pay.' I want them to know, here's my expectations. If you don't meet them, you're going to fail. If you go above and beyond, you're going to get a better grade."

These skills may be taught in many ways, but many teachers noted that they could be done especially well through PBL projects. As one said,

> "one of the big parts of a PBL that's good is that you combine a lot of different things to kind of solve one problem, [and] that's what you do in the real world."

**Cognitive demand.** Rigorous learning is central to inclusive STEM school curricula (LaForce et al., 2016), and teachers reported that this approach is no different in PBL (124 responses by 45 teachers; 70.3% of the sample).

***Rigorous and challenging content rooted in academic standards.*** Rigorous and challenging content engages students in higher-level, critical thinking. When asked "What makes good PBL?," one teacher stated that "I would always start with rigorous content, because that to me is very important." Such content, teachers described, is often derived from and aligned with academic standards set forth by the district, state, or nation. Indeed, one teacher stated, "If you go way back, it always starts with standards." Other teachers supported this idea, with one noting that

> "to just do a project to do a project isn't that meaningful, but to do a project to build on a learning goal or to build on a standard is what we're trying to look for."

**Table 1.** Descriptive statistics and correlations for key study variables

| | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1. Cognitive Demand | - | .31** | .49*** | -.02 | .10 | .33*** |
| 2. Autonomy | | - | .29** | .12 | .25** | .43*** |
| 3. Risk-taking | | | - | -.05 | .07 | .23* |
| 4. Integration of Concepts | | | | - | .29** | .09 |
| 5. Real-world Connections | | | | | - | .12 |
| 6. Student Cooperation and Teamwork | | | | | | - |
| M | 1.01 | 1.00 | 1.35 | .18 | .50 | 1.32 |
| SD | .44 | .63 | .49 | .41 | .61 | .61 |

*Note.* * $p < .05$, ** $p < .01$, *** $p < .001$

Thus, PBL projects must achieve what one teacher described as 'evidence of learning,' and also maintain academic rigor and challenge.

***Higher-level/critical thinking.*** Achieving this balance in PBL is possible through an emphasis on the development of critical thinking skills. Teachers were in agreement on this point: "I like to focus on, in my class, the higher-level thinking." As such, 'expanding their [students'] cognitive processes' is central to completion of complex PBL projects as well as students' overall academic achievement. One teacher elaborated that critical thinking in PBL helps students 'to think about all the ways content or the project impacts themselves, the world, politics, whatever.' Through PBL, teachers reported '[p]ushing them [students] to that higher level [of thinking]' that 'accelerates their learning.'

***The scientific method.*** Underscoring the development of critical thinking skills and focusing on more-advanced, higher-level problem-solving in PBL directly connects to engagement in the scientific method. Carrying out the scientific method requires students to 'do research in [their] area,' as well as to 'make a claim and back it up with evidence.' This process allows students to build skills related to data collection, research design, statistical analysis, and citing sources, particularly important in STEM disciplines. For instance, one teacher highlighted how PBL projects provide a context for the students to practice and enhance their research skills through the scientific method, and that this process evolves over the course of high school students' academic careers in STEM schools;

> "[In PBL] we'll research skills and documentation of evidence, so that they're (...) looking at a community problem and looking at solutions for that problem and advocating for that, that they have the data correct and they know how to cite that data and use the correct sources. That's still a problem by 12th grade. Just that basic research on that. So those skills would include the writing skills in a research paper, the development of a thesis, and using reliable data, not just WebMD. That still happens. The other big skill, besides the research, is then the cohesiveness or synthesizing the data. Then also looking for solutions on that."

### Differences in Instructional Practices in PBL and Non-PBL Classrooms

Understanding how teachers described their PBL practice, we also explored whether these instructional practices were more prevalent in observed PBL classes than non-PBL ones. Results of a series of independent samples t-tests indicated that class sessions classified as PBL experiences had a higher presence of student autonomy ($t(123) = -4.43$, $p < .001$), integration of concepts ($t(39.29) = -2.19$, $p = .04$), and student cooperation and teamwork ($t(87.37) = -3.29$, $p = .001$) compared to non-PBL class sessions. No significant differences emerged between class sessions classified as PBL versus non-PBL experiences for cognitive demand, student risk taking, or real world connections. Descriptive statistics and correlations for key study variables are presented in **Table 1**.

## DISCUSSION

Overall, these findings contribute to understandings of what "PBL" means in the context of inclusive STEM schools—what instructional practices teachers are using, as well as, from the interviews, why and how. As noted earlier, specifications in the definitions of PBL in the literature and in implementation in schools vary (e.g., Brassler and Dettmers, 2017; Savery, 2006). Therefore, in order to ultimately determine if PBL approaches are working in these schools, there is a need to be clear on what exactly PBL in inclusive STEM schools means. This is not to imply that PBL will or should look the same at every school or in every classroom—one of its strengths, in fact, may lie in its flexibility and adaptability to different disciplines, school structures, and groups of students—but our findings show that there are common features of PBL most prevalent or important to the teachers implementing it in the inclusive STEM school context, and that these do differ in some important ways from what is seen in classrooms *not* employing PBL.

In our interviews with teachers, student autonomy, student cooperation and teamwork, integration of subjects, real world connections, and cognitively demanding work emerged as critical to teachers' conceptions of PBL. These findings were echoed in what we saw in practice, as in classrooms using PBL, compared to those that were not, we saw significantly higher levels of student autonomy, student cooperation and teamwork, and integration of subjects. These findings generally support the definitions and common elements of PBL found in the literature, which characterize it as student-centered and driven, often including group work, interdisciplinary, and closely connected to the real world (Buck Institute for Education, n.d.; Brassler and Dettmers, 2017; Savery, 2006; Torp and Sage, 2002). They go further, however, in describing in detail what these practices look like for teachers and students in inclusive STEM high schools, and why PBL serves as a valuable method for implementing them.

The ideas of student autonomy and students' ability to work in teams may seem like opposing ones, however, both came through as important practices in PBL, and in teachers' descriptions, it is clear that they can be considered two sides of the same coin. Both involve students developing understandings of their learning styles, needs, and strengths, and the self-confidence to make decisions and follow through on them. For autonomy, this manifests in managing their time and their work, making choices about the learning processes that work best for them, and working without direct oversight to accomplish their tasks. In working with groups, this facilitates understanding where they can contribute and where they can benefit from the support or skills of their peers, and moving towards the true collaboration (rather than a "divide and conquer" approach to group work) described by teachers as the goal. Through PBL, teachers incorporate more practices that help students learn to both depend on themselves and navigate the challenges of having to depend on others. These skills of self-regulation, self-direction, and teamwork are also considered central to both problem- and project-based approaches in the literature (e.g., Savery, 2006), showing that there is consistency in the understanding of the 'essence' of PBL.

Our findings also stress PBL as a vehicle for contextualizing learning and knowledge—in the "real world" and as situated across disciplines, rather than siloed within them. Teachers described various strategies for accomplishing both, emphasizing that grounding the content and the learning processes in these ways makes the experiences more meaningful for students. Additionally, having students apply what they are learning in real-world scenarios, in the actual world, and across their classes helps combat the stereotypical student lament of 'when am I ever going to need to know this?' as it demonstrates for students how what they are learning can be used. More meaningful experiences, teachers felt, promote student engagement and deeper learning.

None of these types of learning or skills (i.e., autonomy, collaboration, or contextualized learning) are unique to PBL, or can only be accomplished through PBL. However, the quantitative data collected in our classroom observations suggests that teachers more often use instructional practices to facilitate and build student competencies in these behaviors when teaching using PBL than with traditional methods of instruction. Given the variety of ways in which teachers described their approaches to them, it may be that PBL provides a framework that at once emphasizes the importance of these components and allows enough flexibility for teachers to incorporate them in ways that are feasible in their contexts or in which they feel most comfortable. One critique of PBL has been that while it has been shown promote the development of these types of 21st century skills, as well as student interest and engagement, there is less evidence of its effectiveness in delivering content (Strobel and van Bareveld, 2009). Our findings challenge this, as teachers consistently described a specific focus on incorporating rigorous content into their PBL experiences for students, particularly by planning their projects around discipline standards to ensure that the appropriate content learning is occurring. Teachers also noted repeatedly that they felt PBL supported students' engaging in inquiry processes, the scientific method specifically, and greater amounts of higher level thinking. As such, our findings suggest that in inclusive STEM schools, high cognitive demand is indeed an essential piece of PBL.

It is important to note that implementing PBL can be a challenge for teachers,especially in schools where there may be less flexibility in structures (e.g. students' schedules) that support the use of PBL and for teachers in their teaching styles, as it represents a large shift from traditional styles of instruction. Many teachers noted that support from their principals in being able to try and fail was important in their eventual success with PBL—this sort of leadership is characteristic of inclusive STEM schools (Peters-Burton et al., 2014), but may unfortunately not be present for all teachers, regardless of their school type.

## LIMITATIONS AND FUTURE DIRECTIONS

There are several considerations for interpreting the results of this study. First, this study is cross-sectional and correlational, with classroom observations and teacher interview data collected at a single time point. As a result, conclusions regarding changes or growth in teachers' instructional practices and students' engagement in their PBL experiences inside the classroom cannot be drawn. Future research should observe teachers and students engaging in PBL experiences at multiple time points and interview teachers throughout the academic year. Employing longitudinal research methods will help provide a more-thorough understanding of PBL implementation at inclusive STEM high schools, which has the potential to contribute to a greater understanding of how PBL experiences impact students' learning outcomes and future participation in STEM careers.

In addition, the multifaceted and multidimensional nature of PBL poses measurement challenges. PBL is not a "one-size, fits all" educational strategy, and PBL experiences often differ across teachers, grade levels, *and/or* schools, despite sharing the same PBL label. A single definition of PBL, or implementation of PBL, does not exist across all schools. While these inconsistencies in definition and implementation of PBL may somewhat limit the generalizability of these findings to students and teachers in other grade levels and school types, the findings do indicate themes common across all operationalizations of PBL. This suggests that there is some shared understanding of the core elements of PBL approaches across teachers and STEM schools, which are largely consistent with previous research literature. Given that this work focused on high schools, and specifically on inclusive STEM high schools, there is also a limit to the conclusions that can be drawn about the applicability of PBL experiences in other settings. However, one strength of this work, and one that should continue to be investigated in future research, involves pairing quantitative classroom observational data with qualitative teacher interview responses (i.e., mixed-methods) to gain a more in-depth understanding of teachers' instructional practices and students' behaviors during PBL, and how classroom experiences are structured to facilitate engagement in PBL.

Future research should also explore students' perspectives on PBL, particularly given students' active, self-directed involvement in these learning experiences. A wider age range of students should also be investigated to assess elementary and middle school students' participation in PBL experiences, and whether they are developmentally-appropriate learning experiences for younger students. Moreover, such perspectives should not be limited to students (and teachers) from inclusive STEM schools as PBL instructional practices are also implemented in traditional, non-STEM schools. Examination from multiple perspectives can provide a more well-rounded understanding of how PBL is carried out in classrooms with high school students, and highlight similarities and differences in PBL implementation across types of school settings (i.e., STEM versus non-STEM schools), grade levels (i.e., elementary and middle school), and diverse populations of students.

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# Teaching Challenges and Perceptions on STEM Implementation for Schools in Saudi Arabia

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## ABSTRACT

STEM education has become one of the most rapidly growing sectors in educational reform all over the world. Whilst the program has been successfully implemented in most countries, unfortunately it has not been introduced as successfully in Saudi Arabia on account of lack of clarity of the general description of the meaning of STEM and its purpose and framework of application. In 2009, the Ministry of Education (MOE) introduced a new mathematics and science curriculum, in collaboration with Obeikan Research Development Company, as an adapted series of science and mathematics textbooks produced by an American publishing company McGraw Hill. The adapted curricula attempt to make meaningful connection between student's lives and their educational experiences through the implementation of new teaching practices which include student-centred investigation strategies and problem-based learning.

The study was limited to Jeddah, Saudi Arabia and used the interviews of high school mathematics and science teachers and class observational methods as a means of qualitative research in order to address the following research questions:

- What are the major aspects of the new mathematics and science curricula that serve as a means of the implementation of STEM education in Saudi Arabia?
- What are the perceptions of teachers on the implementation of the newly adapted science and mathematics curricula?
- How are the newly adapted mathematics and science curricula delivered in the classrooms as form of STEM education?

Results revealed that even though there is haziness in mathematics and science teachers on the actual meaning of the concept of STEM education and its practice, the new teaching strategies that are required by the MOE for the successful implementation of the adjusted curricula, were found to be equivalent to teaching practices that have been proven effective in the implementation of STEM education.

**Keywords:** STEM, MOE, qualitative analysis, curriculum

## INTRODUCTION

Scientific advancements of the 21st century have impacted every aspect of an individual's social life. Requirement of rapidly changing economies are fulfilled via providing quality education in the fields of Science, Technology, Engineering, and Mathematics (STEM education) and it is considered as a top priority (Asunda, 2011; English and King, 2015; Kelley and Knowles, 2016).

STEM's instructional models are now considered as one of the most emergent areas in the context of education in both developed and developing countries (UNESCO, 2010). STEM education has also been recognized as a way of strengthening mathematics and science curricula. Despite the global and recognition of the benefits of STEM in the educational sector, its application and instructional practices have remained limited (Czajka and McConnell, 2016; English, 2016; Tofel-Grehl and Callahan, 2016). For instance, generally, science education sometimes is unable to encourage and polish the critical thinking abilities of students. Besides, it follows a lecture-based mode of instructions which particularly focuses on the reception of facts in complete dissociation with context and meaning. However, these limitations are overcome by the problem-solving techniques which are not only practiced but also given ultimate value in the STEM education (Trueman, 2013).

In Saudi Arabia, education is now viewed as a key factor for financial and social growth and science and mathematics education have garnered unprecedented common interest (Almazroa, 2013). The new mathematics and science curricula in Saudi Arabia are an adapted version of the curricula, published by McGraw Hill (Obikan for Research and Development, 2010). For instance, curriculum of mathematics is based on adjusted learning which depends on vertical reliance among the educational module and it is built up to create psychological understanding and scientific abilities in children. In particular, this approach relies on inspecting ideas and building subjective aptitudes, and scientific abilities and methods to enhance them.

Science curricula, on the other hand, are centred on writing-based activities with an aim to place students in the centre of the learning and instructing process. Different exercises are designed for recursive learning with an aim to develop and maintain students' interest at all levels. The general theory of science course books underscores the significance of the logic-based examination and reasoning aptitudes (e.g., logical perusing and composing, drawing and gathering tests), and applying scientific information in everyday life (e.g., relating science to other fields of study and society which is considered as an aspect of the implementation of STEM education). In higher grades, science textbooks incorporate subjects such as life processes, cellular structure and heredity. The human body and its systems, movement and relationship with other living beings are basic divisions of science (Mullis et al., 2016).

In the adapted mathematics and science curricula, prioritizing student-centred learning and understanding the concepts instead of relying on memorizing texts follow a constructivist theory. Various theories of progress have been put forward to justify the complex relationship and factors that contribute to changes in the mode of instruction. Some theories stretched the significance of changing the perception of instructors as a major aspect, which in turn prompts changes in instructional practices and the enhancements of students' educational outcomes (Czajka and McConnell, 2016).

In Saudi Arabia, the educational system follows a hierarchical structure that basically comprises of high authorities in the Ministry of Education and lower authorities in schools. Mathematics and science curricula, in the context of this study, is set with relevant material obtained from the Ministry of Education and teachers neither have any role in curriculum development nor the authority to alter or change any topic or subject (Al-Sulaimani, 2010). Alyami (2014) has argued that reform proposals and development projects essentially require the acceptance of the affected division as in educational sector, perceptions of teachers and students greatly influence the success of curricular reforms and development. Policy makers generally believe that changes are brought about by changing the structure; however, in reality, changes can only be made by changing the subjects involved within the procedure. Therefore, the successful outcome of reform measures in educational sector is compromised unless they are formulated and clarified via debate and participatory democratic processes.

The purpose of this study is to determine and comprehend the level of preparedness and inclination of teachers with respect to the implementation of the new mathematics and science curriculum in Saudi Arabia as an advancing step towards the implementation of STEM education. Since this is a new study in this domain, it is important to understand teachers' views and perceptions about the new curriculum and how it will affect their teaching strategies.

Primarily, the focus of this study is to encourage teachers to move away from traditional teaching methods that include lectures and to embrace project-driven methods to project problem- centred learning that establishes a more beneficial learning forum for STEM subjects. As a common practice, in Saudi Arabia, science and mathematics are taught as separate subjects with little or no relevance to real life situations. Therefore, in order to redefine their modes of instruction in the classroom and subscribe to the combined model of STEM education, teachers need to acquire the understanding of what exactly they know about its implementation and integration in the curriculum and how it will improve their teaching experience.

 

## LITERATURE REVIEW

### Theoretical Framework

The development of STEM education approach is based on four different pillars: Science, Technology, Engineering and Mathematics. The approach was further defined as the development of a discipline on the basis of the integration of other disciplinary knowledge into a new whole (Sanders, 2009). This integration of different subjects into a single whole was meant to equip students with the ability to deal with the growing challenges.

Since the early 90s, the concept of STEM education has occupied the interest of policy makers and educators. Since then, the integration of STEM into curriculum has been a part of many curriculum reforms such as the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013).

Most of the changes implemented by the STEM education involved the amalgamation of four different subjects to develop both theoretical and practical skills in students. According to the study of Kloser (2014) the implementation of STEM education has mainly emphasized on the change in teaching practices and caused the emergence of a shift particularly in teaching methodology. The approach further promotes practice-based teaching philosophy which bounds teachers to apply useful knowledge, skills and values to develop a strong student engagement. Another feature of the STEM education is that it promotes a curriculum consisting of integrated content of all four subjects including Science, Technology, Engineering and Maths. These curricula are based on very specific objectives which aim to develop the target skills in students (Alhomairi, 2018).

### Empirical Review

According to a study, Meaningful connections formed between prior and current knowledge and between disciplines can help establish schemas which help in the development of cognitive skills and results in deeper understanding in contrast with surface learning (Beane, 1996). To this effect, STEM education could be seen as "a means that supports a constructivist approach in learning as teachers facilitate and scaffold students' meaningful learning" (Becker and Park, 2011).

The success of the implementation of STEM education is dependent on the perceptions and preparedness of teachers. They need to have adequate prior training and understanding in order to teach the new curriculum to students. However, teachers' perceptions and beliefs that shape their approaches and methodologies for the implementation of curricular reform are usually neglected. These concerns were presented in many researches regarding education in Saudi Arabia (Bin-Salamah, 2001). In order to make such implementations, it is important to identify how mathematics and science teachers perceive the shift from traditional teaching strategies to an advanced "incorporated" STEM training-learning model.

Kennedy and Odell (2014) in their study identified different elements for the successful implementation of high-quality STEM education and curriculum. First element is the rigorous instructions for science and mathematics curricula. Second element is the integration of engineering and technology into mathematics and science curricula. Third element is the encouragement of teachers to promote the trend of asking questions, while conducting the investigations. Fourth element is the provision of opportunities for STEM educators and learners with the increased workforce. Mihelich et al. (2016) on the other hand provided insights regarding the importance of developing student learning in different social scientific studies. Findings of the study emphasized on parents' inclination in developing students' interest and attitudes towards science. The study further emphasized on the inclusion of STEM in the education curriculum of K-12 students.

Zeidler (2016) focused on the socio-cultural and socio-scientific perspective of STEM education. Whereas, El-Deghaidy and Mansour (2015) examined the perceptions of Saudi science teachers regarding the STEM education and its multidisciplinary nature. Findings of the study indicated a need to develop a professional model to analyse the lacking of the science teachers in terms of the pedagogical content that would promote the enactment of STEM education in classes. A similar study was conducted by Madani (2017) which investigated the teacher's perception and instructional practices with respect to the science and mathematics curricula as a positive step towards the implementation of STEM education in the educational system of Saudi Arabia. Findings of the study indicated certain level of haziness regarding the concept of STEM education in the educational curricula. Besides, the new teaching strategies implemented by the Saudi Ministry of Education were found equivalent and effective in the implementation of STEM education.

Aldahmash et al. (2019) conducted another study to analyse the attitudes of Saudi Arabian mathematics and science teachers towards the integration of STEM education in the science and mathematics curricula of middle school. Findings of the study supported the integration of professional development programs which ultimately resulted in decreasing teacher's difficulties regarding the implementation of STEM. Also, a significant improvement in teacher's self-efficiency was identified due to their participation. Williams et al. (2015), on the other hand, highlighted the instructional preferences of teachers who belonged to the system of STEM education.

Findings of the study identified in-class instructions including group work and problem-solving strategies. Besides, most of the teachers preferred summative assessment practices.

Henderson and Dancy (2011) identified the role of individual educational professionals, as they primarily serve as the policy and curriculum developers and tend to create new instructional strategies through educational research, which are then implemented to obtain practical results. Such techniques, in most cases, fail to consider the unique identities of students, teachers and schools in every region. In some cases, these strategies often lead to academic success and provide expected results, while in other cases, undesired outcomes are obtained.

The evidence of teachers' self-efficiency should also be needed. "For teachers to be able to teach integrated STEM, they need professional development experiences, adequate planning periods and adequate content preparation" (Harrell 2010). This study aims to provide evidence that teachers are not adequately supported with the infrastructure and means required to successfully implement the curriculum. The STEM school culture requires "collaboration amongst stakeholders as well as establishment of a collaborative and supportive STEM education community (Basham, Israel, and Maynard, 2010). Teachers are required to have a comprehensive understanding of STEM education and they should be adequately equipped to handle the transition from lecture- centred mode of instruction to student-centred one.

## METHODOLOGY

The methodology provides a descriptive analysis through the use of different forms of qualitative measures such as interviews and observational methods (Ary, Jacobs, Sorensen, and Walker, 2013). The study is specifically conducted in Jeddah, Saudi Arabia, in order to address the following research questions:

- What are the major aspects of the new mathematics and science curricula that serves as a means of the implementation of STEM education in Saudi Arabia?
- What are the perceptions of teachers on the implementation of the newly adapted science and mathematics curricula?
- How are the newly adapted mathematics and science curricula delivered in the classrooms as means of STEM education?

The purpose behind using basic interpretative research was to understand how high school mathematics and science teachers perceive events, processes and activities, while practicing the new mathematics and science curricula in the classroom in a bid to implement STEM education in Saudi Arabia.

The research study focused on using personal open-ended interviews with participating teachers to gain a deeper understanding of the major aspects of the new mathematics and science curricula and class observational methods were applied to comprehend how the new required teaching methodologies are practised in the classroom.

### Sampling

#### *Target population*

The context of this research study is centred on the Kingdom of Saudi Arabia (KSA). However, depending on a homogeneous sampling, the researcher selected similar cases to describe a subgroup in depth rather than all members of the population (Glesne, 2011). It was also used to ensure that the data obtained was related to the scope of the research understudy (Onwuegbuzie and Collins, 2007; Fraenkel et al., 2015). Sampling was limited to Jeddah; the selection of this area was based on the researcher's ease in accessibility to potential study participants and information.

Selection of science and mathematics teachers teaching the new mathematics and science curricula to the higher grades (grades 11 & 12) was made. The teachers were assigned by the participating schools on the basis of their qualifications, willingness to take part in the study and most importantly their experience in teaching both the previous and the new mathematics and science curricula in Saudi Arabia.

Eight high school teachers participated in the study; four of whom were selected for the semi-structured interviews and the remaining four for the classroom observational methods. The entire procedure was carried out to gain deeper and wider perspectives of research objectives from different angles and to gain a clear picture of teachers' perceptions of the new mathematics and science curricula with respect to its implementation practices in the classrooms and. The participants were selected from four schools: one school was only for boys and the other three were only for girls.

Based on the objective of this study, only four subject teachers teaching mathematics, biology, chemistry and physics were interviewed. These interviews were carried out in order to gain in-depth information and observation on each subject to be able to build a convincing analytical narrative which should be based on richness, complexity and detail for each subject.

**Data Collection**

### *Interviews*

Interviews are considered as the most popular form of qualitative methods of research as they provide authentic information of participants' personal experiences and perceptions about a certain matter (Melles, 2005). Interview questions in qualitative studies usually focuses on participants culture, perceptions, experience, understandings, meanings and problems studied, in order to investigate their plans, intentions, roles, behaviour and relationships regarding the understudy research topic (Tuckman and Harper, 2012).

Therefore, interviews are perceived as a powerful tool to gain insight about educational issues by understanding personal experiences of involved individuals and receiving more in-depth responses (Seidman, 2013; Crabtree and Miller, 1999).

The semi-structured instrument consisted of nine open-ended questions designed to investigate mathematics and science teachers' perceptions and classroom practices with regards to the new mathematics and science curricula used as an advancing step towards the implementation of STEM education in Saudi Arabia. The purpose of the instrument was to provide teachers with the opportunity to describe and elaborate the relationship between their perceptions about new mathematics and science curricula and their daily classroom practices.

In order to maintain the quality of an interview, Shensul et al. (1999) suggested three principles: maintain the flow of the interviewer's questioning and participants' responses; sustain a positive relation with the participants and avoid interviewing bias. In this research study, the researcher took the role of the interviewer. Interviews were conducted fairly as all participants were asked the same questions in the similar order. Furthermore, the questions were worded in an open-ended format which allowed participants to contribute in shaping the discussion and feel free to share their perceptions, experiences and attitude regarding the subject (Bogdan and Biklen, 1998).

The duration of each interview ranged between forty-five minutes to an hour, which is an appropriate time for conducting interviews as described by Glesne (2011). Participants were briefed beforehand about the research topic, rationale and objectives and their doubts were also clarified to maximize the successful output of the interviews. The interview questions were first formulated in English and then translated into Arabic: the first language of Saudi Arabia.

In order to ensure the accuracy and validity of the translation and to make sure that the meanings were not lost in translation (Kapborg Bertero, 2002) assistance of two certified translators was taken (Simon, 2011). Appointments with the school principals of the participating schools were taken ahead of time.

Four teachers were interviewed; three of them were female who were teaching mathematics, biology and physics in three different girls' schools in Jeddah, Saudi Arabia. Each interview was held within the school premises and lasted for approximately forty-five to sixty minutes. The fourth interview was conducted with a male high school teacher teaching chemistry. Due to gender segregation policy in Saudi Arabia's schools, the interview was conducted over the phone after getting the school principal's permission.

Methods used for documentation and later analyses included note taking and audio tape recording (DiCicco-Bloom and Crabtree, 2006). Participants' consent was obtained prior to the interview regarding the audio recording of the interview. After the completion of data collection process, each interview was carefully listened and noted to eliminate the chances of bias in results. More precisely analysis of data obtained from the observational method was carried out by using Krathwohl's (2009) three main stages. The first stage involved familiarization and organization of the observed facts. The second stage involved coding and recoding of obtained data and finally the third stage involved thorough summarizing and interpreting of the obtained results.

In order to test the trustworthiness of interview questions, a panel of educational experts including educators and teachers were asked to judge the translation, context and validity of the instrument. Three educational experts assisted in reviewing the questions including a science professor from Dubai, a school principle from Jeddah Saudi Arabia, having a 25-year experience of teaching mathematics in Saudi Arabia and a retired Biology teacher with 22 years of teaching experience in Saudi Arabia.

### *Classroom observations*

Tofel-Grehl and Callahan (2016) described that the best path to understand the implementation of STEM education within STEM schools is via the study of classroom discourse. The main focus of classroom observational methods in this study was to describe whether teachers' perceptions are aligned with the applied teaching practices regarding the implementation of the adapted mathematics and science curricula as an advancing step towards the implementation of STEM education in Saudi Arabia.

In order to conclude and to effectively answer the research question: "*How is the newly adapted mathematics and science curricula delivered in the classrooms as a means of STEM education?*", the researcher conducted classroom observational methods within participating schools in Jeddah, Saudi Arabia.

Four schools participated in the qualitative part of the research study as it was described earlier; one school was a boys' school, while the remaining three were girls' schools. In accordance with the gender segregation policy implemented in Saudi Arabia, only three schools were included in the class observational method. It was due to the fact that the researcher was denied access to the boys' schools, on account of being a Saudi female. Moreover, since the research was not under the research panel of Ministry of Education, video tape recordings were also denied. Therefore, class observational methods were limited to the selected girls' schools of Jeddah, Saudi Arabia. Classroom observations of the biology and chemistry teachers were conducted in only one school, while for physics and mathematics, each observation was conducted in a different school.

The primary focus of the classroom observations was to investigate teachers' application of the new instructional practices implemented by the Ministry of Education to teach the new mathematics and science curricula as an advancing step towards the implementation of STEM education. The observations were purposefully conducted during participants' STEM integration lessons by using an observational checklist that was developed by the researcher, which is relevant to the scope of the research topic and the nature of the research questions. The observational checklist included two sections. The first section dealt with the investigation of the applied teaching strategies to answer the following question: "*How well did the teacher cover the following teaching approaches in the classroom?"* This investigation was done via the observation of the following subdivisions: lesson opening, quality of teaching, mode of instruction, association of taught subjects with students' daily life issues, and developing connections in different STEM subjects when teaching. The second section included the observation of the overall learning environment in the observed mathematics and science classrooms.

In order to ascertain trustworthiness of the instrument, a pilot classroom observation was undertaken with a female mathematics teacher who was teaching students of 12$^{th}$ grade in one of the participating schools in Jeddah, Saudi Arabia. The observational trial assisted the researcher to focus on the required observational techniques and note taking with respect to the scope of the research topic. The trial helped in clustering the observational checklist. Some of the columns were deleted and more emphasis was given on observing the subject integration between the topic taught and STEM subjects.

In order to eliminate bias, the researcher took the position of a silent uninvolved member during all classroom observational methods, as no interaction was made with the teacher or any of the students during the classes. The researcher was observing the classes silently, not pass judgement on the settings as everything was recorded as it occurred. Further, the researcher adapted the two-column field note taking strategy (Hammer, Prel, and Blettner, 2009).

In the observational checklist, the researcher used two columns for taking classroom notes: one column to report the indicators for teacher-student interactions, while the other column was used for writing personal thoughts and comments, which separates the observer's personal comments and thoughts from the actual observations.

The classroom observational method was applied to investigate all the activities and interactions between participating teachers and their students to monitor their interactions with the activity (Merriam, 2009). As the format of the lesson plans varied significantly among teachers teaching different STEM subjects (mathematics, physics, chemistry and biology), the number of classroom observations was also varied depending on the coverage of each STEM subject and chapter, each class was 45 minutes long. In chemistry, a total of six classes of the same teacher of grade 11 and 12 were observed.

Topics covered during the six classes included the ionic and covalent bond which was covered in two classes; alkaline battery topic was covered in two classes and the hybridization chapter was also completed in two classes. In biology, a total of five classes of the same teacher of grade 11 and 12 were observed. Topics covered during the five classes included bird anatomy which was completed in two classes including one conducted in the science laboratory and the circulatory system which was covered in three classes. In physics, three classes of the same teacher of 11 and 12 grade were observed. Topics covered during the three classes included the Quantum theory, Kinetic energy and Newton's first law. In mathematics, five classes of the same teacher of grade 11 and 12 were observed. Topics covered during the five classes included Pascal theory, binomial theory, polar coordination, resume limits and tangent and velocity. The reason behind choosing to observe more than one chapter in each subject was to ensure that the researcher gathered enough evidence for the comprehensive analysis and investigation of the applied instructional practices.

 

## RESULTS

### Teachers Interviews

***Q1) Are you familiar with the concept "STEM education", if yes please describe it for me?***

Not all interviewed teachers heard the term 'STEM'; however, description of the meaning of the term revealed that three participants were familiar with it. The physics teacher was the most familiar with the theory of STEM education as she was able to give a complete definition of its implementation, purpose and objectives. Further, the teacher described that finding relevance between different STEM subjects when teaching and relating given topics to students' lives is a requirement of the new curricular implemented by the Ministry of Education.

***Q2) Do you believe that the new mathematics and science curricula is a step forward in Saudi Arabia's educational reform and a step towards STEM implementation? Explain.***

In this question, all participants shared positive views regarding the new mathematics and science curricula as being a sign of educational improvement in Saudi Arabia. Moreover, they all agreed to the existing challenges lying ahead in the implementation of the new curricula to accomplish the objectives and academic success. The physics teacher explained "*The new curricula are more advanced in terms of the information included and the level of coordination among subjects including the sequence of its topics. Since education in the Arab world was initially introduced, teachers were viewed as a sole source of knowledge and information. However, in present times, their roles have transformed to facilitators, as students are now more indulged in their own learning. To me, this is a major aspect when it comes to STEM implementation, I cannot say that the new curriculum is fully meeting its objectives yet, but with time and more training I'm sure it will*". The teacher further described, "*When the given topic is related to a real-life scenario, students become more interested and feel the connection with the topic, which makes it difficult for them to forget or neglect new information, especially if it is related to their life or health circumstances. STEM implementation is not yet considered as a requirement from the Ministry of Education, connections between different STEM subjects are applied as an extra effort from the teachers*".

The new curriculum is a form of STEM education though a lot of teachers and students might not have noticed it yet. Additional focus is required for the implementation of STEM education and subject integration in specific and on the whole learning and teaching experience in general.

***Q3) Do you have the experience in teaching the old curricula? If your answer is yes, did you experience differences in your coursework and instructional approaches required for the implementation of the new curricula when compared with the old one?***

The teachers that were interviewed were able to identify differences between the old and new curricula. The biology teacher noted "*The new curriculum is better, as there are stated objectives at the start of each chapter, which could be used as a framework for lessons. However, some topics required more evaluation before presenting lessons to students*". The physics teacher on the other hand described, *"As teachers we are challenged not only in our ability to carry a class using new active learning, student-centered teaching techniques, but are also to be informed about other STEM subjects as well. Moreover, the new curricula add excess load on teachers when compared with the old one, as it requires teacher's knowledge and experience to read information that are found between the lines and be able to clarify them to students. Implementing new instructional practices including student-centered teaching techniques requires not only teaching experience, but also more time in class*". The mathematics teacher on the other hand, explained, "*The new mathematics curricula is stronger in content, as it focuses more on the basics of mathematics through new engaging teaching techniques, that increases students' interest and encourages classroom engagements".* The above-mentioned statements sufficiently explain that most of the teachers supported the use of new teaching method. However, one of the major concerns raised by the respondents included that the new approach demands regular updating of the subject knowledge remain in line with the new advancement and development in their respective fields of studies. This further emphasizes the need for frequent development of professional development programs, as suggested in the studies of Aldahmash et al. (2019) and El-Deghaidy and Mansour (2015) respectively.

***Q4) In your opinion, in the new curricula does the Ministry of Education aside from connecting mathematics and science subjects to real life scenarios, focus on STEM implementation or subject's integration in their annual visits?***

Most mathematics and science teachers indicated that the new curricula focus more on students' engagements and puts more weight on the relevance of subjects to students' daily lives. However, implementation of STEM education and the integration of its subjects are carried out within that process.

The physics teacher explained that the Ministry of Education focuses mainly on the new active learning strategies and new student-centred teaching techniques, according to which teachers are supposed to act as facilitators and help and guide their students to search and get the information by their selves. Additionally, the teacher explained, "*Minimum emphasis is concentrated towards the implementation of STEM education or subject integration between physics and other different science subjects*". Despite the fact that implementation of STEM education is not a part of the Ministry's direct requirements, it is still required to accomplish the goals and objectives of the new curricula.

***Q5) Are teachers qualified to teach the new mathematics and science curricula? Explain the challenges that faced you as an instructor.***

With respect to the issue of teacher's qualifications to teach the new mathematics and science curricula, teachers shared mixed views. The biology teacher stated, "*In this school we have three biology teachers, I believe all of us are qualified and well-informed in teaching the new biology curricula, in terms of its content and are aware of all new teaching requirements and methods*". On the other hand, the physics teacher disagreed, as she described teachers as unqualified in teaching the new physics curricula, highlighting two challenges: the language barrier because most teachers are not familiar with the meaning and pronunciation of most scientific terminologies included in the new curricular textbooks and the challenge of implementing new instructional practices required for teaching the new mathematics and science curricula as teachers tend to revert to their old teaching methods. Further, the teacher added, "When the new mathematics and science curricula was first introduced, it created a huge gap for both the teachers and the students, as it was very challenging for us teachers to build new information with students having no base. "

***Q6) As a teacher, were you offered any sort of teachers' development programs or workshops as a preparation to teach and implement the new mathematics and science curricula? How important do you think is it for teachers?***

It was concluded from the participant's different answers that teachers were not all required or obliged to get enrolled in workshops or teachers' developing programs before teaching the new mathematics and science curricula. The chemistry teacher stated, "*I do not deny the importance of teachers' development programs and workshops; I believe it is the most effective tool to curricular reform success and a window for teachers to learn how to apply new different teaching techniques. Despite that, I have been teaching high-school chemistry for a couple of years now, so far I was not obliged to enrol in any courses or workshops.*"

This indicates that many teachers, despite knowing and understanding the value of teacher's development programs refrained themselves in getting enrolled in these programs to optimize their productivity. The responses further indicated that most of the teachers, despite their willingness were unable to attend these programs on account of strict work schedule. This pinpoints towards another factor that may support the given argument that teachers are unable to manage time for attending such purposeful events due to their workload.

***Q7) What do you think are the major aspects of the new mathematics and science curricula, that are considered as a step towards implementing STEM education in Saudi Arabia?***

The mathematics teacher highlighted the fact that mathematics, unlike other science subjects, is considered as rigid and difficult, which makes it very challenging for the teacher to engage students in the entire learning process. Nevertheless, the new curricula aim to raise the interest of students by challenging them to solve mathematical problems that are related to real life scenarios. Furthermore, numerous exercises given at the end of each chapter are considered as an excellent addition to the mathematics textbooks. The exercises highly vary in their level and style, which helps students practice beyond the confines of their books and consequently become more familiarized with international exam questions.

The physics teacher indicated several aspects of the new physics curricula that were not the part of the old one including summary at the end of each chapter to help students review and reorganize the chapter's points and build up on this information. The new curriculum is more research oriented and relevant to students' real-life situations and circumstances. The biology teacher pointed out three characteristics of the new science curricula which verified that educational reformation in Saudi Arabia is on the right track. Most of the teachers observed that the new methods were sufficient in developing critical thinking skills in students as well as increased classroom interaction and response. From these responses, it can be safely concluded that the new methods are sufficient in directing students towards the development of required skills.

***Q8) What is your overall conclusion on the newly implemented mathematics and science curricula?***

Despite the fact that most participants shared mixed views and feelings regarding the new mathematics and science curricula, they were all optimistic that this educational reformation is a positive step towards the improvement in Saudi Arabia's educational system in general, and students' output in STEM subjects in specific.

Most of the teachers identified high improvements in students' understanding of the basic concepts. Further improvements were also observed in the methods of assessments conducted by teachers with respect to the student's performances.

***Q9) Do you have any additional comments that you would like to share?***

The mathematics teacher explained, "*Improving the overall process of learning does not depend solely on coming up with new curricula. In order to improve our educational standards, schools must rely on outside exams that are given from someone other than the teacher who is teaching the topic, so both the teacher and the students can be encouraged to put more effort to improve. I believe that there will be no improvements in education as long as the teachers do not improve, also, there are too many holidays during the semester, which carries a negative effect on students learning*". She added "*The down side is that the Ministry of Education does not consider STEM as part of the new curricula's major requisites*".

The above statement therefore emphasizes on the fact that the existing measures of the government are insufficient regarding the inclusion of STEM education in the current educational system. This identifies the gap found in the strategies planned by the government which are insufficient to fulfil the academic needs of both students and teachers.

### Classroom Observational Results

Observation of instructors' teaching practices in classrooms plays a significant role in enhancing students learning in different disciplines of STEM education (Smith et al., 2013). In this section, the researcher relied on an open-ended observational protocol in which the researcher attended classes, took notes and commented on students' involvements and interaction within the classroom by using a formulated observational checklist.

Within each observational section, results were further classified into two parts: the first part was the observation of science classes including physics, biology and chemistry and the second part was the observation of mathematics class. Analysis of the data obtained from observational method was carried out using Krathwohl's (2009) three main stages. The first stage involved familiarization and organization of observed facts. The second involved coding and recoding of obtained data and the third stage involved summarizing and interpreting of the results. At the end, a table was created to summarize the points between different subjects observed via the class observational checklist.

Through observations it was found that all the four teachers opened their lessons through a brief discussion about the topic and its relevant background. Besides, the quality of teaching was determined on the inclusion of student-centred teaching strategies which ultimately supported quality teaching. Mathematics teachers incorporated different short classroom activities to enhance students' skills and science teachers incorporated further instructional activities which ultimately increased students' response in classroom discussions. Students' participation further increased with the inclusion of different short exercises meant to develop a connection between scientific facts and real-life situations.

## DISCUSSION

Results were analysed to investigate teachers' perceptions and instructional practices of the new mathematics and science curricula as an advancing step towards bring about educational reforms in the Kingdom of Saudi Arabia. The objective was to gain an insight of how teachers perceive, acknowledge and implement the new teaching practices required for teaching the new curricula, and its relevance with instructional practices required for the implementation of STEM education. Findings were presented with an aim to generate a base for further research to improve the standards of Saudi Arabia's educational system in general and the abilities of students in the fields of mathematics and science in specific.

The fact that STEM education is not a familiar term among most individual participants of this research, thi study determines fact that there is a general haziness regarding the terminology and meaning of STEM education. A successful integration of mathematics and science subjects mainly depends on teachers' academic competence with respect to subject knowledge and the integration processes. There are many challenges in the implementation of STEM education; one of the main challenges is the need of a clear definition of the acronym STEM in STEM education (Brown et al., 2011). Moreover, many teachers face some difficulties in teaching their own subjects when they are asked to integrate other subjects as this could be challenging and may lead to miscommunication. This confusion affects the delivery of information by the teacher and its reception by the students (Stinson et al., 2009). Notwithstanding the many possible benefits STEM education provides, it is vital to concentrate on teachers' understandings, practices, efficiency and strategies required for a successful implementation of integrated STEM education (Stohlmann et al., 2012).

The results indicated that when teachers were asked about their familiarity with STEM concept, three out of the four teachers responded by using the "yes" word as an answer but only one of them was able to further explain the meaning of STEM. Further, participants' responses were also found to be consistent in classroom observational results which indicated that the focus was more towards the application of new teaching methods than the integration between subjects.

Several ways were highlighted for getting acquaintance with STEM education including subject integration within different disciplines of STEM education, the application of new teaching practices, relevance of the new curricula and the encouragement of students' involvement. These points were related to the interview responses regarding the application of new instructional practices as demanded from the Ministry of Education. Moreover, they were relevant with the observational data obtained by observing different mathematics and science classes. These findings are in line with those provided in the study of Madani and Forawi (2019), according to which the new curricula implemented by the Saudi Ministry of Education were effective in developing meaningful connections between student's real life and educational experiences. This further involved the inclusion of new teaching strategies. Aldahmash et al. (2019) endorsed the results of this study and indicated that most of the implementation of STEM education was instrumental in improving students learning efficiency. It was also instrumental in increasing teachers' self-efficiency by the adoption of different teaching approaches. Results of this study further indicated that some teachers were unable to identify the appropriate meaning of STEM education, which showed unpreparedness with respect to the criteria of STEM education. These results were also in line with those presented in the study of El-Deghaidy et al. (2017), according to which most of Saudi science school teachers reflected lack of preparedness regarding the implementation of STEM education practices. However, recommendations regarding the provision of teacher's development programs were provided to improve the education level of both teachers and students.

Respondents described several points which they considered as interior and exterior barriers that challenged the implementation of new teaching strategies and subsequently, the implementation of STEM education. These barriers included poor instructional design, rigid school structures, isolated subjects and topics, insufficient teacher preparation programs and workshops, time constraints, resistance of teachers and students to accept change, lack of recognition of teachers and students, lack of encouragements, insufficient school resources, large class size and the lack of a unified assessment form.

Ramli et al. (2017) conducted a similar study to identify the challenges faced by teachers in the implementation of STEM education. Findings of the study outlined some important challenges that are in contrast with those postulated in this study. According to the study, most of the teachers faced issues such as lack of confidence, lack of related teaching materials and lack of teaching expertise required to implement STEM education.

Most of the shared themes focused around the idea that the new curricula is more suitable for the next generation with respect to both its material contents and applied teaching strategies. Analysis of teachers' responses revealed that all respondents favoured the new mathematics and science curricula on account of the following factors: its relevance to real life situations, concentration on the development of students' self-efficiency, confidence and motivation and most importantly educational outcomes. Therefore, from the above discussion it can be concluded that the implementation of STEM education is instrumental in supporting the advanced educational standards. However, there has been lack of training sessions and workshops for teachers' professional development which are mandatory to fill the gaps in the successful implementation of STEM education.

## CONCLUSION

The study sought to address a shortfall in the educational system in Saudi Arabia. It sought to examine the perceptions of teachers towards the implementation of STEM education and the interdisciplinary curriculum. An important result of the study revealed the need to enhance dialogue between teachers of different STEM education subjects in order to provide cohesion and promotion of the new curriculum at schools. The idea aims to establish a STEM culture and create a dialogue to enhance partnerships with all key role players. Stoll and Fink (1996) list collegiality as one the features of a positive school culture which includes shared goals and responsibility for success, continuous improvement, lifelong learning, risk-taking, support, mutual respect, openness and humour. Findings further revealed that teachers are not adequately prepared or educated with regards to the implementation of STEM in schools.

Teachers also voiced their concern in the interviews regarding common internal and external issues such as the lack of adequate facilities and infrastructure required to support the implementation of STEM education. There were also issues related to the insufficient resources, confusion about examinations, insufficient time to focus on STEM activities, lack of necessary teaching materials and large class sizes which impacted on teaching time. It was evident that teachers were facing difficulties to fully embrace and implement the STEM curriculum. Teachers expressed concern that workshops that were intended to prepare them for the implementation of STEM education could not provide them the necessary tools required for implementing STEM.

It was concluded that in order to comprehensively understand all the elements of STEM education and its integration and implementation, teachers need to be involved in open discussions and intensive collaboration and partnership.

## LIMITATIONS

When conducting a research study, limitations affect the degree of trustworthiness of the research and generalization of its obtained results (Creswell, 2013). The following are some of the limitations that need to be taken into account as they might have had an effect on the findings of the research.

 

First, this study is limited by the validity of measurement held by the applied instruments, including semi-structured and open-ended interviews of teachers and class observational methods. In the second place, the study was limited to Jeddah and the study sample comprised only eight teachers. Further, participants were only post-secondary mathematics and science teachers who had experience in teaching both the old and the newly adapted mathematics and science curricula in Saudi Arabia. Therefore, results of the findings may not be applicable to new teachers who have prior experience of only teaching the old curricula or to teachers outside the domain of higher secondary education. In the third place, the proposed conceptual framework does not address all the problems concerning the new science and mathematics curricula and educational program such as those imposed by law, by the politics or by teachers' professional development programs. Further on account of the uniqueness of the research topic, at present, there is no protocol purposefully designed to observe STEM integration classes or structured interviews for STEM implementation. Therefore, qualitative instruments applied were developed by the researcher with consideration of the scope of the research study as well as social and cultural concerns. Another important limitation was that the classroom observational methods were implemented only in girls' schools since on account of cultural and religious restriction in Saudi Arabia, schools are gender segregated and the researcher, being a female, couldn't gain access to the science or mathematics classrooms of boys' schools and also videotape recordings were not permitted for classroom observational methods. Finally, much of the research study's literature review was based on research studies conducted in western countries due to the fact that STEM education is considered as a relatively new domain in the educational system with very limited available research especially in the Middle East other Arab countries.

## RECOMMENDATIONS

The outcomes of the research highlighted the need to improve the practical implementation of STEM education in the schools of Saudi Arabia. The results have shown extensive and strong evidence that these results would assist in comprehending the major role that teachers play in the implementation of educational reforms.

The results further provided a window to evaluate the applied teaching strategies and identify the weak spots that should be addressed to provide future support and assistance in the implementation of the new curricula. Recommendations related to research identify several fields of action to improve the impact and diffusion of the STEM education in Saudi Arabia. On account of the lack of supporting studies available in Saudi Arabia, more research is recommended to provide conclusive vision of the new mathematics and science curricular reform. A call for more regional research is necessary to improve scientific educational systems to keep up with the much-needed rapid speed of development as Saudi Arabia is considered far behind. This exploration study ought to be conducted with a larger sample to affirm its discoveries, where additionally investigations should be done in other geographic areas and crosswise over other STEM orders to recognize whether the techniques distinguished in this review are like those discovered somewhere else. Furthermore, it has been observed that there is very little research regarding the coherence between mathematics and science subjects in the given curriculum and more research is required to investigate how curricular coherence works for students.

Research works should also be carried out on how students perceive and observe these connections. Additionally, the introduction of *Reformed Education* approaches and its teaching methods should be the focus of teacher's development programs and workshops. Reformed education deals with recruiting and adequately preparing teachers with both the subject knowledge as well as the pedagogical knowledge which is necessary to implement specific teaching strategies needed to effectively teach their subjects. Additionally, inadequate understanding about inquiry-based instruction, complexity of the approach and educational significance to future educators and STEM professionals provide justification to offer and investigate inquiry-based STEM professional development. This development would be useful for faculty members teaching mathematics and science subjects in all school levels.

Regarding practice, additional investments by the authorities in optimizing interaction and collaboration between mathematics and science teachers are required. It could be in the form of establishment of an educational platform that brings together curricular developers, trainers, and teachers to provide resources and reference sources for the formulation of best practice regarding STEM reform in the kingdom. Furthermore, research is required to study redesigning and the restructuring of teachers' development programs and workshops with the addition of STEM training and its implementation practices. Moreover, the enhancement of mathematics and science teachers' participation in workshops and professional development programs especially those that prepare teachers to design and implement integrative STEM education and improved instructional practices. Furthermore, coordination within teachers of different STEM disciplines, should be enhanced and encouraged in order to accomplish successful implementation of STEM education.

For the recommendations related to the field of education, findings have suggested that more effort to increase public awareness on STEM education and strategies are needed for promoting its adoption and implementation.

In order to implement STEM education in Saudi Arabia, additional focus in organizing and developing correlation between topics within individual STEM subjects are required. Reorganization of the new mathematics and science curricula should be carried out in a way that the topics of different STEM subjects are in sequence and consistent with each other. Furthermore, the development of professional development programs and workshops need to be restructured in accordance with the educational needs, standards and should be as beneficial as possible to match the objective and purpose of the new mathematics and science curricula.

Also, in order to ensure maximum participation of teachers in faculty development and teaching related endeavours, educational institutions as the Ministry of Education and school heads should value such efforts. This can be achieved by motivating faculty members that additional time they spend on developing new instructional strategies will be taken into account in annual reviews, pay revisions, promotions, etc. There is also a need to develop a unified documented tool to investigate instructional practices being carried out in the classroom as a means of assessment and quality control.

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# Manipulatives and Multiplicative Thinking

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## ABSTRACT

This small study sought to determine students' knowledge of multiplication and division and whether they are able to use sets of bundling sticks to demonstrate their knowledge. Manipulatives are widely used in primary and some middle school classrooms, and can assist children to connect multiplicative concepts to physical representations. Qualitative data were generated from semi-structured interviews with 32 primary and middle school children aged nine to eleven years. Participants were asked to work out the answer to multiplication and division examples and explain their thinking using bundling sticks. Results suggest that the majority of participant students may have a limited knowledge of aspects of the multiplication process and even less knowledge of the division process. The study also identified that many of the students appeared uncomfortable and/or unfamiliar with using bundling sticks and a number of them had difficulty in using bundling sticks to explain the multiplication and division processes. We conclude that manipulatives such as bundling sticks do not magically lead children to mathematical learning but are sufficiently powerful to warrant teachers familiarising themselves with how manipulatives can be used to develop conceptual understanding.

**Keywords:** procedural, conceptual, multiplicative, manipulatives

## INTRODUCTION

Multiplicative thinking is one of the 'big ideas' of mathematics and is widely acknowledged as underpinning much of the mathematics learned beyond the early and middle years of primary school (Siemon, Bleckly, & Neal, 2012). It is a complex set of inter-related ideas ranging from equal groups problems, inverse relationship between multiplication and division, multiplicative relationships in place value, and proportional reasoning (Siemon, Beswick, Brady, Clark, Faragher, & Warren, (2015). Most students do not fully understand until they are well into their early secondary school years (Siemon, Breed, Dole, Izzard, & Virgona, 2006). Students who continue to think additively find it difficult to progress beyond early mathematical concepts (Devlin, 2008) and it is incumbent on them to reconceptualise their thinking to fully understand multiplicative concepts (Wright, 2011). The level at which students understand these concepts may depend on the way they are taught and whether they have been encouraged to think conceptually, and in a relational and connected way, as opposed to learning procedurally and having only an instrumental view (Skemp, 1976). Teaching from a conceptual standpoint is likely to involve the use of manipulatives to support the later use of procedures and algorithms (Swan & Marshall, 2010). This paper considers the role of manipulatives in teaching aspects of multiplicative thinking and also looks at the use of manipulatives as a tool for enabling teachers to assess students' knowledge of certain multiplicative concepts.

## LITERATURE REVIEW

### Manipulatives – Some Background

Manipulatives have been variously described as physical or concrete objects or materials that can be handled. Van de Walle, Karp, and Bay-Williams (2013, p. 24) also included pictures and drawings and stated that "Manipulatives are physical objects that students and teachers can use to illustrate and discover mathematical concepts, whether made specifically for mathematics (e.g., connecting cubes) or for other purposes (e.g., buttons)".

Laski, Jor'dan, Daoust, & Murray (2015, p. 1) said that manipulatives are "used to demonstrate a mathematics concept or to support the execution of a mathematical procedure". This is a point that will discussed later when considering results from the study. Swan and Marshall (2010, p. 14) defined a manipulative as "an object that can be handled by an individual in a sensory manner during which conscious and unconscious mathematical thinking will be fostered". They also added that manipulatives have "the potential to lead to an awareness and development of concepts and ideas linked with mathematics" (2010, p. 14). Their use of the word 'potential' is important as it infers that the extent to which such concept development occurs is dependent on the quality of the teaching and teacher knowledge. Swan and Marshall (2010) also indicated that virtual manipulatives should be withheld until children have experienced working with real objects.

The use of manipulatives in mathematics is not new and has been in vogue to various degrees for over a hundred years. Maria Montessori was one of the first mathematics educators to develop manipulatives for use with specific mathematical concepts (Laski et al., 2015). Montessori used manipulatives such as 'golden bead materials' to represent the Base 10 number system to teach place value, relative magnitude of numbers, and operations with numbers up to 10 000 (Laski et al., 2015). During the 1950s and 1960s, Jean Piaget said that children's learning developed through concrete and pictorial stages, to the abstract. Specifically, they progress through a 'concrete operational' stage of learning, which prompted an increase in the use of manipulatives. This is notably similar to what was proposed by Jerome Bruner (Reys, Lindquist, Lambdin, Smith, Rogers, Falle, Frid, S. & Bennett, 2012). Bruner's work gave rise to the concrete > semi-abstract > abstract learning sequence with a strong focus on the use of manipulatives. Specifically, Bruner developed a framework of stages through which children develop, beginning with the enactive stage (manipulation of real-world objects), and followed by the iconic stage based on representation of pictures, and the symbolic stage involving manipulation of symbols (Reys, et al., 2012). This was also facilitated by educators such as Georges Cuisenaire and Zoltan Dienes with the development of their Cuisenaire Rods and Multi-base Arithmetic Blocks (MABs) respectively. Cuisenaire Rods can be used to develop various concepts such as fraction, ratio, and proportion. MABs are most commonly used to build representations of numbers to four digits, and to develop the concepts of trading up and down when operating with numbers. MABs have individual units marked on them whereas Cuisenaire Rods do not. (Furner & Worrell, 2017). Bundling sticks or popsticks are another extremely useful model for developing place value understanding. Van de Walle et al. (2013) describe them as an example of a groupable model as bundles can be bound together and undone. Bundling sticks were used in this study for that reason.

### Effective and Ineffective Use of Manipulatives

Several prominent mathematics education researchers (Baroody, 1989; Ball, 1992; Ma, 1999) have written about manipulatives and urged caution in the way in which they are regarded. In his short but seminal paper, Baroody (1989, p. 4) stated that manipulatives "must be used judiciously and cautiously for good results" and that there is no guarantee that student learning will follow from their use. He posed two criteria which he said teachers should consider when planning to use manipulatives – does the manipulative have meaning for students because it connects with their existing knowledge, and does its use require students to reflect and think? Baroody (1989) suggested that, in order to determine whether or not the criteria are met, teachers need to observe their students at work to see if they followed the designated procedure or if they used a different method. Further to that, he suggested that teachers have students use their manipulative-based procedure to solve word problems and justify their solutions" (Baroody, 1989, p. 4). Ball (1992) took a similar stance in debunking the idea that manipulatives could somehow magically teach children. She noted that "manipulatives – and the underlying notion that understanding comes through the fingertips – have become part of educational dogma" and that teachers are encouraged to think that the use of manipulatives will lead to children coming to correct conclusions (Ball, 1992, p. 17). Baroody and Ball wrote their respective pieces over 25 years ago and their views no doubt reflected the great faith placed in manipulatives at the time.

Ma (1999) made similar points and described effective practice as being when teachers held class discussions after the use of manipulatives enabling them to explicitly construct the links between the interactions with the manipulative and the related symbolic procedures. Ma also noted that such discussions would likely give rise to questions that would deepen students' understanding of the mathematics but that would ultimately depend on the extent and quality of the teacher's content knowledge. Ma (1999, p. 26) made a particularly evocative comment about this – "A good vehicle, however, does not guarantee the right destination. The direction that students go with manipulatives depends largely on the steering of their teacher".

More recently, Roberts (2007, p. 9) echoed Ball in saying that there was nothing magical about manipulatives and that their power rested "in the careful orchestration of the task by the teacher and thoughtful reflection by the students". Again, this requires sound teacher knowledge in order to not only identify the appropriate manipulative to use for representing a particular concept, but to explicitly link the representation in the form of the manipulative to the concept. Laski et al. (2015) also noted manipulatives are merely physical representations of concepts, that abstract thinking is needed to understand the concept, and that the teacher's role is critical. By using the physical resource and the abstract concept together over a period of time, "it allows for an understanding of the two to co-evolve" (Laski et al., 2015, p.2).

Puchner, Taylor, O'Donnell and Fick (2010) described a study of lessons at multiple grade levels from Year K to Year 8. In the Year Six lesson, students were asked to use manipulatives (arrays, base ten blocks) to work out the solution to a two-digit by two-digit multiplication example. Most students were unable to do so but knew how to use the standard algorithm and solved the problems that way. Hence there was no point in using manipulatives because they had already worked out the answer. Puchner et al. (2010, p. 321) explained it this as an example of ineffective manipulative use saying that

> "The manipulative was turned into an end in and of itself, rather than a tool leading to better understanding. This likely occurred because of the deeply embedded focus in U.S. mathematics teaching on the procedure and the product".

Furthermore, Puchner et al. noted that teachers find the use of manipulatives appealing but attempt to use them with traditional procedural teaching methods. The result, they claimed, is that such lessons are likely to be ineffective. Puchner et al., (2010, p. 315) stated that

> "Teachers often use manipulatives in a procedural manner, instructing students to apply a manipulative in a particular manner to obtain the correct answer. Such use obstructs rather than helps conceptual learning".

Other comments they made also align with those made by Ball and Baroody in that teachers often assume that a manipulative will automatically create an internal representation for students and that they find it hard to understand why students fail to form a clear understanding. Puchner et al. (2010, p. 314) then allude to a considerable issue in saying that "the reason teachers experience poor results when attempting to use manipulatives may be because effective use of manipulatives is more difficult than most realize". This seems to be something of a dilemma because teachers often cite poor results with using manipulatives as a reason for not using them.

**Principles for Manipulative Use**

Laski et al. (2015) made a number of important observations about how manipulatives should be used. They proposed four principles for 'maximizing the effectiveness of manipulatives' which reflect what others have said. These principles involve the consistent use over time, characterized by a transition from concrete to abstract, avoidance of manipulatives which have distracting features or closely resemble everyday objects, and explicitly connecting the manipulative to the concept being developed. They suggested that the more basic the manipulative the better. That is, a manipulative that is "stripped of all irrelevant perceptual features – then it helps children direct all of their attention to thinking about its relation with the mathematics concept it represents" (Laski et al., p. 5).

Delaney (2010) stated that the most effective way of using manipulatives was to combine teacher demonstration with students physically handling them. He said that "A resource which facilitates demonstration and interaction mediates discussion in powerful ways" (Delaney, 2010, p. 82). Teachers are able to explain and demonstrate but also to listen to students, interpret their responses, and see what level of knowledge is developing. This is supported by the findings of Carbonneau, Marley, and Selig (2013) in that greater effect sizes resulted when the use of manipulatives was accompanied by extensive instructional guidance rather than when they were used with low levels of guidance. Similarly, Van de Walle et al., (2013, p. 26) said that unless students are engaged in conversation about the mathematical goal, "the manipulative is not serving as a tool for developing the concept".

Boggan, Harper, and Whitmire (2010, p. 3) reinforced what was said by Puchner et al. (2010) and others in that appropriate choice of manipulatives was critical and must match the teaching objectives surrounding the concept being developed but also that "Children must understand the mathematical concept being taught rather than simply moving the manipulatives around [and] explicit instruction and scaffolding of supports is necessary". In order to bring this about, Cope (2015) stated the importance of teachers having the pedagogical training required to make effective use of manipulatives. As Swan and Marshall (2010, p. 16) said, "unless teachers have a clear understanding of how manipulatives assist children learn, they are likely to make only token use of them which may be detrimental to learning".

**Teacher Beliefs about Manipulatives**

In reviewing the work of Golafshani (2013), Furner and Worrell (2017) noted how teachers reported various 'disabling factors' for using manipulatives. Disabling factors included lack of time to prepare, lack of knowledge of multiple uses of manipulatives, lack of confidence and time to practice, difficulty with classroom management, and administrative support for teacher training. Earlier, Pushner et al. (2010) had said that teachers regarded time investment and poor results as factors that lead to non-use. Furner & Worrell also noted various beliefs of teachers about why they used manipulatives. Some of the reasons were to provide a change of pace, a reward, a visual model for introducing concepts, providing reinforcement of enrichment, and to make it more fun.

> "Teachers seemed to distinguish between 'real math' and 'fun math'. 'Real math' referred to lessons where they taught rules, procedures and algorithms to their students through textbooks, and 'fun math' was used when teachers described parts of their lesson where students were utilizing manipulatives" (Furner & Worrell, 2017, p. 12).

This is quite concerning and seems to indicate that some teachers did not see that manipulatives have a real purpose in teaching concepts. Furner & Worrell (2017, p. 13) added that

> "Teachers who believe manipulatives are just used for a change of pace, reward or privilege or fun are not going to genuinely incorporate manipulatives and the concepts they were meant to convey into their lessons".

The implicit message that students would receive is that manipulatives are akin to 'toys' and have little mathematical value.

Swan and Marshall (2010) found similar sentiments when they surveyed some 820 teachers about the advantages of using manipulatives. The highest response was for the category that included 'Heighten interest, helped engage students, enjoyment, fun, motivation' (191), followed by 'Visual aid, assist in concrete visualisation' (188). 135 said 'Provide hands-on learning' and 126 said 'Build better understanding'. In response to what could be termed 'higher order categories', only 61 said 'Help children grasp concepts' and 36 said 'Can be used to introduce concepts'. Similarly, only 27 said 'Teachers can more easily note what the child is thinking' and 23 said 'Encouraged oral language'. The higher order comments did not attract as many comments as the relatively lower order comments such as fun, enjoyment, visual aid etc. This aligns well with the work of Furner & Worrell about why teachers use manipulatives. It seems that a relatively small proportion of teachers see that manipulatives can be used to develop conceptual understanding.

Earlier work by Perry and Howard (1994) reported that the use of manipulatives was favoured more by teachers of Year 4 and below. They considered that this is likely due to the belief that Piaget's 'concrete operational' stage is completed by the age of ten or eleven years and that manipulatives are not needed after that age. As well, Perry and Howard (1997, p. 29) found that "As students grow older, many have a perception that is 'babyish' to use manipulatives". They also noted a common perception that Years 5 and 6 are preparation years for secondary school, where manipulatives are unlikely to be used, so their use diminishes in upper primary classes. This is generally supported by the findings of Swan and Marshall (2010) who asked teachers how often they used manipulatives. The responses for 'daily' or 'several times a week' ranged from 100% of Pre-primary teachers and 96% of Year 1 teachers to 54% of Year 5 teachers and 48% of Year 6 teachers.

**Conceptual/Relational Understanding v. Procedural/Instrumental Knowledge**

In his seminal paper, Skemp (1976, p. 89) discussed the differences between relational and instrumental understanding, noting that the latter is difficult to equate with 'understanding' at all as it more akin to "rules without reasons" whereas relational understanding is "knowing both what to do and why". For the purpose of this paper, relational understanding is equated with 'conceptual understanding' and 'connected knowledge' while instrumental knowledge is equated with 'procedural knowledge'. Skemp (1976, p. 92) went on to outline several advantages of relational understanding, one being that "it is more adaptable to new tasks".

Researchers (Hiebert, 1999; Puchner et al. 2010) have stated that students who have learned and practiced a procedure or algorithm, which they may not understand, are less likely to want to understand conceptually the underpinning mathematics. Mason, Stephens, and Watson (2009) view procedural and conceptual knowledge as intertwined rather than as alternatives. They suggest that although procedures are important in mathematics, recalling and using them without conceptual knowledge places too large a load on memory. They refer to this intertwined knowledge as an "appreciation of mathematical structure" (Mason et al., 2009, p. 12) and argue that relationships between mathematical ideas can be used for determining how appropriate a procedure is for solving a particular problem. From this perspective, procedural knowledge has to be appreciated in relation to the mathematical structure and context of the problem. These observations seem to point to the benefits of teaching conceptually rather than just focusing on procedures.

**Multiplicative Thinking**

Multiplicative thinking is considered to be one of the 'big ideas' of mathematics (Hurst & Hurrell, 2014; Siemon, Bleckley, & Neal, 2012) and is a complex set of connected mathematical ideas. It has been defined by (Hurst, 2017) with the definition based on earlier work by Siemon et al. (2006) and Siemon, Bleckley, & Neal (2012). Multiplicative thinking is characterised by the capacity to:

- Work flexibly with a wide range of numbers including very large and small whole numbers, decimals, fractions, ratio and percentage
- Work conceptually with the relative magnitude of whole and decimal numbers in a range of representations, demonstrating an understanding of the notion of 'times as many'
- Demonstrate a conceptual understanding of the multiplicative situation, the relationship between multiplication and division, numbers of equal groups, factors and multiples, and the various properties of multiplication
- Articulate a conceptual understanding of a range of multiplicative ideas in a connected way with explicit language and terminology.

This study is particularly concerned with aspects of each of the dot points. That is, to see numbers in flexible ways through partitioning, demonstrate an understanding of the relative magnitude of numbers with respect to place value, and use manipulatives in the form of bundling sticks to articulate an understanding of the concepts of equal groups and the relationship between multiplication and division.

**Multiplication and Division – The Inverse Relationship**

Jacob and Mulligan (2014) and Hurst (2015) discussed the importance of considering the 'multiplicative situation' and seeing multiplication and division together, rather than as separate processes. That is, the three quantities – number of groups, number in each group, and total – can be used to consider a multiplication problem and its inverse that is division. Hurst (2015, p. 11) pointed out the following – "If we know the group size and the number of groups, we multiply. If we know the total amount and one of the other quantities, we divide to find the one we don't know". Hence, an array with five rows of three can be used to describe a multiplication situation of $5 \times 3 = 15$ but can be used equally well to describe the inverse situation of $15 \div 5 = 3$, where the total of fifteen is split into five equal groups of three (Hurst, 2015).

Downton (2013, p. 242) stated that, "The notion that division of whole numbers can be interpreted in two different ways reflects its relationship to multiplication, namely division by the multiplier (partitive model) and division by the multiplicand (quotitive model)". She described partitive division in terms of knowing the number of equal parts but not the size of the parts, and quotitive division as knowing the size of the equal parts but not how many parts there are. Downton (2013, p. 242) suggested that children needed "to develop their conceptual understanding of the multiplicative relationships inherent in a problem" through working with a range of problem types, and that it was important to teach division alongside multiplication, not after it. Ultimately, Downton (2013, p. 242) saw the conceptual understanding of division and its inverse relationship with multiplication as being more important than "whether a task involves partitive or quotitive division".

**Manipulatives and Multiplicative Thinking**

Various researchers have discussed the use of manipulatives to develop multiplicative concepts. Jacob and Mulligan (2014) describe how the multiplicative array is an ideal representation for the notion of equal groups as it can show the three quantities involved – number of groups, number in each group, and product – at the same time. Arrays can be made with manipulatives such as counters or tiles. Siemon et al. (2015) discuss the development of early place value knowledge through the use of bundling sticks or stacks of cubes. They note the importance of counting such bundles, not in terms of 'ten, twenty, thirty' etc., but 'one ten, two tens' etc. as, "it is important to emphasise the count of tens" (Siemon et al., 2015, p. 297).

As noted earlier in this discussion, it is the way in which manipulatives are used, not merely that they are used. Askew noted the importance of assisting children to move 'from using them as models *of* to being models *for* and then to becoming *tools for thinking with*' (Askew, 2016, p. 139). To do this, teachers need to make the connections between the mathematical structure and the manipulative explicit for children, whether the manipulative/s be counters or tiles forming an array, bundling sticks or cube stacks to demonstrate partitioning, or other manipulatives.

The proposition is that if students know about partitioning based on place value and have developed a knowledge of the distributive property of multiplication and numbers of equal groups through the use of the array, they are in a position to learn about the grid method of multiplication, and consequently, the standard multiplication algorithm. Similarly, if they have a conceptual understanding of the multiplicative situation based on numbers of equal groups, they better placed to learn about the splitting of quantities and eventually represent this as a division algorithm. As noted earlier, the notion that manipulatives could be used to develop an understanding of multiplicative concepts was of interest. In particular, the study reported on here is particularly concerned with an understanding of multiplication and division.

### Research Questions

The following research questions were posed:

- What processes do primary and middle school children use for multiplication and division?
- Do primary and middle school children use place value partitioning for multiplication and division?
- Are primary and middle school students able to explain the processes of multiplication and division through the use of manipulatives such as bundling sticks?

## METHODOLOGY

The use of manipulatives in mathematics teaching, in particular for the teaching of multiplicative concepts, has been discussed in the previous section. The study reported on here is part of a large on-going project on multiplicative thinking that has involved teachers and their students aged between nine and thirteen years from schools in Western Australia, New Zealand, and the United Kingdom. This particular part of the study was conducted to find out the extent to which a sample of primary and middle school students knew about the processes of multiplication and division, and if they were able to explain their thinking with the use of manipulatives.

A sample of 32 New Zealand students from Year 4 (six students), Year 5 (nine students), and Year 6 (17 students) were interviewed by the researchers. Interviews were conducted in the latter part of the school year, and children's ages ranged from nine to eleven years. Three or four students were selected from each of nine classes and they were identified by their class teachers as representing a cross section of mathematical ability. Interviews were audio recorded and manually transcribed. Photographs were taken of applicable work samples and/or use of manipulatives. Students were asked the following four questions:

1. Show me and/or tell me how you would work out the answer to $7 \times 15$.
2. Please show me with some of the bundling sticks what is happening in the working out that you explained/showed me.
3. Show me and/or tell me how you would work out the answer to $90 \div 7$.
4. Please show me with some of the bundling sticks what is happening in the working out that you explained/showed me. [* Students who were unable to work with the numbers in Questions 1 and 3 were given 'easier questions with single digits to eliminate the possibility that the size of the numbers had an impact on their capacity to complete the task.]

Bundling sticks were used in the study to facilitate children's ability to demonstrate their understanding of place value, which is closely linked to multiplicative thinking. The ability to multiply and divide with numbers greater than one digit necessitates an understanding of place value. Specifically, children needed to make the conceptual link between a bundle/s of ten sticks and the tens digit in the numbers 15 (the multiplication question) and 90 (in the division question). The multiplicand 15 was chosen for the multiplication problem because children were likely to know the multiplication facts for five and so lack of known facts would be unlikely to be a distractor. Bundling sticks (popsicle sticks) were provided in pre-bundled sets of ten and as single sticks. They were used in preference to Multi-base Arithmetic Blocks (MABs) as the bundles can be easily split and re-grouped. Van de Walle et al. (2013, p. 195) noted that "put-together-take-apart" models such as bundling sticks "most clearly reflect the relationship of ones, tens, and hundreds [because] the ten can actually be made or grouped from the single pieces". They also said that pre-made bundles of ten provide a good transition to pre-grouped models like MABs. In New Zealand, the second tier curriculum material places an emphasis on children grouping physical objects to make ten, and suggests bundling sticks or containers of plastic beans. The division question may appear difficult but bundling sticks were used to facilitate children's chances of understanding and demonstrating the remainder in the answer. If an easier task had been used a child might have known there would be a remainder because the dividend was not an answer to a known multiplication fact. As it transpired, some children were able to demonstrate the remainder and some could not do so. (Siemon, et al., (2015) also noted the importance of bundling sticks as children need the physical experience of making up the bundles of ten, and moving to the pre-grouped MABs too soon can cause confusion for some children. Bundling sticks have a high 'epistemic fidelity'. (Siemon, et al., 2015, p. 110) describe 'epistemic fidelity' as

> "the measure of the quality of the mapping between the material's features and the target knowledge domain. If this mapping is strong, the model is often termed transparent as it allows students to 'see through it' to the underlying mathematics".

## RESULTS

### Multiplication 7 × 15

The results for Question 1 – Show me and/or tell me how you would work out the answer to 7 × 15 – are presented here in **Table 1**.

**Table 1.** Summary of responses to Question 1

| Response and frequency by year level | All | Y4 | Y5 | Y6 |
|---|---|---|---|---|
| *Completely demonstrated knowledge of the multiplication process (19)* | | | | |
| Correctly used part products 7 × 10 and 7 × 5 based on place value partition | **18** | 1 | 6 | 11 |
| Correctly used different part products – 7 × 12 and 7 × 3 | **1** | | 1 | |
| *Partially demonstrated knowledge of the multiplication process (6)* | | | | |
| Used an additive strategy to work out the answer | **3** | 3 | | |
| Used an appropriate alternative strategy to work out the answer | **3** | | 1 | 2 |
| *Unable to demonstrate knowledge of the multiplication process (7)* | | | | |
| Unable to work out the answer to 7 × 15 | **7** | 2 | 1 | 4 |

Over half of the students who correctly used the standard partition or part products were able to work out the answer mentally. When they were asked to explain how they arrived at the answer, most showed something similar to Kim (Year 5) and Tom (Year 6).

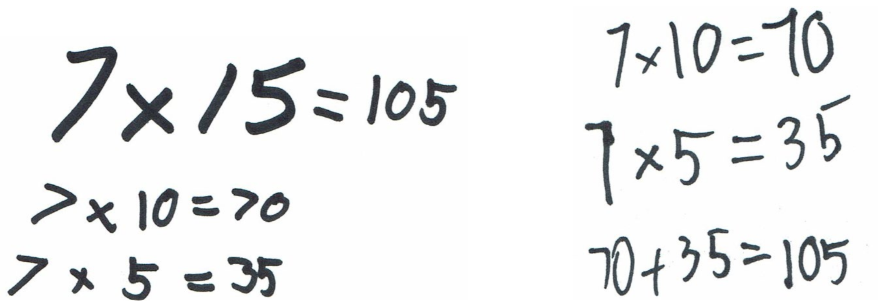



**Figure 1.** Samples from Students Kim (Year 5) and Tom (Year 6)

Only one student wrote the standard vertical multiplication algorithm and one other said that she visualised it in her head.

In Question 2, students were asked – Please show me with some of the bundling sticks what is happening in the working out that you explained/showed me. The responses are compiled here in **Table 2**. There are several categories of student responses ranging from completely representing the multiplication process to being unable to use the bundling sticks.

**Table 2.** Summary of responses to Question 2

| Responses and frequency by year level | All | Y4 | Y5 | Y6 |
|---|---|---|---|---|
| ***Completely represented the multiplication process (11)*** | | | | |
| Showed 7 groups of 15 (1 ten and 5 singles), grouped the 7 tens as 70 and the 7 fives as 35, before regrouping the 35 as tens and singles | **10** | | 3 | 7 |
| Made a 7 × 15 array | **1** | | 1 | |
| ***Partially represented the multiplication process (6)*** | | | | |
| Did not make 7 groups of 15. Made bundles of answers to partial products only. Did not combine partial products. | **2** | 1 | 1 | |
| Showed 7 groups of 15 but did not physically combine and regroup them | **4** | 1 | 1 | 2 |
| ***Incorrectly represented the multiplication process (1)*** | | | | |
| Made bundles of only the two factors (i.e., they made a group of 7 and a group of 15) | **1** | | | 1 |
| ***Unable to use the bundling sticks (14)*** | | | | |
| Not able to use the bundling sticks in a meaningful way, despite prompting | **14** | 4 | 3 | 7 |

It can be seen that there is much wider range of responses to Question 2 than for Question 1. Only ten students represented the multiplication process by showing seven groups of 15, combining the seven ten bundles and the seven bundles of five, before regrouping the fives as tens and showing the total. This reflects the partial product method and also the algorithm. Typical samples of a student's work in completely representing the process is shown in **Figure 2**. Lisa (Year 5) made the seven groups of 15 (picture 1 in **Figure 2**), then put the seven bundles of 10 together (picture 2 in **Figure 2**) and finally regrouped the 35 bundle into three tens and five singles (picture 3 in **Figure 2**).

**Figure 2.** Samples from Student Lisa (Year 5)

**Figure 3** contains some examples of how some students used the bundling sticks incorrectly. Tyler (Year 4) was able to work out the answer for 7 × 15 by using partial products of 7 × 10 and 7 × 5 (in Question 1) but when he used the bundling sticks he made only groups of sticks to represent the factors – that is, groups of 7, 10, 7 and 5 (picture 1 in **Figure 3**). Joss (Year 5) was unable to solve 7 × 15 and was asked to work out 4 × 14 to see if different numbers would enable him to complete the task. He used the sticks to show the factors of 4 and 14 (see picture 2 in **Figure 3**). Rowan (Year 6) was also unable to work out 7 × 15 and was asked to show 4 × 5 with bundling sticks (see picture 3 in **Figure 3**). Rowan was given the 'easier' question to find out if it were the sizes of the numbers in 7 × 15 that were causing him difficulty. However, there appears to be no knowledge of the concept of numbers of equal groups with the three students whose responses appear in **Figure 3**.

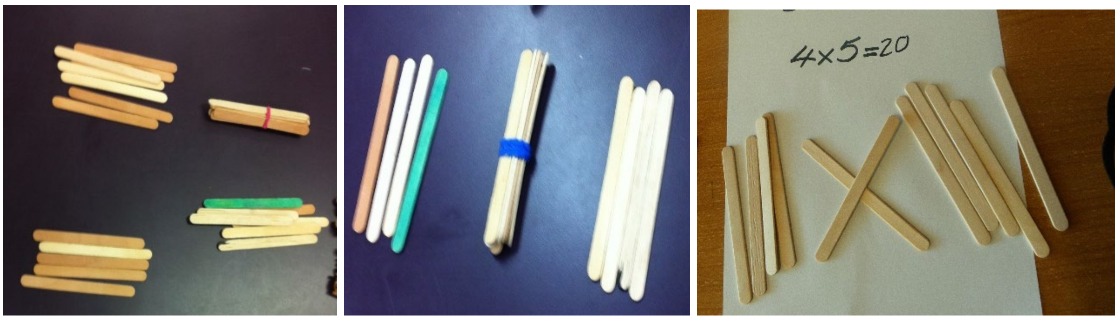



**Figure 3.** Samples from Students Tyler (Year 4), Joss (Year 5), and Rowan (Year 6)

A comparison of responses to Questions 1 and 2 about the multiplication of 7 by 15 also provokes some useful discussion. As is seen from **Tables 1** and **2**, 19 students responded correctly to Question 1 by using a partial product strategy or a viable alternative. However, only ten were able to use the bundling sticks to completely represent the multiplication process, that is, by showing seven groups of 15, combining the seven bundles of ten and the seven bundles of five, before regrouping the fives as tens and showing the total. One student made a 7 by 15 array, which although correct, is different to depicting seven bundles of fifteen. Six other students partially represented the multiplication with bundling sticks. Four of them made seven groups of fifteen and two made bundles of parts products but none physically combined or re-grouped the bundling sticks.

In seeking a reason/s for the fact that only eleven students were able to fully represent the multiplication process with the sticks, it is tempting to conclude that it is due to their lack of familiarity with the bundling sticks. Both researchers who worked on this study commented that many of the students who were interviewed seemed uncomfortable about using the bundling sticks and many took a long time in coming to terms with what to do with them. They did not seem to connect what they had said when explaining how they solved 7 × 15 with the physical representation of it. This supports the comments reported earlier by Baroody (1989), Ball (1992), Boggan et al. (2010), and Carbonneau et al. (2013), that teachers need to be explicit about helping their students to make the connection between the concept and the manipulative. Although it might be expected that students had worked with concrete materials before using the formal algorithm, our results suggest that this may not have happened. It is encouraging that the majority of students were able to use partial products based on place value partitioning to work out the answer to 7 × 15 as this situates them well to understand the distributive property, the grid method for multiplication, and later, the vertical multiplication algorithm. However, to really consolidate their knowledge, it is important that they are able to translate their use of partial products in terms of a physical representation. They needed to show the seven groups of ten and the seven groups of five, combine them into groups of 70 and 35, then regroup the 35 into three tens and five, and finally to make a bundle of ten tens and five singles to show the answer of 105. Six students did this partially which suggests that their knowledge of the multiplication process is not sufficiently robust, perhaps because they have not been accustomed to using bundling sticks. Indeed, nearly half of the students were not able to use the bundling sticks to show seven groups of fifteen.

**Division 90 ÷ 7**

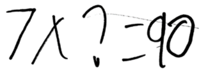
Responses to Question 3 – Show me and/or tell me how you would work out the answer to 90 ÷ 7 – are contained in **Table 3**.

**Table 3.** Responses to Question 3

| **Responses and frequency by year level** | **All** | **Y4** | **Y5** | **Y6** |
|---|---|---|---|---|
| *Completely demonstrated knowledge of the division process (7)* | | | | |
| Obtained correct answer of 12 remainder 6 having used a strategy starting with a split of 90 into 7 × 10, and then splitting the remaining 20 | **6** | | 2 | 4 |
| Obtained correct answer after re-writing the example as a multiplication sentence 7 × __ = 90 | **1** | | | 1 |
| *Partially demonstrated knowledge of the division process (4)* | | | | |
| Indicated that 90 ÷ 7 required splitting 90 into seven groups but was unable to complete the working out | **4** | | 1 | 3 |
| *Unable to demonstrate knowledge of the division process (21)* | | | | |
| Unable to work out 90 ÷ 7 in any way | **21** | 6 | 6 | 9 |

Cam (Year 6) explained his thinking in this way – "7 times 10 is 70 and 7 times 2 is 14, and there would have to be six left over. It would be 12 . . . but there are 6 left over . . . I don't know how to write that". Maxine (Year 6) showed some sound reasoning and perseverance during this exchange with the interviewer:

MAXINE: I haven't done anything like this before.
INT: OK, so when you see 90 divided by 7, what is it asking you to do, do you think?
MAXINE: It's like seven times what equals ninety – she then wrote down . . .




INT: Any idea how you might do that?
MAXINE: Well 7 times 12 is . . . 84, so 7 times 13 would be . . . 91, so . . . it's more than 90 so it probably wouldn't be a whole number . . . Twelve times . . . and six more makes 90

Responses to Question 4 – Please show me with some of the bundling sticks what is happening in the working out that you explained/showed me – are contained in **Table 4**. As with Question 2, there are several categories of responses to this question – completely representing the division process with bundling sticks, partially doing so, and being unable to do so.

**Table 4.** Responses to Question 4

| Responses and frequency by year level | All | Y4 | Y5 | Y6 |
|---|---|---|---|---|
| *Completely represented the division process (8)* | | | | |
| Collected 9 bundles of 10, made 7 shares of 10, and split the remaining 20 into seven shares of two sticks, with 6 left over | **8** | | 2 | 6 |
| *Partially represented the division process (1)* | | | | |
| Made 7 groups of 10 and split the remaining 20 sticks but didn't make all groups the same and didn't have a remainder | **1** | | 1 | |
| *Unable to use the bundling sticks (23)* | | | | |
| Unable to use the bundling sticks in any meaningful way, despite prompting | **23** | 6 | 6 | 11 |

When comparing the responses to Questions 3 and 4, some very interesting observations can be made. Of the seven students who obtained a correct answer for Question 3, only one of them, Cam (Year 6), also correctly represented the division process with the bundling sticks. It is possible that the other six students who were unable to use the bundling sticks did not have a robust knowledge of the division process and had possibly learned it in a procedural way. However, eight of the students who did not obtain a correct answer for Question 3, were able to correctly represent the division process in Question 4. It is possible that the bundling sticks enabled those eight students to organize their thinking and to understand exactly what was happening in the division or sharing process. Some of their responses follow here beginning with Lyle (Year 5).

Lyle (Year 5) counted out seven of the ten bundles and then said, "Now what do you do with these ones? [i.e., the last two ten bundles] . . . you have to divide the twenty between the seven groups. You could try three . . . [He counted out the sticks and got to the last group] . . . but then you have that" [not enough to go round]. [See his arrangement in **Figure 4**]

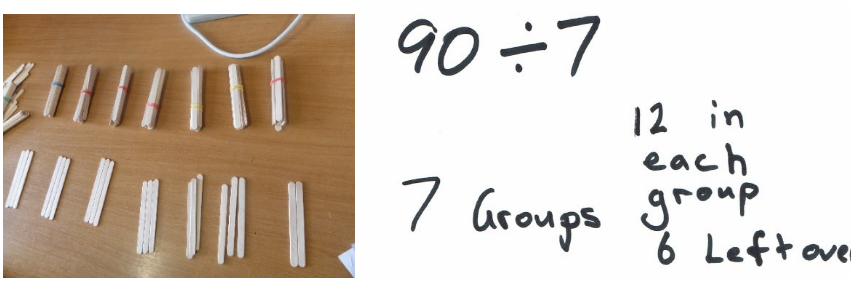



**Figure 4.** Sample from Student Lyle (Year 5)

INT: What do the groups have to be?

LYLE: "They have to be even . . . I put too many in". He counted out seven and allocated one to each group and repeated the process and had six left over. LYLE recorded it as above.

Sally (Year 5) was also unable to work out the answer to 90 ÷ 7 but did so when using the bundling sticks. Following is the conversation between Sally and the interviewer. **Figure 5** contains her work samples.

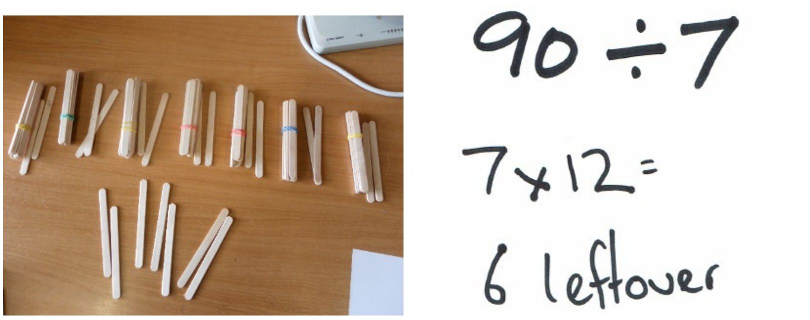



**Figure 5.** Samples from Student Sally (Year 5)

SALLY made seven groups with a bundle of ten in each group.

INT: What are you going to do with the others?

SALLY: "I'd probably split them up. I'd just keep adding the sticks to the groups". SALLY shared the single sticks into the seven groups

INT: What's happened?

SALLY: "We're one short".

INT: What's important about the seven groups?
SALLY: "They have to be even". [See **Figure 5**]
INT: How many are there in each group now?
SALLY: "There's 12". SALLY recorded the division on her work sample, as above.

Zac (Year 6) also had difficulty with 90 ÷ 7, as the following conversation shows. However, when he used the bundling sticks, he was able to work out the answer. **Figure 6** shows his work samples. The first picture shows the unfinished array that he drew initially.

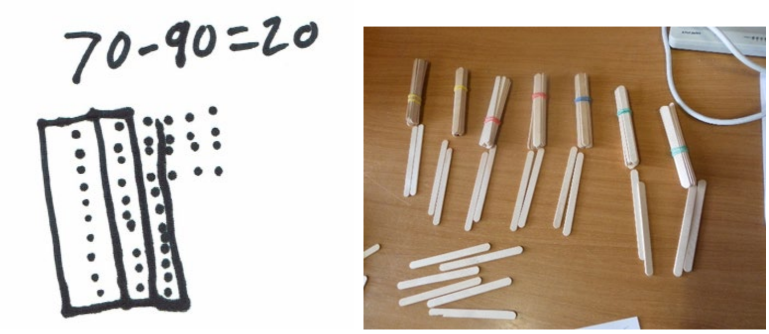



**Figure 6.** Samples from Student Zac (Year 6)

Zac drew an array of sorts [See sample] He then wrote 70-90=20 and said "You can't do it, because . . . if there was one added to the 90, you could do it because it would be even".

INT: So what's this actually asking you to do?
ZAC: "Divide it into seven groups". He selected 9 bundles of ten and shared them into seven sets of ten and had 20 left over.
INT: What are you going to do with the 20? ZAC unbundled the two sets of ten and counted them out one by one to give equal groups of 12 and 6 left over [See **Figure 6**].

It seems that a combination of discussion and questioning from the interviewer and the availability of the bundling sticks assisted Lyle, Sally, and Zac to more clearly understand the division process, which they were unable to do initially. This supports the comments made by Delaney (2010) and Van de Walle et al. (2013) about the use of dialogue in association with manipulatives. Also, they demonstrated that they do understand the notion of numbers of equal groups, depending on the situation and context. It is also worth noting that Zac attempted to solve for 90 ÷ 7 by drawing an array and it would have been interesting had he continued that to its conclusion.

With regard to the six students who correctly answered Question 3 (work out the answer for 90 ÷ 7), but could not use the bundling sticks to demonstrate it, there is perhaps one clue in one student's response as to why they were unable to use the bundling sticks. Kal (Year 6) appeared very capable and almost instantaneously gave the answer for Question 1 (7 × 15) and Question 3 (90 ÷ 7). When asked to use the sticks, Kal said, "I don't know. I've never worked with sticks before". It is possible that Kal, and perhaps others in the group, had learned to calculate examples like those in Questions 1 and 3 in a procedural way as they do not seem to understand at a conceptual level about numbers of equal groups.

## DISCUSSION OF FINDINGS

There are several points to emerge from the data for this short study. First, the majority of the participants (78%) were able to calculate for 7 × 15 but only 34% could do so for 90 ÷ 7. It is surprising that the difference is as great as it is, given that multiplication and division are the inverse of one another. Indeed, only one student (Maxine) identified that when working out the answer for the division example. This seems to indicate that students have been taught a process for multiplying a one-digit and two-digit number but have not been taught how to divide a two-digit number by a one-digit number. This conjecture is supported by the observation that most of the students who were interviewed were clearly uncomfortable with the use of bundling sticks. Had they been used to manipulating bundling sticks, accompanied by some explicit teaching, they may have been able to see the connection that exists between multiplication and division and that it is based on the number of equal groups. In the case of the multiplication example (7 × 15 = 105), that would have been manifest as 15 × 7 = 105 (commutative property) but also as 105 ÷ 7 = 15 and 105 ÷ 15 = 7.

Second, 59% of the participants used a partial product strategy to calculate the answer for 7 × 15. Most used (7 × 10) + (7 × 5) based on place value partitioning. However, as shown in **Table 2**, only 34% were able to use the bundling sticks to fully demonstrate the multiplication process. It seems clear that they have not made the connection between the physical representation provided by the bundling sticks and the concept of partial products or the distributive property. There are two points to consider here – one is that the students have probably not had much exposure to bundling sticks to build knowledge of the processes of multiplication and division, as suggested above. The second is the power of bundling sticks to identify students who do not have a robust knowledge of the multiplication and division processes and the relationship between them.

Third, student responses to the use of bundling sticks for Question 4 has created something of a dilemma. Five of the seven students who actually obtained the correct answer for Question 3 (12 remainder 6) were unable to demonstrate the process using the bundling sticks. It may be that the students who obtained the correct answer but couldn't demonstrate with the bundling sticks, were unfamiliar with using the bundling sticks. On the other hand, eight of the students who did not arrive at the answer of 12 remainder 6 for Question 3, *were* able to demonstrate the division process using the bundling sticks. It appears as if the bundling sticks facilitated the development of knowledge for some students but not for others. As suggested earlier, perhaps the students who were unable to demonstrate the division process with the bundling sticks held a very procedural view of it. Also, for Questions 3 and 4, only 34% of students were able to provide the answer for 90 ÷ 7 or suggest it required 90 being split into seven groups and only 28% could use bundling sticks to completely or partially represent the division process.

It appears that the majority of students (59%) calculated the answer for 7 × 15 using partial products and also either completely or partially demonstrated the multiplication process with the bundling sticks. This appears to place them in a good position for learning about grid multiplication and later, the vertical multiplication algorithm. Grid multiplication is developed by combining the array and the distributive property and is an important pre-cursor for understanding the written multiplication algorithm (Hurst & Hurrell, 2018a). Initially, an array for a two-digit by one-digit example is used (e.g., 7 × 15) based on standard place value partitioning and then a two-digit by two-digit example can be developed as the foundation for the written algorithm (Hurst & Hurrell, 2018b). However, the concept of splitting quantities into numbers of equal groups does not appear to be as well understood. Hence, it is unlikely that the students in this sample have sufficient conceptual understanding to learn about an algorithm for division.

With regard to the responses by year level, the majority of students in each year level were able to demonstrate or partially demonstrate the multiplication process (Question 1) in terms of part products or an alternative strategy. However, a minority of Year 4 students could demonstrate the process using bundling sticks (Question 2) whilst approximately half of the Year 5 and Year 6 students could do so. For the division question (Question 3), no Year 4 student could demonstrate the process, and a minority of year 5 and Year 6 students could do so. This pattern was the same for the use of bundling sticks to represent the division process (Question 4) where no Year 4 student could do so, and a clear minority of Year 5 and Year 6 students could do so. This raises an interesting issue. It might generally have been expected that students in Year 4 might be more familiar with the use of bundling sticks than students in Years 5 and 6 yet a greater proportion of students in the latter year levels were able to appropriately use the bundling sticks.

## CONCLUSIONS AND IMPLICATIONS

It needs to be stated at the outset that the number of participants in the sample was relatively small and therefore it is not appropriate to claim that any major generalisations can be made on the basis of these results. Nonetheless, observations suggest that similar research with a larger student sample is worth pursuing.

The research questions for the study were as follows:

- Research Question 1: What processes do primary and middle school children use for multiplication and division?
- Research Question 2: Do primary and middle school children use place value partitioning for multiplication and division?
- Research Question 3: Are primary and middle school students able to explain the processes of multiplication and division through the use of bundling sticks?

In terms of these research questions, the following can be said:

The majority of students in the sample demonstrated knowledge of partial products based on place value partitioning and were able to solve the multiplication example in that way. However, a large proportion of these successful students were not able to demonstrate the multiplication process using the bundling sticks. It is reasonable to suggest that they may have procedural knowledge rather than conceptual knowledge of multiplication. Only a minority of students could solve the division example suggesting that perhaps the connection between multiplication and division has not been made explicitly clear to them. Furthermore, only one of these successful students correctly represented the division process with the bundling sticks, again suggesting procedural rather than conceptual knowledge.

There are several implications to emerge from this study. The power of manipulatives such as bundling sticks is clear, both as a tool for teaching conceptually and as an assessment resource for quickly identifying whether or not students have a conceptual understanding. However, the results from the study seem to indicate that the participants were uncomfortable and unfamiliar with using bundling sticks. Our study provided little indication of children having learned multiplicative concepts through use of manipulatives in their instruction. As was suggested in the literature review (Puchner et al., 2010; Swan & Marshall, 2010; Furner & Worrell, 2017), teachers should consider manipulatives as a powerful tool for teaching concepts and regard them as much more than a motivational aid, or to add a dimension of 'fun' to mathematics lessons. They are clearly more than the latter and targeted professional learning in the use of manipulatives is likely to be of assistance to teachers. Professional learning for teachers could be based around the principles for manipulative use developed by Laski et al. (2015) and incorporate training in specific pedagogies for manipulative use including how to incorporate effective discussion, questioning, and demonstration (Delaney, 2010; Swan & Marshall, 2010). These principles could be used to develop a sound understanding of the standard multiplication algorithm from children's use of arrays.

Baroody (1989), Ball (1992), and Ma (1999) all made some evocative statements about the use of manipulatives and these were reported in the literature review. Clearly, there are no guarantees with using manipulatives, they do not magically lead children to mathematical learning, and their use requires careful direction by the teacher. More importantly, teachers need to familiarise themselves with just how manipulatives can be effectively harnessed to help students develop a deep knowledge of multiplicative concepts.

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# Cognitive Load in Solving Mathematics Problems: Validating the Role of Motivation and the Interaction Among Prior Knowledge, Worked Examples, and Task Difficulty

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## ABSTRACT

Cognitive load can play a key role in learners' abilities to solve complex problems like mathematics. Many factors can affect the presence of cognitive load in learning including instructional strategy, task difficulty and prior knowledge. To understand the interaction of above factors and their influence on learner cognitive load and performance, a three-way interaction study was conducted with worked example (full- vs. completion-worked examples), task difficulty (easy vs. difficult) and prior knowledge (high vs. low) serving as independent variables, and cognitive load and performance as dependent variables. One hundred and sixty participants were recruited who were randomly assigned into one of eight learning conditions. Results revealed a significant three-way interaction by posttest. It was found that higher-prior knowledge learners performed better with completion-worked examples than full-worked examples whereas lower-prior knowledge learners performed better with full-worked examples than completion-worked examples. Significant positive correlation was found between intrinsic and germane cognitive load implying that interest in the instructional domain is an important determinant in effecting germane cognitive load.

**Keywords:** cognitive load, math education, motivation, prior knowledge, worked examples

## INTRODUCTION

It is widely recognized that learners' performance in complex learning like mathematics and STEM related domains can be significantly influenced by the cognitive load during learning (Ayres, 2018; Sweller & Chandler, 1991). Further, the amount of cognitive load and learner performance are found to be related to factors like domain prior knowledge (Kalyuga, Chandler, & Sweller, 1998; Richter & Scheiter, 2019), task difficulty (Lee, Plass, & Homer, 2006; Lynch, Hurley, & Cumiskey, 2019), and instructional strategy (Saw, 2017; Wallen, Plass, & Brunken, 2005). Despite the individual correlations between cognitive load and the above factors, the question of how these factors together function to affect the degree of cognitive load presence and performance remains unanswered. It is argued that factors like domain prior knowledge, task difficulty, and instructional strategy may concurrently influence and mediate the functional role of cognitive load in learning (Gupta, 2015). As such, studying how these factors interact to impact cognitive load may help reveal the roles of key individual and educational variables on learners' outcomes in learning, particularly in STEM learning. The first goal of present study is therefore to explore the interaction among the factors previously mentioned in terms of their influence on cognitive load and learner performance.

There is ample evidence indicating the correlation between learners' interest and performance in complex learning (Hosbein & Barbera, 2020). It is found that learners who are motivated are more likely to engage in deep-level thinking (Liu, Toprac, & Yuen, 2009; O'Conner & Domingo, 2020). Evidence from empirical research further suggests that the status of cognitive load and mental effort investment are closely associated with learner's motivation (Plass & Kalyguga, 2019; Schnotz, 2010). Learners who are cognitively overloaded often experience frustration and are less motivated. In contrast, learners with low cognitive load are more likely to avail themselves of precious cognitive resources in working memory to engage in meaningful learning and become motivated. Regardless, the research on motivation and cognitive load is underexplored, particularly the relationship between types of cognitive load and motivation in the context of prior knowledge, instructional strategy and task difficulty interaction. Thus, the second goal of this study is to examine the relationship between types of cognitive load and motivation in a STEM related domain.

## Cognitive Load Theory (CLT)

Working memory poses significant constraints on human learning due to its limitations in processing capacity and duration (Baddeley, 1990; Baddeley & Hitch, 1974; Zheng & Gardner, 2020). Studies have also shown that working memory processing capacity is closely associated with the availability of its cognitive resources (Cook, Zheng, & Blaz, 2009; Smith et al., 2019). Smith et al. (2019) find that by activating learners' schemas in domain areas, the learners experience lower cognitive load as they are able to retrieve information in chunks, which in turn makes cognitive resources available in working memory for learning. Smith et al.'s findings consist with the literature showing a strong correlation between cognitive resources, cognitive load and performance. Similar findings were obtained by Fuchs, Fuchs and Seethaler (2020) who confirmed the relationship between cognitive resources and working memory capacity in mathematics problem solving.

However, high cognitive load does not necessarily end up in low performance and low cognitive load does not mean learners will always perform well in learning. In fact, the functional role of cognitive load is determined by its relevance to learning (Sweller, 2010; Sweller, Van Merriënboer, & Paas, 1998). According to Sweller (2018), there are different types of cognitive load and they differ from each other depending on their relevance to learning. Cognitive load relevant to learning facilitates the construction of knowledge and schemata whereas irrelevant cognitive load can be detrimental to learning resulting in the reduction of cognitive resources in working memory. The following discussion focuses on the types of cognitive load and their relevance to learning.

Three types of cognitive load exist in learning. They are: intrinsic, extraneous and germane cognitive load. Intrinsic cognitive load is defined by the difficulty of the instructional materials that cannot be changed or altered. Extraneous cognitive load refers to the mental load caused by improper instructional design like imposing redundant information in learning materials that requires learners' additional processing effort. The extraneous cognitive load is irrelevant to learning and therefore should be eliminated. The last type of cognitive load is germane cognitive load. It is the mental load induced by the efforts to construct new knowledge or build new schema (Sweller et al., 1998). As such, it is relevant to learning and should be optimized to support learning. According to Sweller (2010; 2018), the three types of cognitive load are additive and they together cannot exceed the total working memory capacity. Therefore, in any instructional situation, intrinsic and extraneous cognitive load cannot be both high at the same time. In other words, if intrinsic cognitive load is high, extraneous cognitive load must be low to allow working memory to have sufficient cognitive resources to process the information. On the other hand, if extraneous cognitive load is high, intrinsic cognitive load must be low so the learner is able to deal with additional mental load caused by the improper design of instruction. The negative relationship between intrinsic and extraneous cognitive load also applies to the relationship between germane cognitive load and extraneous cognitive load. That is, the higher the extraneous cognitive load is, the fewer cognitive resources become available in working memory, and the lower the germane cognitive load will be.

The relationship between germane and intrinsic cognitive load reflects a state of cognitive resource distribution in working memory. For germane cognitive load to occur, the content must be difficult enough so the learner experiences cognitive pressure at some level to become motivated to learn. Overly difficult material will impose high intrinsic cognitive load on the learner thus depleting his/her cognitive resources in working memory. The design of instruction should thus follow what Vygotsky (1978) described as the zone of proximal development (ZPD) where the content is challenging enough but not cognitively overwhelming, which "induces learners' germane cognitive load to engage in meaningful and sustained effort in knowledge acquisition" (Zheng & Gardner, 2020, p. 73).

Researchers (e.g., Sweller et al., 1998; Zheng and Greenberg, 2018) point out that the goal of instructional design should focus on reducing extraneous cognitive load and optimizing germane cognitive load so the learner has sufficient cognitive resources to engage in meaningful knowledge construction.

 

### Domain Prior Knowledge and Intrinsic Cognitive Load

As previously mentioned, intrinsic cognitive load refers to the content difficulty and cannot be altered or changed. However, some researchers (e.g., Pollock, Chandler, & Sweller., 2002) argue that content difficulty is relative to individuals' prior knowledge in a specific domain. A mathematics problem that is difficult for a novice learner may be less challenging for an experienced learner who has meaningful mathematical knowledge units stored in his or her long-term memory. Pollock et al. (2002) conducted a study to investigate the relationship between domain prior knowledge and intrinsic cognitive load in science. They employed a two-step instructional strategy by first providing the learners with isolated concepts of electric circuit (e.g., current, resistance) followed by more complex content related to the testing of electric current. Pollock et al. artificially isolated concepts, which, in turn, reduced learners' intrinsic cognitive load during learning, albeit an incomplete understanding of the problem by the learners. With the initial schema constructed, the learners were able to better deal with the problem presented in full complexity later on. Clarke, Ayres and Sweller (2005) investigated the role of intrinsic cognitive load and prior knowledge in mathematics learning. They found high level of intrinsic cognitive load would render learners incapable of learning new content. By implementing an instructional strategy called sequencing, they discovered the learners were able to build their prior knowledge, thus alleviating their intrinsic cognitive load in learning. Given the relationship between domain prior knowledge and intrinsic cognitive load, the variable of domain prior knowledge is included in this study to understand the connection among cognitive load, cognitive resources and learner performance in mathematical problem solving.

### Relationship between Domain Prior Knowledge and Instructional Strategy

While studies (Clarke et al., 2005; Pollock et al., 2002) have shown the role of instructional strategy in prior knowledge construction, it remains unknown whether levels of domain prior knowledge (e.g., high and low) would affect the outcomes of instructional strategy. Kalyuga (2007) hypothesized that an instructional strategy that is beneficial for low-prior knowledge learners may become relatively inefficient for high-prior knowledge learners, or vice versa. Kalyuga, Chandler, and Sweller (1998) conducted a longitudinal study on the effect of instructional strategy (visual diagrams) on high- and low-prior knowledge learners in science learning. The novice learner initially studied the content with diagrams embedded in the text and scored well on the performance test. After a period of intensive training a reversal effect was observed: the same group of learners learned the content with diagrams only and demonstrated a high performance on the subsequent test. The authors explained that at the beginning novices lacked the adequate schemata to understand the complex content, therefore, the additional text explanation helped the novices comprehend the content. However, as the learners gained more knowledge, the additional text information became unnecessary to their learning. Kalyuga (2007) describes this phenomenon as expertise reversal effect. The expertise reversal effect principle advances Pollock's findings by revealing the interaction between domain prior knowledge and instructional strategy. The significance of this principle lies in its explanatory power of the role and function of domain prior knowledge in relation to instructional strategy. That is, the outcome of an instructional strategy is subject to the level of domain prior knowledge of the learner. The following section examines the function of worked example – an instructional strategy relevant to the current study and its relation to domain prior knowledge.

### Expertise Reversal Effect and Worked Example in Mathematics

One of the widely studied and well applied instructional strategies in mathematics instruction is worked example (Große, 2015). As an instructional strategy, worked example facilitates schema construction and alleviate the mental load in learning since worked example demonstrates the problem-solving steps and solutions before learners try to solve the problems themselves (Richey & Nokes-Malach, 2013; Saw, 2017; Yeo & Tzeng, 2020). Worked example can be categorized into completion- and full-worked examples. Completion-worked example provides partial solution steps and expect the learners to finish the rest of the problem based on partial solution. Contrary to completion-worked example, full-worked example shows the entire steps of problem solving solution.

Sweller and Cooper (1985) examined the role of completion-worked example in complex mathematical problem solving. Two conditions were created: completion-worked example group and control group. The learners in completion-worked example condition were allowed to view half of the examples before they worked on the problems. The learners in control condition studied the problem without worked examples. Results showed that learners who studied with completion-worked examples outperformed those who did not ($U > 30$, $\eta^2 = .16$). To further understand the effect of different types of worked examples on learning, Richey and Nokes-Malach (2013) studied learners' differences in deep understanding of the instructional materials between two types of worked examples: completion- and full-worked examples. In completion-worked example condition the learners were given worked examples with partial explanation and in the full-worked example condition the learners were provided with full explanation of the problems. What they found was that participants in the information withholding condition (i.e., completion-worked examples) demonstrated better conceptual learning and far transfer than participants in full explanation condition (i.e., full-worked examples) ($p < .01$, $\eta^2 = .13$). The authors argued that withholding instructional explanations may provide learners with an opportunity to engage in constructive learning activities to facilitate deeper learning and far transfer, whereas materials that include full explanations could suppress inference generation because the explanatory information was already present, thereby encouraging more passive learning activities such as rehearsal and paraphrasing. However, full-worked examples may be useful in schema construction as the step-by-step full explanations are effective in building knowledge blocks in long-term memory. Richey and Nokes-Malach thus concluded that the completion-worked examples facilitate constructive learning whereas the full-worked examples are conducive for schema construction. In the context of current study, the role of worked example is examined from the lens of domain prior knowledge. That is, it seeks to answer whether high- and low-prior knowledge learners would demonstrate the same level of engagement in constructive learning with completion-worked examples, or whether they would equally benefit from schema construction with full-worked examples.

While efforts have been made to investigate the differences in the types of worked examples, research that examines the interaction between domain prior knowledge and types of worked examples in mathematics is scarce, which has hampered the effective design and application of worked examples in education. As such, further research in domain prior knowledge and worked example is warranted. Based on Kalyuga's (2007) expertise reversal effect principle, it is hypothesized that low domain-prior-knowledge learners would benefit from full-worked examples as the strategy would facilitate novices' schema construction, whereas high domain-prior-knowledge learners would perform well with completion-worked examples since they promote constructive thinking in learning (Richey & Nokes-Malach, 2013).

### Task Difficulty

Of particular interest to researchers is the relationship between instructional strategy and task difficulty (Lynch et al., 2019. Latta, 1978). Task difficulty refers to the task requirements defined by the level of content difficulty and associative cognitive demands. Latte (1978) conducted a study on learning orientation, feedback, and task difficulty (easy and difficult). The results showed a significant interaction between feedback and task difficulty ($p < .01$, $\eta^2 = .11$) with feedback responding differently to the level of task difficulty. It was found feedback had little impact on easy tasks but had positive effects on difficult tasks.

Evidence from preliminary studies further demonstrates that domain prior knowledge may play a role in the interaction between task difficulty and instructional strategy (Dhlamini, 2016; Orvis, Horn, & Belanish, 2008). Orvis et al. (2008) examined the role of instructional strategy in video-game based learning. They found an interaction between instructional strategy and task difficulty with the forced adjustment strategy increasing task difficulty and the learner-centered adaptive adjustment strategy alleviating the task difficulty, which was largely explained by the learners' domain prior knowledge. That is, the task difficulty was mitigated due to an adaption of the content to the learner's domain prior knowledge. So far, the research on task difficulty in light of domain prior knowledge and instructional strategy has been focused on (a) the interaction between task difficulty and instructional strategy (Janning, Schatten, & Schmidt-Thieme, 2016) and (b) the supplementary role of domain prior knowledge (Orvis et al., 2008). There is no study, to the best of our knowledge, that exploits the interaction between task difficulty and instructional strategy based on expertise reversal effect principle. Moreover, there have been mixed results regarding instructional strategy and task difficulty. Cevik and Altunt (2016) compared three instructional strategies (information only; information with demonstration; information with demonstration and application) in complex cognitive task performance and found no significant differences in group performances among three strategies in terms of task difficulty ($p > .05$). Given the equivocal findings and a lack of research taken from expertise reversal effect, the current study examined the role of task difficulty in instructional strategy by putting in perspective the learners' expertise reversal effect to further understand the interaction among task difficulty, worked example and domain prior knowledge in mathematical problem solving.

### Motivation and Cognitive Load

Research suggests that cognitive load, especially germane cognitive load is strongly correlated with motivational aspects of learning including science education (Um, Plass, Hayward, & Homer, 2012). Researchers have been trying to find the psychometric correlation between the motivation measures and the types of cognitive load (Schnotz, Fries, & Horz, 2009). Schnotz et al. (2009) compared Questionnaire of Current Motivation (QCM) developed by Rheinburg, Vollmeyer and Burns (2001) with Paas's (1992) Cognitive Load Measure (CLM) that measures overall cognitive load. They concluded that there was an overlap of probability of success between QCM and CLM. Recently, Leppink. Paas, van der Vleuten, van Gog, and van Merriënboer (2013) developed a ten-item questionnaire based on Paas's (1992) CLM. The instrument treats three types of cognitive load (e.g., intrinsic, extraneous and germane cognitive load) as distinct cognitive constructs in measurement that provides the opportunity to directly compare the motivation measures with each type of cognitive load, particularly the germane cognitive load in learning.

Notwithstanding the efforts to advance the understanding of the relationship between motivation and cognitive load, empirical research that focuses on motivation and germane cognitive load using specific measures like QCM and Leppink et al.'s CLM is lacking. Given the connection between germane load and motivation (Kirschner, 2002), an important endeavor of the current study was to verify the connection between germane cognitive load and motivation based on Leppink et al.'s CLM and Rheinbutg et al.'s QCM measures in mathematics problem solving.

## Research Questions

Based on the literature, the following research questions were proposed as a basis to guide the current study:

Research Question 1: Is there a three-way interaction between prior knowledge, worked example and task difficulty as measured by posttest and three types of cognitive load?

Research Question 2: Are there interactions between (a) prior knowledge and worked example and (b) prior knowledge and task difficulty as measured by posttest and three types of cognitive load?

Research Question 3: Are there any correlations between three types of cognitive load defined in Leppink et al.'s CLM and the submeasures defined in Rheinbutg et al.'s QCM?

## The Study

The present study considered the effects of domain prior knowledge, worked example, and task difficulty on learners' abilities to solve algebraic problems as measured by performance achievement and cognitive load. It also aimed to examine the relationship between three types of cognitive load and sub-dimensions of QCM measures. To understand the interaction between prior knowledge and worked example, two forms of worked examples were created: full- and completion-worked examples (**Table 1**). The full-worked examples provided the learners with solution directions and steps at each level whereas the completion-worked examples provided partial solutions with answers withheld at each step. It was predicted that the full-worked examples would benefit low prior-knowledge learners' schema construction as the provision of full solution steps makes it easy for learners to understand and master the content. The completion-worked examples, on the other hand, would support high prior-knowledge learners constructive learning as withholding solutions steps promotes constructive cognitive thinking and processing (Richey & Nokes-Malach, 2013).

**Table 1.** Samples of full- and completion-worked examples for simultaneous equation algebra problems

| **Full Worked Example** | **Completion Worked Example** |
|---|---|
| Solve the following simultaneous equations for variables x and y: | Solve the following simultaneous equations for variables x and y: |
| **12x + 3x = 45 ------------ Eq 1**<br>**4x – 5y = 62 ------------ Eq 2** | **2x + 13x = 75 ------------ Eq 1**<br>**–x + 2y = 5 ------------ Eq 2** |
| <u>**Solution:**</u> For this particular question, in order to solve for variables x and y, we first need to combine the like variables. We can see that Eq 1 has all x variables. Therefore, they can be combined. | <u>**Solution:**</u> For this particular question, in order to solve for variables x and y, we first need to combine the like variables. We can see that Eq 1 has all x-terms. Therefore, they can be combined. |
| *Objective 1:* <u>**Combine**</u> x-terms in Eq 1<br>Given from Eq 1 that 12x + 3x = 45<br>Add x-terms as 15x = 45<br>Divide by 15 on both sides gives x = (45/15)<br>Simplify **x = 3** **(A)** | *Objective1*: <u>**Combine**</u> x-terms in Eq 1<br>Given from Eq 1 that 2x + 13x = 75<br>Adding all x-terms ___x = 75<br>Dividing by the coefficient of x on both sides<br>x = (75/___)<br>Simplify **x = ____** **(A)** |
| *Objective 2:* <u>**Plug-in**</u> value of x from A in Eq 2<br>Given from Eq 2 that 4x – 5y = 62<br>Substitute value of x from A above 4(3) – 5y = 62<br>Simplify 12 – 5y = 62<br>–5y = 62 – 12<br>–5y = 50<br>Divide by –5 **y = –10** | *Objecitve 2:* <u>**Plug-in**</u> value of x in Eq 2<br>Given from Eq 2 that –x + 2y = 5<br>Substitute value of x from A above – ___ + 2y = 5<br>Simplify 2y = 5 + ____<br>2y = ____<br>Divide by 2 on both sides **y = ____** |
| <u>**Answer**</u>: **x = 3; y = –10** | <u>**Answer**</u>: **x =____; y = _____** |

 

**Problem 1**

$$\begin{cases} 3x = 18 & \text{----- Eq. 1} \\ 2x + 2y = 36 & \text{----- Eq. 2} \end{cases}$$

**Problem 2**

$$\begin{cases} y - 4x = 9 & \text{----- Eq. 1} \\ x + 2y = 36 & \text{----- Eq. 2} \end{cases}$$

**Figure 1.** Simultaneous equation problems

**Table 2.** Levels of difficulty in simultaneous equation problems

| Type | Levels | Variable | Solution Step |
|---|---|---|---|
| Easy | Level 1 - Problem with two different variables. One variable in the first equation. | $\begin{cases} 2x = 6 \\ x + y = 9 \end{cases}$ | 4 |
| | Level 2 – Problem with two different variables. Same two variables in the first equation. | $\begin{cases} 4x - x = 9 \\ 2x + 2y = 36 \end{cases}$ | 6 |
| | Level 3 - Problem with two different variables. Each is on different side of the first equation. [It is easy because one does not have to take the step of moving one variable to the other side] | $\begin{cases} x = y - 4 \\ 2x + 2y = 36 \end{cases}$ | 9 |
| Difficult | Level 4 – Problem with two different variables. Both are on one side of the first equation. [This is harder than level 3 because one needs to move one variable to the other side of the equation] | $\begin{cases} x - 2y = 10 \\ 2x + 2y = 80 \end{cases}$ | 12 |
| | Level 5 – Problem with 3 different variables. [This is harder than level 4 because one needs to solve equations 1 and 2 before solving equation 3] | $\begin{cases} 2x - y = 6 \\ 6x + 2y = 36 \\ 3z + 2x - 3y = 120 \end{cases}$ | 18 |

### *Defining difficult and easy tasks*

The task difficulty is defined based on Sweller's (1988) production/solution step method. According to Sweller, the difficulty of the content, which is often considered a proxy for intrinsic cognitive load, is determined by the production/solution steps involved in problem solving or learning. Thus, the solution step method was used to define the difficult level of the problems. Five difficult levels were identified: Levels 1-3 were defined as easy problems since they contained fewer solution steps with one or two variables, whereas Levels 4-5 were defined as difficult because they involved more solution steps with more variables. Consider solving following two simultaneous equation problems (**Figure 1**). Problem 1 involves two different variables (x and y) and requires three solution steps. In solving Problem 1 the learner will (a) obtain the $x$ value in Eq.1 by dividing 3 on both sides of the equation ($3x/3 = 18/3$), (b) replace the $x$ value in Eq.2 with the $x$ value obtained in Eq. 1 ($2 * 6 + 2y = 36$), and (3) calculate the value $y$.

In contrast, the solution steps become more complicated when solving Problem 2. There are several ways to solve Problem 2. Assume the problem can be solved by (a) finding the value of $y$ in Eq.1 ($y = 9 + 4x$), (b) replacing the $y$ in Eq.2 with the $y$ value obtained in Eq.1 ($x + 2(9 + 4x) = 36$), (c) finding the $x$ value in Eq.2, and finally (d) substituting the $x$ value in Eq.1 with the $x$ value obtained in Eq.2 to find the $y$ value. Evidently, the solution to solving Problem 2 involves more steps and thus requires more mental effort than these in Problem 1. As such, the task of Problem 2 is considered more difficult compared to that of Problem 1. **Table 2** shows the levels of task difficulty by variables and solution steps.

### *Defining high- and low-prior knowledge learners*

Since domain prior knowledge was used as an independent variable to test the interaction between worked example, task difficulty and learner expertise, the issue of how to divide the prior knowledge variable into categorical data came to fore. Two different methods exist in regard to how to define high- and low-prior knowledge learners. They are: median split method and tri-split method. The median split method finds the median point and splits a continuous variable like prior knowledge into half (Aziz, Wuensch, & Brandon, 2010; Iacobacci, Posavac, Kardes, Schneider, & Popvich, 2015). The drawback of median split method is that it arbitrarily defines the participants who are one position above and below the median point as high- or low-prior knowledge learners which, as Liu and Reed (1994) point out, may significantly skew the outcomes. McClelland, Lynch, Irwin, Spiller, and Fitzsimons (2015) warned that median-split method is likely to increase Type II error (also see Rucker, McShane, & Preacher, 2015). In contrast to median split method, Liu and Reed (1994) proposed a tri-split method that divided the participants into upper-third quarter, lower-third quarter and middle-third quarter. It eliminates the middle-third quarter and only keeps the upper- and lower- third quarters in its final analysis. Since the tri-split method eliminates middle one-third sample, it clearly creates the high and low categories by retaining top and bottom one-third samples, thus avoiding artificially labelling the samples as high or low and minimizing the risk of Type II error.

## METHOD

### Participants

One hundred and sixty participants were recruited from a Research I university in the western United States. Participants were non-science major college students enrolled in different academic programs. Of 160 participants, 114 participants earned credit towards their coursework, 46 participants received monetary compensation with an honorarium mentioning their participation in the study. The average age of participants was 23.25 with a standard deviation of 6.01. About 117 participants were females and 43 were males. Regarding ethnicity composition, 116 were whites, 19 were Hispanic, 13 were Asians, 1 was African-American and 11 were others. Participants were informed of the nature of the study and were asked to complete the consent process before participating. Participation in the study was voluntary. Approval from the appropriate Institutional Review Boards was obtained prior to beginning the study.

### Instrumentation

The instruments consisted of (a) learning materials, (b) pretest, (c) posttest, (d) Cognitive Load Measurement (CLM), and (e) Questionnaire on Current Motivation (QCM).

*Learning Materials.* The learning materials (12 algebraic problems) were developed based on a middle school algebra textbook (McGraw Hills, Algebra-2) that covers topic of systems of equations. Problems on simultaneous equations were adapted for the study. Feedback from content experts and university faculty members was received with subsequent modification made to better meet the purpose of the study. A pilot study was run with the final problems reporting a high item reliability of Cronbach's Alpha = .89.

Two versions of problems were created: full- and completion-worked examples. The full-worked examples provided complete solution steps at every level; the completion-worked examples provided partial solution steps by withholding information in the problem solving process. The problems ranged from easy to difficult based on the variables and production steps involved in the problem solving (see **Table 2**).

*Pretest.* A 10-problem pretest was developed to understand learners' domain prior knowledge on the subject. Problems varied from easy and difficult with a maximum of 2.5 points for each problem. The total possible points to be obtained on the pretest was 25 points. Participants were required to solve the problems in the time span of 15 minutes. They were not only required to write down the answers but also to show all their work in solving pretest problems. The test results were graded by two independent graduate students showing an interrater reliability of Cronbach's Alpha = 0.993.

*Posttest.* The posttest consisted of 10 problems on simultaneous equations. Like pretest, the problems varied in difficulty ranging from easy to difficult with a maximum of 2.5 points for each problem. The total possible points to be obtained on the pretest was 25 points. The test results were graded by two independent graduate students showing an interrater reliability of Cronbach's Alpha = 0.969.

To ensure that difficulty level for the posttest was appropriate and met the purpose of the study, an additional item difficulty analysis was conducted. The biserial correlations showed a range between 0.22 and 0.64 for easy problems and a range between 0.31 and 0.52 for difficult problems, both of which were within the admissible range (Kavitha, Vijaya and Saraswathi, 2012) indicating the test items fit well with the purpose of the study.

*CLM.* To understand the impact of worked example, domain prior knowledge and task difficulty on cognitive load, the CLM (Leppink et al., 2013) was used. It is a 10-item self-report questionnaire with a Likert scale from 0 (Not at all the case) to 10 (Completely the case). The instrument measures three aspects of cognitive load: intrinsic (items 1-3), extraneous (items 4-6), and germane (items 7-10) cognitive load. Examples of intrinsic cognitive load measure would include: "The topic/topics covered in the activity was/were very complex", "The activity covered concepts and definitions that I perceived as very complex." The maximum possible points the participant could obtain on intrinsic load are 33. The examples of extraneous cognitive load measure would be: "The instructions and/or explanations during the activity were very unclear", "The instructions and/or explanations during the

 

**Table 3.** A 2 x 2 x 2 Design for Prior Knowledge, Worked Example, and Task Difficulty

| | **Higher Prior Knowledge** | | **Lower Prior Knowledge** | |
|---|---|---|---|---|
| | **Easy** | **Difficult** | **Easy** | **Difficult** |
| **Full worked examples** | High PK / Easy full WE | High PK / Difficult full WE | Lower PK / Easy full WE | Lower PK / Difficult full WE |
| **Completion worked examples** | High PK / Easy Completion WE | High PK / Difficult Completion WE | Lower PK / Easy Completion WE | Lower PK / Difficult Completion WE |

activity were very unclear." The maximum possible points the participant could obtain on extraneous load are 33. Finally, the examples of germane cognitive load measure would include: "The activity really enhanced my knowledge and understanding of the topic(s) covered", "The activity really enhanced my understanding of concepts and definitions." The maximum possible points the participant could obtain on germane load are 44. The instrument reported a consistent reliability with Cronbach alpha of .81 for intrinsic load, .75 for extraneous load, and .82 for germane load.

*QCM.* The QCM, developed by Rheinberg, Vollmeyer, and Burns (2001) is an 18-item self-report questionnaire with a 7-point Likert scale in which 1 means one agrees least to the statement and 7 means one agrees most to the statement. The possible maximum points one can obtain in QCM is 126 points. The instrument measures four constructs in motivation: interest, probability of success, anxiety, and challenge. For example, the statement "After reading the instruction, the task seems to be interesting to me" measures participants' interest, the statement of "I think everyone can manage this" probes probability of success, the statement of "If I think about this task, I feel a little bit worried" measures anxiety, and the statement of "I feel up to the difficulty of this task" measures challenge. The instrument reported high item reliability with Cronbach alpha .90.

## Design of the Study

The interaction between worked example (full- vs. completion-worked examples), prior knowledge (high vs. low) and task difficulty (easy vs. difficult) were studied with a 2 x 2 x 2 factorial design. This allowed us to explore possible effects of full- and completion-worked examples in the context of domain prior knowledge and task difficulty and answer the question of to what extent domain prior knowledge and task difficulty may influence the outcomes of full- and completion-worked examples. **Table 3** presents eight possible learning conditions to which high- and low-prior knowledge learners were randomly assigned.

## Procedure

After signing the consent form, participants ($N$ = 160) were asked to complete the pre-QCM which measured motivation in learning, followed by the pretest on simultaneous equation algebra. Based on the results of pretest, the participants were divided into high, low, and middle prior-knowledge levels with one-standard deviation above the mean as high-prior knowledge ($n$ = 55, $m$ = 10.564, $SD$ = 1.808) and one-standard deviation below the mean as low-prior knowledge ($n$ = 60, $m$ = 3.458, $SD$ = 1.808). The middle sample ($n$ = 45, $m$ = 6.7, $SD$ = 3.3) was eliminated from final analysis, leaving 55 in the high-prior-knowledge group and 60 in the low-prior-knowledge group for final analysis.

Then the participants were randomly assigned to one of the eight learning conditions (**Table 3**). During the learning phase, the participants were asked to study the simultaneous equation algebraic content on a computer with either full- or completion-worked examples depending on the condition, followed by the practice of the problems in the booklet. The learning phase was self-paced but the maximum time to complete the session was one hour. Immediately upon completing the learning phase along with the practice booklet, participants were given the self-report CLM questionnaire to report their cognitive load on learning. Participants were then asked to complete a posttest on simultaneous equation. A post-QCM survey was also administered.

## Results

This study explored the interaction between domain prior knowledge, worked example and task difficulty in algebraic problem solving. A 2 x 2 x 2 one-way ANOVA was employed to analyze the three-way interaction. The independent variables included domain prior knowledge (high vs. low), worked example (full vs. completion worked examples) and task difficulty (easy vs. difficult) with post achievement test, CLM and post QCM scores as dependent variables. A family-wise alpha level of .05 was adopted for all analyses with p-values between .05 and .10 labelled as marginal effects and those greater than .10 as not significant.

**Table 4.** Means and Standard Deviations for A 2 x 2 x 2 Design with Post-Achievement Test, Three Categories of Cognitive Load, and Post-QCM Scores

| Worked Examples | Expertise | Task Difficulty | Posttest | Intrinsic Load | Extraneous Load | Germane Load | Post QCM |
|---|---|---|---|---|---|---|---|
| Completion WE | Lower PK | Difficult | 4.79(2.09) | 15.50(6.93) | 5.25(5.57) | 25.92(9.28) | 75.00(12.61) |
| | | Easy | 5.94(2.70) | 12.59(7.45) | 3.06(3.59) | 25.06(12.09) | 75.41(14.76) |
| | Higher PK | Difficult | 11.19(2.06) | 11.08(5.64) | 9.15(8.18) | 13.23(9.00) | 67.46(14.21) |
| | | Easy | 10.87(2.49) | 5.00(3.84) | 3.56(3.61) | 11.50(10.18) | 75.13(12.75) |
| Full WE | Lower PK | Difficult | 6.68(2.95) | 15.44(7.50) | 8.31(7.19) | 24.06(10.93) | 74.00(18.09) |
| | | Easy | 6.16(1.91) | 13.40(6.94) | 7.20(6.46) | 24.67(11.48) | 77.67(16.06) |
| | Higher PK | Difficult | 10.00(2.78) | 10.46(9.66) | 8.92(10.10) | 16.77(11.67) | 74.46(6.91) |
| | | Easy | 12.00(2.38) | 6.08(6.88) | 2.92(2.95) | 23.46(11.28) | 73.77(8.42) |

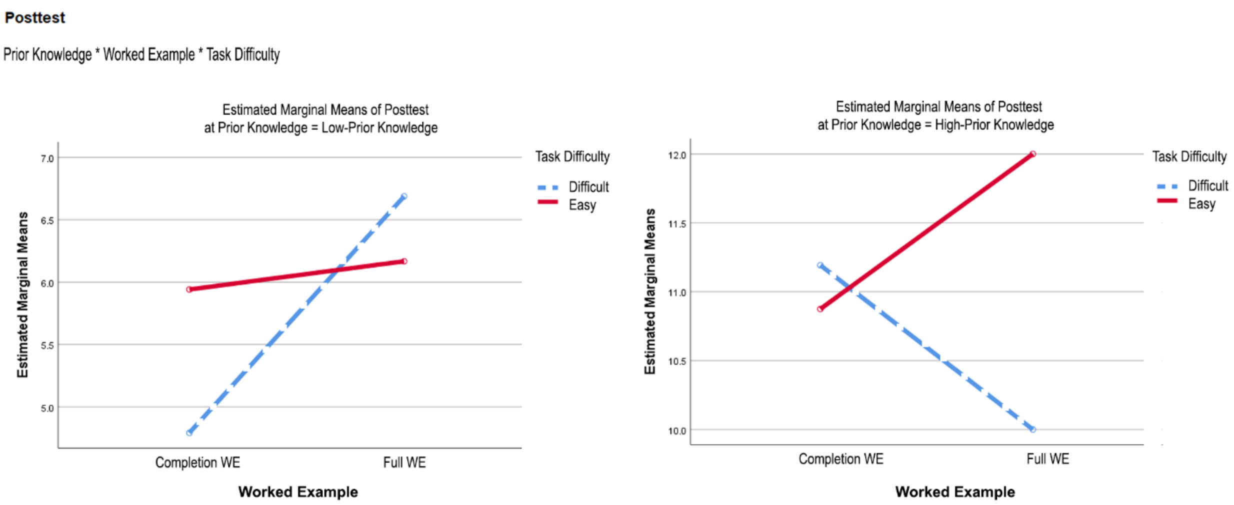


**Figure 2.** Three-way interaction between prior knowledge, worked example and task difficulty by posttest

The means and standard deviations for domain prior knowledge, worked example, and task difficulty with post-test, three categories of cognitive load, and post-QCM scores are presented in **Table 4**.

Research question 1 exploits the interaction between three independent variables in terms of (a) posttests and (b) types of cognitive load. There was a significant three-way between-subjects effects by posttest ($F_{1, 107} = 4.61$, $p < .05$, $\eta^2 = .04$) (**Figure 2**), but no significant three-way interaction for types of cognitive load was detected. Further analyses revealed some interesting trends in terms of prior knowledge and task difficulty regarding types of cognitive load. None of the cognitive load was significant for worked example.

*Prior knowledge*. There were significant differences between high- and low-prior knowledge learners in terms of intrinsic ($F = 22.424$, $p < .000$) and germane cognitive load ($F = 18.417$, $p < .000$), but no significance was found between high- and low-prior knowledge learners for extraneous cognitive load ($F = .018$, $p = .895$), suggesting the weak presence of extraneous cognitive load may have contributed to the active roles of intrinsic and germane cognitive loads in learning. In other words, with the influence of extraneous cognitive load abated, the cognitive resources in the working memory become available for the efforts to solve complex mathematics problems that were related to germane (efforts) and intrinsic (content complexity) cognitive load.

*Task difficulty*. Significant differences were found between difficult and easy tasks in terms of intrinsic ($F = 9.152$, $p < .001$) and extraneous cognitive load ($F = 10.761$, $p < .001$), but no significance was found for germane cognitive load ($F = .204$, $p < .653$). The results indicate high intrinsic or extraneous cognitive load due to task difficulty may render germane cognitive load unavailable for learning.

Regardless of the non-significance of three-way interaction by cognitive load, Research Question 1 was partially supported with a significant three-way interaction by posttest.

Research question 2 examines the interactions between (a) prior knowledge and worked example and (b) prior knowledge and task difficulty as measured by posttest and three types of cognitive load. The results are reported as follows.

*Prior knowledge and worked examples*. No significant differences were observed between prior knowledge and worked example as measured by intrinsic or extraneous cognitive load. However, a significant interaction by germane cognitive load ($F_{1, 107} = 4.72$, $p < .05$, $\eta^2 = .04$) was found between prior knowledge and worked example, suggesting germane cognitive load may serve as a valid indicator for the cognitive process of high- and low-prior knowledge learners when studying with worked examples. There was no significant interaction between prior knowledge and worked example by posttest.

 

**Table 5.** Correlations between Intrinsic, Extraneous, Germane Cognitive Load and Motivation

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Intrinsic Load Total | 1 | .311** | .216** | .324** | –.299** | –.077 | .221** |
| Extraneous Load Total | | 1 | –.264** | .136 | –.191* | –.046 | –.054 |
| Germane Load Total | | | 1 | –.140 | .129 | .264** | .008 |
| QCM_Anxiety | | | | 1 | –.322** | –.182 | .304** |
| QCM_Probability of Success | | | | | 1 | .288** | –.194* |
| QCM_Interest | | | | | | 1 | .203** |
| QCM_Challenge | | | | | | | 1 |

* $r < .05$ (2-tailed); ** $r < .01$ (2-tailed)

The follow-up analysis revealed a relationship between prior knowledge and worked example. Lower-prior knowledge learners performed better on the posttest with full-worked examples than completion-worked examples ($t(1,26) = 1.98$, $p = .05$, 2-tailed). In contrast, higher-prior knowledge learners demonstrated higher performance mean in completion-worked examples ($M = 11.19$, $SD = 2.06$) than full-worked examples ($M = 10.00$, $SD = 2.78$). However, the difference did not reach significant level ($p = .22$, *ns*.).

*Prior knowledge and task difficulty*. No significant interaction was observed between prior knowledge and task difficulty. The follow-up analysis revealed significant main effects for high- and low-prior knowledge learners by posttest ($F_{1,107} = 121.64$, $p < .001$, $\eta^2 = .53$), intrinsic cognitive load ($F_{1,107} = 21.40$, $p < .001$, $\eta^2 = .17$), and germane cognitive load ($F_{1,107} = 18.12$, $p < .001$, $\eta^2 = .15$). The analysis on the main effect of task difficulty was significant (Wilks' Lambda $\lambda = .86$, $p < .05$, $\eta^2 = .14$) as measured by intrinsic ($F_{1,107} = 8.60$, $p < .01$, $\eta^2 = .07$) and extraneous cognitive load ($F_{1,107} = 9.92$, $p < .01$, $\eta^2 = .09$), suggesting task difficulty may play a significant role in determining the presence of intrinsic and extraneous cognitive load. The findings are consistent with the literature on prior knowledge, cognitive load and performance (Kalyuga, 2007; Kalyuga et al., 1998; Pollock et al., 2002).

To address research question 3, the correlation analyses were performed with three types of cognitive load (i.e., intrinsic, extraneous, and germane cognitive load) and subcategories of QCM (i.e., anxiety, probability of success, interest, and challenge). The results showed that germane cognitive load was significantly positively correlated with interest ($r = .264$, $p < .01$) suggesting the connection between germane cognitive load and learners' interest in learning. It was found intrinsic cognitive load was positively correlated with anxiety ($r = .324$, $p < .01$) and challenge ($r = .221$, $p < .01$), but negatively correlated with probability of success ($r = -.299$, $p < .01$), indicating learners' anxiety and the content challenge may negatively impact the success of learning. A negative correlation between extraneous cognitive load and germane cognitive load ($r = -.264$, $p < .01$) was detected which confirms Sweller et al.'s (1998) hypothesis about the negative relationship between extraneous and germane cognitive load. Finally, extraneous cognitive load was found to correlate negatively with the probability of success ($r = -.191$, $p < .05$) in QCM.

## DISCUSSION

The current study investigated the relations between prior knowledge, worked example, and task difficulty. A three-way 2 x 2 x 2 one-way ANOVA was performed. The following discussion of the results will be based on the three research questions proposed earlier.

### The Interaction between Prior Knowledge, Worked Example and Task Difficulty

A significant three-way interaction was found by posttest suggesting high- and low-prior knowledge learners' performance can be significantly influenced by worked example like full- and completion-worked examples and the variances in task difficulty. The finding provides preliminary evidence on how prior knowledge, worked example and task difficulty interact with each other to influence the learners' performance in algebraic problem solving.

### The Interaction between (a) Prior Knowledge and Worked Example and (b) Prior Knowledge and Task Difficulty

The analysis on the interaction between prior knowledge and worked example shed light on how full- and completion-worked examples may impact high- and low-prior knowledge learners' germane cognitive load in problem solving. That is, by applying the type of worked examples to individual learners based on their prior knowledge, learners are more likely to exert their efforts in learning. This is particularly true with low-prior knowledge learners who studied with full-worked examples and high-prior knowledge learners who studied with completion-worked examples.

Although no significant interaction was found between prior knowledge and task difficulty, there were significant main effects for task difficulty by intrinsic cognitive load and extraneous cognitive load. This means task difficulty may play a significant role in determining the presence of intrinsic and extraneous cognitive load. Further, the significant main effects for prior knowledge indicated that high- and low-prior knowledge learners differed significantly in intrinsic cognitive load and germane cognitive load when solving complex algebraic problems with different worked examples suggesting an expertise reversal effect, which confirmed the findings in previous research (Kalyuga, 2007; Kalyuga et al., 1998; Pollock et al., 2002).

### Relationship between Cognitive Load and Motivation

The study reported a positive correlation between germane cognitive load and interest confirming the connection between germane cognitive load and learners' interest as suggested by researchers in previous studies (Schnotz et al., 2009). The finding supports the germane cognitive load and interest correlation hypothesis showing that interest may be an important variable in designing effect instruction in learning.

The study further confirmed Sweller et al.'s hypothesis that extraneous cognitive load and germane cognitive load are negatively correlated, indicating higher extraneous cognitive load led to lower germane cognitive load. This finding has significant implications in STEM related education: in order to increase learners' efforts to learn (germane cognitive load), the educators must improve the design of instructional materials to lower the extraneous cognitive load by eliminating, for example, the redundancy or split-attention content in learning (Mayer & Moreno, 2003). This is further supported by the findings of negative correlation between extraneous cognitive load and probability of success in the current study, suggesting with high extraneous cognitive load the learners would have few cognitive resources left in working memory, hence making little room for germane cognitive load in learning.

## CONCLUSIONS

Complex learning like simultaneous equation problem solving can be cognitively demanding. While many factors (e.g., social, economic, cognitive, metacognitive, etc.) can influence learners' complex thinking, the current study focused on prior knowledge, worked example, and task difficulty from the perspectives of achievements, cognitive load and motivation in learning. By taking into perspective the interaction between prior knowledge, worked example and task difficulty, the current study revealed the relationship between learners' prior knowledge, worked examples, and task difficulty in complex learning in mathematics. It was found that lower-prior knowledge learners performed better with full-worked examples than completion-worked examples whereas higher-prior knowledge learners performed better with completion-worked examples than full-worked examples when solving complex math problems. The findings of the study also revealed that task difficulty may play a significant role in determining the presence of intrinsic and extraneous cognitive load. It is suggested that learners' intrinsic cognitive load can be largely explained by the difficulty of the tasks. Moreover, low-prior knowledge learners who experienced the task difficulty could undergo higher extraneous cognitive load if improper instructional strategy like completion-worked examples were used.

In addition to the findings regarding prior knowledge, worked example and task difficulty, the current study exploited the relationship between cognitive load and motivation. It was found that germane cognitive load is positively correlated with motivation as represented by interest in QCM. The findings provide empirical evidence showing the connection between germane cognitive load and interest suggesting motivational indicators like interest may be used as a proxy for germane cognitive load measure. The results also confirmed Sweller's (2018, Sweller et al., 1998) addictive hypothesis by showing the negative relationship of extraneous cognitive load with intrinsic and germane cognitive load. This finding is significant in that it guides the design of instruction in terms of cognitive load management in STEM learning.

### Implications of the Study

As an important component of STEM (Science, Technology, Engineering and Mathematics), mathematics shares with science domains many cognitive and instructional processes in learning. The current study focuses on an important issue in STEM education: the management of cognitive resources in working memory for optimal learning. Taking from a cognitive load theory perspective, the study examines the relationship between learners' domain prior knowledge, task difficulty and worked example. While the domain of mathematics is used as the testbed in this proof-of-concept study, the findings are applicable to general science investigation and related instructional development since managing the cognitive resources in working memory by addressing the cognitive load is important to all learning including STEM education. As such, the findings of the current study have contributed to the research and practicing communities the understanding of the relationship between cognitive load and learning in light of learner prior knowledge, worked example and task difficulty.

 

**Limitations of the Study**

Like any empirical studies, the current study is not without limitations. The failure to obtain a significant three-way interaction by cognitive load indicates that more work is needed to help learners understand the types of cognitive load when responding to the questionnaire. Sweller (2018) expressed similar concern by arguing that learners may not be familiar with the categories of cognitive load. Another limitation is the power of the study. More participants may be needed, especially the current study used the tri-split methods in defining high- and low-prior knowledge learners which could weaken the power of the study.

The current study explored the immediate effects of worked examples in relation to prior knowledge and task difficulty. Future research may examine the long-term effect by inviting participants back after a period of time to study learners' knowledge retention and transfer. A large sample size may be needed in future study. Studies in future may include online cognitive load measures like eye-tracking, dual-task, etc. to better understand the dynamic changes of cognitive load including peak load, cumulative load, and overall load in complex learning.

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