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STEM Education: A review of the contribution of the disciplines of science, technology, engineering and mathematics

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ABSTRACT: Recent global educational initiatives and reforms have focused on increasing the number of students pursuing STEM subjects, and ensuring students are well-prepared, and suitably qualified to engage in STEM careers. This paper examines the contributions of the four disciplines - Science, Technology, Engineering and Mathematics - to the field of STEM education, and discusses STEM literacy; factors influencing students' engagement in STEM education; effective pedagogical practices, and their influence on student learning and achievement in STEM; and the role of the teacher in STEM education. Through a critical review of 237 studies, three key factors were identified: (1) the importance of focusing on the junior secondary phase of schooling to maintain student interest and motivation to engage in STEM, (2) the implementation of effective pedagogical practices to increase student interest and motivation, develop 21st century competencies, and improve student achievement, and (3) the development of high-quality teachers to positively affect students' attitudes and motivation towards STEM.

KEY WORDS: STEM, STEM literacy, student interest, STEM pedagogies

INTRODUCTION

Science, technology, engineering and mathematics (STEM) is a major emphasis in global initiatives seeking to enhance economic prosperity via a highly-educated workforce (Office of the Chief Scientist, 2014; Riegle-Crumb, King, Grodsky, & Muller, 2012). As such, many countries have made significant investments in STEM educational initiatives largely driven by concerns about potential shortfalls in STEM qualified professionals in the future (van Langen & Dekkers, 2005). The focus of many initiatives in school education (Kindergarten-grade 12, or K-12 hereafter) is twofold; to increase the number of students pursuing STEM subjects, and to ensure students are well-prepared and suitably qualified to engage in STEM careers (Barker, Nugent, & Grandgenett, 2014; Bryan,

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Glynn & Kittleson, 2011; Sha, Schunn, & Bathgate, 2015; Vedder-Weiss & Fortus, 2012).

STEM is an acronym commonly used to describe education or professional practice in the areas of science, technology, engineering, and mathematics. An authentic STEM education is expected to build students' conceptual knowledge of the inter-related nature of science and mathematics, in order to allow students to develop their understanding of engineering and technology (Hernandez et al., 2014). In many schools, STEM education is heavily focused on science and mathematics, and generally ignores the critical role of engineering and technology in preparing students to participate in an increasingly digital world (English, 2015). Importantly, it is recognised that interdisciplinary and transdisciplinary approaches to STEM integration (whereby the knowledge and skills learned in two or more STEM disciplines are applied to real-world problems and/or used to deepen understanding), represent the ideal approaches to implementing authentic STEM in the classroom (STEM Task Force Report, 2014). However, the large majority of STEM research in the field of education has been conducted from a disciplinary perspective. As such, this paper seeks to examine and integrate findings from this body of research. An emerging body of research that examines STEM integration from an interdisciplinary and transdisciplinary approach is beginning to take shape in the field (Honey, Pearson, & Schweingruber, 2014), and this future research will provide greater insights into effective STEM pedagogical practices in school education.

Workforce representation in STEM is uneven, with research indicating women are under-represented in STEM professions (Bøe, Henriksen, Lyons, & Schreiner, 2011), particularly in mathematics, physics, technology and engineering at the secondary and tertiary level; and computer science and engineering at the professional level (Sullivan & Bers, 2013). Importantly, although gender disparity is evident in the field, meeting the projected demands of an increased STEM workforce has only been found to be a concern in particular professional fields. For example, current enrolments in tertiary life and health sciences are considered to be adequate to fulfill future workplace needs, however concerns have been raised regarding a potential shortage of qualified engineers and ICT professionals (Bøe et al., 2011). At the school level, research indicates that students in developed countries are reluctant to participate in STEM subjects, particularly mathematics and physics (Anderson, Chiu, & Yore, 2010; Hipkins & Bolstad, 2005; Lyons & Quinn, 2010; Stine & Matthews, 2009) although interestingly, students in developing countries display a stronger interest in engaging in STEM subjects and professions (Sjøberg & Schreiner, 2010).

Students make decisions influencing their participation in STEM careers during the secondary years of schooling. Around the age of 15, students in many developed countries have the ability to choose whether they will enroll in post-compulsory STEM subjects. As many of these subjects are prerequisites for future study in tertiary settings, students who elect not to study STEM subjects have fewer opportunities to engage in society as STEM professionals (Ainley, Kos, & Nicholas; 2008). Thus, positive experiences in the junior secondary years of schooling are critical to facilitate future engagement in STEM subjects. Research indicates that although most students recognise the importance of STEM to society, they fail to see the importance of STEM to themselves as individuals. Many students who do choose to enroll in STEM subjects in secondary school make these decisions to aid entry into tertiary courses, as achieving highly in STEM subjects generally facilitates higher tertiary entrance scores (Bøe et al., 2011).

Other researchers have called for a focus on STEM in the earlier years of schooling. Developing the competencies required to effectively engage in STEM requires an extended time period (English & King, 2015). As such, primary schools need to ensure they are providing a supportive teaching and learning environment to cultivate the skills and competencies needed for effective STEM engagement in the post-compulsory years of schooling, and beyond (Blank, 2013; Duschl, Schweingruber, & Shouse, 2007). The implementation of effective STEM pedagogical practices by highly qualified teachers is critical to meet this goal.

REVIEW OF STUDIES

Research indicates that schools that do teach the four STEM disciplines often do so in a disjointed manner, failing to integrate STEM in a unified way (Atkinson & Mayo, 2010). An integrated STEM approach uses real-world contexts to investigate authentic problems using active learning and teaching approaches (Hernandez et al., 2014), leading to improved motivation, and enhanced achievement in science and mathematics (Furner & Kumar, 2007). This paper examines the contributions of the four disciplines - Science, Technology, Engineering and Mathematics - to the field of STEM education. In doing so, it adopts a disciplinary approach to STEM integration (Vasquez, Sneider, & Comer, 2013) whereby the contributions of the different disciplines are firstly examined for evidence of best practice. Following this examination, common themes are identified which are then amalgamated into a discussion of

STEM literacy; factors influencing students' engagement in STEM education; effective pedagogical practices, and their influence on student learning and achievement in STEM; and a discussion of the role of the teacher in STEM education.

In the first round of analysis, 25 high quality, peer-reviewed journals (refer to Table 1) were identified in the disciplines of science education, mathematics education, technology education, and a variety of interdisciplinary and general education journals. A search was conducted in all 25 journals over the period 2010-2015. Keywords used to facilitate the search included *STEM, literacy, best practice, effective pedagogies, interest, engagement, motivation, high-quality, teachers,* and *achievement*. In the second round of analysis, reference lists in papers deemed relevant from the keyword search were scrutinised and key papers from these lists were identified and accessed. Results of the analysis yielded a total of 237 papers, which were reviewed for the present paper.

STEM LITERACY

The development of 'literate' citizens in the various disciplines that encompass STEM has been an important focus in international reform documents. STEM literacy can be defined in numerous ways, including "STEM literacy is the ability to identify, apply, and integrate concepts from science, technology, engineering, and mathematics to understand complex problems and to innovate to solve them" (Balka, 2011, p. 7). However, it is more common for reform documents to provide separate definitions of literacy from each of the four disciplines. For example, the development of scientifically literate citizens is a key goal of 21st century science education across the globe (Tytler, 2007). Scientifically literate citizens are critical thinkers who are able to effectively deal with the consequences of our technologically-enhanced world (Bryan et al., 2011). The construct of scientific literacy is multi-faceted and includes the development of competencies for lifelong learning (Bybee, 1997), including an ability to engage in reasoning about complex societal issues (Sabelli, 2006). For students to achieve scientific literacy they require: an understanding of core scientific ideas, an appreciation of the variety of methods of scientific inquiry, and an awareness of epistemological views of science (Leuchter, Saalbach, & Hardy, 2014). Recent reform efforts in the United States evidenced in the *Next Generation Science Standards* (NGSS, 2013) promote active learning, the provision of motivational support for science students, and the development of communities of practice for authentic science learning (Scogin & Stuessy, 2015).

Table 1. Journals Reviewed Over 2010-2015 (N=25)

Journal name
American Educational Research Journal
Australian Journal of Education Technology
Computers and Education
Design and Technology Education: An International Journal
Educational Researcher
Educational Technology Research and Development
International Journal of Science and Mathematics Education
International Journal of Science Education
International Journal of STEM Education
International Journal of Technology and Design Education
Journal of Educational Psychology
Journal of Mathematics Teacher Education
Journal for Research in Mathematics Education
Journal of Research in Science Teaching
Journal of Science Education and Technology
Journal of Technology Education
Mathematical Thinking and Learning
Mathematics Education Research Journal
Research in Science and Technological Education
Research in Science Education
Review of Educational Research
Science Education
Science Education International
Studies in Science Education
Technology, Pedagogy and Education

Similarly, technological and digital literacy are critical 21st century capabilities all students need to develop to effectively participate in our ever-changing world as lifelong learners (Beavis, 2007; Chan, 2010; Gee, 2010). The exponential growth of digital technologies in recent years has changed the face of school education (Kong, 2014), and students are now required to develop new competencies to effectively engage in our digital world (Gut, 2011). The terms 'technological literacy' and 'ICT literacy' are often used interchangeably, with the following definition commonly utilised to define this construct "the interest, attitude and ability of individuals to appropriately use digital technology and communication tools to access, manage, integrate and evaluate information, construct new knowledge, and communicate with others in order to participate effectively in society" (OECD, 2003). Related to this construct is the term 'digital literacy', which can be conceptualised as "the cognitive processes that individuals partake in during the utilisation of computer-based, multimodal information" (Greene, Seung, & Copeland, 2014).

In recent years, many developed countries have implemented reforms for engineering education in K-12 schools (Lachapelle & Cunningham, 2014). The rationale for this reform is originally underpinned by the idea of developing students' technological literacy, and design-based competencies (Cajas 2001). More recently engineering education has been the focus of reforms in the US (NGSS, 2013) that have sought to integrate engineering with other STEM disciplines, with the goal of developing students' engineering literacy. Instrumental to the development of engineering literacy is the construct 'engineering thinking', which encompasses engineering design processes and engineering habits of mind (including competencies such as systems thinking, collaboration and creativity) (NRC, 2012).

Global initiatives to improve the quality of school mathematics have been a dominant focus in education for over half a century, with many of these initiatives designed to elevate the competitive status of countries in the international arena, via improved levels of student achievement (Tarr, Grouws, Chávez & Soria, 2013). Mathematical literacy is commonly defined as the capacity to identify, understand, and engage in mathematics; and the ability to make informed judgments about the role that mathematics plays in everyday life to act as a reflective citizen (Organisation for Economic Cooperation and Development, 2006). Improving the quality of classroom mathematics instruction by changing teachers' implementation of transmissive pedagogical practices emphasising rote learning and memorisation, to more active and collaborative practices, which develop students' problem-solving and sense-making abilities, are deemed necessary to help facilitate the shift to a more mathematically literate society (ACARA, 2015; Common Core State Standards Initiative, 2010).

DECLINING ENROLMENTS AND INTEREST IN STEM DISCIPLINES

The importance of developing STEM literacy is critical to ensure students leave school with the necessary knowledge, skills and attitudes to engage in an increasingly technological world. However, this requirement cannot be expected to be achieved unless students chose to remain in the STEM pipeline during their school education. Research indicates there are declining numbers of students studying post-compulsory science (Lyons & Quinn, 2010; Marginson, Tytler, Freeman, & Roberts, 2013) and mathematics (Forgasz, 2006) across the developed world. These declines have significant implications for the scientific literacy levels and mathematical competency of the general community, and for future participation in STEM careers (Tytler, 2007). For mathematics in particular, there are additional concerns regarding the quality of mathematics graduates (McPhan, Morony, Pegg, Cooksey, & Lynch, 2008). As mathematical knowledge is considered to be fundamental to many important disciplines and professions, declining numbers of high-quality, mathematically-competent individuals has serious implications on both a national and global scale (Martin, Anderson, Bobis, Way, & Vellar, 2012).

A frequently cited reason for declining participation focuses on students' attitudes and interest in mathematics and science subjects. Many studies have reported students' low interest and motivation in school science (e.g., Hidi & Harackiewicz, 2000; Lyons & Quinn, 2010; Sjøberg & Schreiner, 2006), which has been largely attributed to transmissive, teacher-centred pedagogies; perceived irrelevancy of school science to the real world; heavy, difficult and content-driven curriculum; curriculum focused on preparing the academic elite; and a lack of attention to the human aspects of contemporary science (Fensham, 2006; Goodrum, Hackling & Rennie, 2001; Lyons, 2005; Osborne & Collins, 2001; Tytler & Symington, 2006). A recent review by Krapp and Prenzels (2011) found that pedagogy was the most significant influence on students' situational science interest, thus reform efforts that promote student-centred, inquiry-based pedagogical practices embedded in contextualised settings are likely to increase students' interest in school science (Tytler, Symington, & Smith, 2011). Similarly, for mathematics, a number of studies have shown that many students have negative attitudes towards mathematics, and low engagement (Grootenboer & Hemmings, 2007; Zan, Brown, Evans & Hannula, 2006). McKinney and colleagues (2009) identify the implementation of ineffective pedagogies as a key factor influencing student disengagement in mathematics. Other factors include a perceived lack of relevancy to students' everyday lives, and transmissive teaching strategies.

Another reason proposed for the decline in students' interest in school science and mathematics relates to the transition from primary school to high school. It is widely recognised that this transition can disrupt social and emotional development, decrease motivation, and negatively affect student achievement (Mizelle & Irvin, 2000; Sullivan, Tobias & McDonough, 2006). Students move from a learning environment in primary school that stimulates student interest, highlighting the pivotal role of primary school teachers in the early stages of a students' STEM education (Fitzgerald, Dawson, & Hackling, 2013). For the science disciplines, studies from across the globe have indicated that students' interest in school science decreases at an early age, with the majority of students displaying positive attitudes around age 10, with a rapid decline in attitudes evident by age 14 (Lyons, 2006; Renninger & Hidi, 2011). In addition, this is a critical time for mathematics learning as the development of algebraic reasoning during this period is considered to be a gatekeeper strongly influencing students' future decisions about careers in STEM professions (Adelman 2006). Thus, it is also crucial to maintain students' engagement in mathematics in the junior secondary years, as studies have also shown that disengagement in mathematics negatively influences student achievement (Doig, 2005). Ensuring students appreciate the value of mathematics both in the classroom, and in their everyday lives; in addition to providing enjoyable pedagogical practices where students are actively engaged, are some strategies that have been shown to increase student engagement in mathematics (Attard, 2011).

Importantly, an emerging body of research suggests that the integration of technology and engineering in K-12 school settings can facilitate student interest and engagement in STEM disciplines. Findings from these studies indicated engagement in technology and engineering learning experiences fosters creativity and higher order thinking skills, facilitates integration across the STEM disciplines, and contextualises learning resulting in improved motivation and achievement (Cunningham & Lachapelle, 2014; English, 2015; Moundridou & Kaniglonou, 2008). For example, Moore and colleagues (2015) provide the following three arguments for integrating engineering in school education: engineering pedagogies may facilitate improvements in student achievement, engineering thinking contributes to the development of students' 21st century skills and competencies, and engineering contexts may lead to enhanced student interest in STEM.

However, it is important to note that some studies have highlighted challenges when attempting to integrate engineering in school education, including a lack of teaching and learning resources to support integration in the classroom (Roehrig, Moore, Wang, & Park, 2012), and negative teacher perceptions regarding integrating engineering into an already crowded curriculum (Coffey & Alberts, 2013). Similarly for technology, it cannot be assumed that students are 'digital natives' (Prensky, 2001), who are able to successfully navigate and engage effectively in the digital world. On the contrary, a growing body of research has indicated students lack key digital literacy competencies (Eysenbach, Powell, Kuss, & Sa, 2002), including an inability to retrieve, select and integrate information from digital sources (Bennett, Maton, & Kervin, 2008; Selwyn, 2009). They also have difficulties in critically analysing the reliability of sourced information (Padilla, 2010), thus highlighting the need to both diagnose and develop students' digital literacy capabilities. As such, it is imperative to ensure effective pedagogical practices are implemented in school classrooms by high quality STEM teachers, who are competent and confident to ensure effective learning takes place.

EFFECTIVE PEDAGOGICAL PRACTICES IN STEM EDUCATION

The following subsections explores pedagogical practices that have been shown to be effective in promoting student engagement and achievement in STEM disciplines, including inquiry-based learning, argumentation and reasoning, digital learning, and computer programming and robotics. Importantly, for STEM pedagogical practices to be effective, it is critical that teaching approaches are altered from traditional, teacher-centred pedagogies to active, student-centred pedagogies to support student learning (Kennedy & Odell, 2014).

Inquiry-based learning

Inquiry-based approaches to learning are active pedagogical strategies that develop students' abilities to ask questions, design investigations, solve problems, interpret data and evidence, form explanations and arguments, and communicate findings. Inquiry-based approaches to learning are promoted in all STEM disciplines to enable students to engage in authentic and meaningful activities that are connected to the real world. A multitude of definitions exist in the research literature regarding scientific inquiry., A commonly utilised definition, provided by the National Research Council, is stated as: scientific inquiry is a set of abilities and understandings that include asking scientific questions, designing scientific investigations to answer questions, using appropriate tools to interpret and analyse data, formulating scientific explanations using evidence, and being able to communicate and defend relationships between evidence and scientific explanations (NRC, 2012). The implementation of an inquiry-based science curriculum incorporates a range of scientific experiences designed to explicitly facilitate and scaffold students' engagement in inquiry practices such as planning investigations, and providing evidence for claims (McNeill, Pimentel, & Strauss, 2013). Importantly, students must also be supported and encouraged to engage in scientific discourse in collaborative groups to communicate their findings, to ensure they learn to consider multiple, and often conflicting perspectives on scientific problems (Clark & Linn, 2003; Linn & Hsi, 2000).

Mathematical inquiry has been conceptualised in a similar manner, and is commonly defined as a process whereby students use their mathematical knowledge to argue, justify, hypothesise and direct their inquiry (Fielding-Wells & Makar, 2012). The establishment of a collaborative learning environment is necessary to successfully implement an inquiry-based mathematics approach, where students value the processes of reasoning and negotiation (Cobb & McClain, 2006). Refining inquiry questions, peer collaboration, considering alternatives, re-evaluating conclusions, and resolving ill-structured problems are all key practices involved in mathematical inquiry (Magnusson & Palincsar, 2005). Research indicates engaging students in mathematical inquiry has the potential to develop important 21st century competencies, including resilience, coping with uncertainty, self-reliance, and creativity; in addition to increasing interest and engagement in mathematics (Fielding-Wells, 2013; Goos, 2004). Importantly, engaging in mathematical inquiry develops students' problem-solving abilities and mathematical thinking, enabling them to apply their knowledge to situations other than the classroom. As recent reform efforts in mathematics education advocate situating mathematics content in real world contexts that are applicable to students' daily lives (Common Core State Standards Initiative, 2010), inquiry-based approaches are critical to help facilitate this process. Embedding mathematics in real world contexts helps narrow the gap between school knowledge and everyday knowledge, increases accessibility to students, engages students in problem-solving, and increases motivation due to enhanced student interest (Boaler, 1994; Lesh & Zawojewski, 2007).

In the technology and engineering domains, inquiry-based learning is underpinned by the principles of design-based learning (DBL). DBL is an inquiry-based learning approach focusing on the generation of novel and creative artifacts, systems and solutions (Puente, van Eijck, & Jochems, 2013). Students are engaged in solving real world design problems, and incorporate reasoning processes and reflective practices. The process includes planning and design in authentic learning environments, iterative decision-making, formulating predictions, creating solutions, testing prototypes, and communicating findings (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008). The principles of DBL underpin pedagogical practices focusing on engineering design. Engineering design has been the focus of recent attention in educational literature due to its ability to engage students in real world problem solving (e.g., English, Hudson, & Dawes, 2013; Purzer, Goldstein, Adams, Xie, & Nourian, 2015). This focus has also been evident in recent reform documents such as the Next Generation Science Standards (NGSS, 2013) whereby engagement in engineering design is deemed necessary to develop students' technological literacy. The process of engineering design consists of three components: identifying the problem, including constraints and limitations; designing and evaluating solutions; testing and refining solutions, and improving the final design (NRC, 2012). Research indicates that the design process is iterative and complex, with multiple ideas and solutions possible. A variety of tools and schemas may need to be implemented to arrive at a suitable end-product, with earlier designs and prototypes often superseded by more effective products (Lachapelle & Cunningham, 2014). Research indicates that engaging students in engineering design leads to gains in student achievement in science and mathematics (Hmelo, Holton, & Kolodner, 2000), in addition to increased interest in engineering as a career (Apedoe, Reynolds, Ellefson, & Schunn, 2008). As a relatively new addition to the school curriculum, more research is needed to determine effective pedagogical practices in both primary and secondary school settings for technology and engineering disciplines.

Notably, some debate has been evident in the education community concerning the value of inquiry-based instructional approaches (Kirschner, Sweller, & Clark, 2006), due to a lack of understanding of commonly utilised terms in the literature. For example, inquiry-based approaches are often clustered with other learning approaches such as discovery learning and problem-based learning (Lee, Linn, Varma, & Liu, 2010; Ødegaard, Haug, Mork, & Sørvik, 2014). This assumed connection is problematic (Hmelo-Silver, Duncan, & Chinn, 2007), as minimally guided instructional approaches such as discovery learning (in particular, unassisted discovery) have been found to present challenges to student learning (Alfieri, Brooks, Aldrich, & Tenenbaum, 2011). In addition, problems have been documented by teachers attempting to implement inquiry-based approaches in mathematics classrooms who are unfamiliar with these student-centred learning approaches. Identified issues include problems surrounding the establishment of collaborative learning environments, an inability to cope with increased noise levels and more relaxed classroom organisation, an inability to accept uncertainty, and a lack of scaffolding to support the development of student autonomy (Goos, 2002). These constraints highlight the importance of providing professional development to teachers to support and scaffold understandings of this pedagogical approach to learning (Crawford, 2000).

Argumentation and reasoning

Closely related to inquiry-based learning approaches, argumentation and reasoning practices have been promoted in two STEM disciplines, science and mathematics, and are implicit in DBL strategies employed in technology and engineering. Engaging in the pedagogical practice of argumentation, whereby students participate in discussing evidence, considering alternative views, evaluating claims and debating ideas, is considered to be an authentic science learning experience (Duschl & Grandy, 2008; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003), mirroring the practices professional scientists engage in on a regular basis. Encouraging students to engage in critical thinking, discussion and debate has many benefits, including participating in scientific discourse, improved learning of scientific concepts, generating questions, formulating informed positions, and engaging in socioscientific decision-making (Chin & Osborne, 2008; Erduran & Jimenez-Aleixandre, 2008; Varelas, Pappas, Kane, & Arsenault, 2008). Research conducted in science education indicates that engaging students in argumentative practices can also lead to improvements in student achievement (Asterhan & Schwarz, 2009). Thus, encouraging a supportive classroom atmosphere where students feel confident to express their views on scientific issues is vital to enable argumentation-based learning to occur.

The development of mathematical thinking is considered to be a core goal of mathematics education (Schoenfeld, 1992). This type of thinking is needed to enable students to analyse, explain and justify their ideas as they attempt to solve mathematical problems (Cobb & McClain, 2006). A specific focus in mathematics education relates to algebraic and proportional reasoning, and the development of these competencies has been a key focus in international reform initiatives in school mathematics education, due to research findings highlighting the significant impact of these competencies on students' higher mathematical study and future career options (Kaput, 1999). As stated earlier, the development of algebraic reasoning is considered to be a gatekeeper that strongly influences students' future decisions about careers in STEM professions (Adelman 2006), therefore insufficient understandings may deny students' access to careers requiring mathematical competency. Similarly, the development of proficient proportional reasoning competencies has been identified as a reliable predictor of students' ability to engage effectively in higher mathematical study (Lesh & Zawojewski, 2007). Without this competency, students find it difficult to successfully proceed into post-compulsory mathematics (Staples & Truxaw, 2012).

Previous research has consistently shown that students experience difficulties in developing algebraic and proportional reasoning (Fielding-Wells, Dole, & Makar, 2014; Kaput, 2008). Thus, many researchers have advocated that algebraic and proportional reasoning instruction needs to start as early as Kindergarten, to enable students to have deep and sustained experiences in these reasoning practices across the years of schooling (Blanton, Stephens, Knuth, Gardiner, Isler, & Kim, 2015; Fielding-Wells et al., 2014). As such, primary teachers may require additional professional development in these areas to support their students in developing these key mathematical competencies.

Digital learning

Digital classrooms are modern learning environments that enable students to develop their technological literacy and critical thinking skills throughout their daily learning activities (Kong, 2014). In essence, they are standard classrooms that integrate mobile technologies, such as laptops, tablets and smartphones into the teaching and learning process. Students are able to use their mobile devices to access digital learning objects and resources to support the learning of relevant content (Chan, 2010). The rationale for the use of mobile technologies is a pragmatic one – the majority of students own and use mobile devices, and these devices have become a pervasive influence in their daily lives (Song, 2014). Thus, the *Bring Your Own Device* (BYOD) model is now a common feature in schools in many countries. Digital classrooms support the creation of constructivist STEM learning environments, whereby the learner is able to conveniently access, develop and share relevant knowledge on a progressive basis, with the teacher acting as a facilitator of knowledge construction (Kong, 2011). Other advantages of these classroom environments include providing students with access to a variety of learning sources and developing their ability to critically process and assimilate information from a variety of sources across the STEM disciplines (Gut, 2011; Wong & Looi, 2011).

Two digital learning approaches that have been found to be effective in STEM classrooms are digital game-based learning and computer simulations. Digital game-based learning is a computer-supported learning approach that has been shown to increase student motivation and facilitate learning in technology-enhanced environments (Gee, 2007; Kiili, 2007; Prensky, 2001). Research indicates the majority of children and adolescents engage in digital game playing, thus providing a powerful impetus to engage them in meaningful learning with relevance to their daily lives. Many positive educational outcomes have been cited by researchers regarding the effectiveness of digital game-based approaches including: facilitating independent learning, improving information processing ability, promoting higher order thinking, developing problem-solving ability, and effectively scaffolding learning (Annetta 2008; Mayer & Wittrock, 2006). As a student-centred instructional approach, digital game-based learning aligns with constructivist teaching approaches that value active learning, and student-led inquiry. It is an intrinsically motivating approach that has been shown to enhance students' motivation for learning (Papastergiou 2009), and promote students' learning performance (Sung & Hwang, 2013).

Computer simulations are computer modelling tools that present theoretical or simplified models of real-world processes and phenomena, and include visualisations, animations, and virtual laboratories (Smetana & Bell, 2012). Recent studies indicate that these tools may assist in the implementation of education reforms by facilitating inquiry-based learning (Bell & Trundle, 2008; Papeveridou, Constantinou, & Zacharia, 2007; Schnittka & Bell, 2009), and the development of students' STEM literacy (Rutten, van Joolingen, & van der Veen, 2012). For example, computer simulations provide authentic contexts for learning where students are afforded immediate feedback (Rose & Meyer, 2002) enabling them to hone and develop their evolving ideas (Lee et al., 2010), and take ownership of their learning. They promote active engagement in higher-order thinking and problem-solving, and facilitate the learning of more abstract concepts (Hargrave & Kenton, 2000). Simulations can also provide opportunities to visualise phenomena that are too dangerous, time-consuming or complicated to interact with in the classroom or laboratory (van Joolingen, de Jong, & Dimitrakopoulout, 2007).

Research indicates that computer simulations have positive effects on students' attitudes (Zacharia & Anderson, 2003), and, when implemented appropriately, are equally effective as more traditional pedagogies in supporting student learning and achievement (e.g., Binns, Bell, & Smetana, 2010; Trundle & Bell, 2010; Zucker, Tinker, Staudt, Mansfield, & Metcalf, 2008). Importantly, four decades of research on computer simulations shows that these tools are most effective when they are used to complement, not substitute, other pedagogical practices, and students must be provided with effective support and scaffolding to interact with these tools (Smetana & Bell, 2012).

Computer programming and robotics

An important pedagogical approach that has received increased attention in recent years focuses on the integration of computer programming and robotics across the years of schooling (Israel, Pearson, Tapia, Wherfel, & Reese, 2015). Research suggests that many of the technology-based activities students engage with in classrooms tend to focus on operating technologies as end-users, rather than focusing on learning to develop new technologies (Kafai, Burke, & Resnick, 2014). As such, pedagogical practices in the classroom need to shift towards activities that promote learning and creating, and computer programming and robotics have been proposed as learning technologies that can enable the development of competencies, such as problem-solving and higher-order thinking skills (Fessakis, Gouli, & Mavroudi, 2013).

Computer programming requires students to engage in a problem-solving process termed computational thinking. The process is multi-dimensional and iterative, and comprises a number of phases including: framing problems in a manner that enables them to be solved using computational tools; organising and analysing data; using models and simulations to represent data; implementing algorithmic thinking to automate solutions; evaluating solutions; and implementing the problem-solving process to other contexts. Engaging students in computer programming experiences has been shown to be beneficial for their learning, attitudes and motivation (Lambert & Guiffre, 2009; Liao & Bright, 1991), particularly with younger students. For example, simple computer programming activities have been shown to facilitate learning with Kindergarten children (Fessakis et al., 2013). Foundational concepts of pattern recognition, sequencing and ordering are able to be explored through early programming experiences, which can be adapted to suit differing developmental levels (Strawhacker & Bers, 2015).

Engaging students in robotics has also been shown to be a highly effective pedagogical practice, particularly in the area of programmable and interactive robotics (Bers et al., 2014). Similarly to computer programming, research has indicated that engaging younger students in robotics can facilitate effective learning. In addition to developing problem-solving skills, engagement in robotic manipulatives has been shown to develop fine-motor skills and hand–eye coordination (Bers, 2008). Kindergarten children have been shown to be able to engage in robot construction and programming (Bers, Ponte, Juelich, Viera, & Schenker, 2002), in addition to developing their computational thinking (Bers, 2008). The importance of play in the early childhood curriculum is highly valued, and engaging children in robotics activities allows them to both play and learn in a creative environment (Resnick, 2003). Thus, it is important to provide opportunities for students to engage in computer programming and robotics from the start of their schooling to facilitate the development of their computational thinking skills. Other research has highlighted the importance of developing other competencies such as core mathematical understandings in the early childhood years to not only engage students in learning, but also bolster student achievement (Claessens & Engel, 2013). A consideration of student achievement and STEM is discussed in the following section.

STEM AND ACHIEVEMENT

The integration of technology and engineering into school education has been proposed as an effective means to enhance student learning and raise student achievement in STEM disciplines (Brophy, Klein, Portsmore, & Rogers, 2008). Technology and engineering activities have been shown to develop STEM literacy and increase motivation, in addition to providing real world contexts for learning scientific and mathematical concepts (NRC, 2012). Engaging students in activities that are fun, hands-on and linked to everyday contexts improves students' attitudes towards STEM subjects, which may then encourage them to pursue STEM-based careers (Koszalka, Wu, & Davidson, 2007). Importantly, research indicates that an increasing number of teachers are integrating these types of pedagogical practices in their classrooms, although the scope and level of implementation varies between teachers, schools and countries (Lim, Zhao, Tondeur, Chai, & Tsai, 2013; Tondeur, Cooper, & Newhouse, 2010).

A growing body of research has examined the influence of technology integration on student achievement, with findings from these studies reporting mixed results. Some early studies reported positive but small to moderate effect sizes (e.g., Kulik & Kulik, 1991), whereas more recent research has yielded mixed findings (Machin, McNally, & Silva, 2007), with many studies reporting comparable achievement levels when technology was not implemented (e.g., Ehri, Dreyer, Flugman, & Gross, 2007; Torgesen, Wagner, Rashotte, Herron, & Lindamood, 2010). Implications from this research highlight an important point – the provision of technological resources to schools is not sufficient – teachers and students require technological competency to engage effectively with these tools. Interestingly, international research examining the influence of one type of mobile technology – laptops - on student learning outcomes has generally shown no significant increase in learning outcomes when 1:1 laptop initiatives were implemented in schools (e.g., Lowther, Inan, Ross, & Strahl, 2012; Silvernail, Pinkham, Wintle, Walker, & Bartlett, 2011). Thus, further research is needed to inform future strategies for effective mobile technology integration in the classroom.

In the area of mathematics, research indicates that children enter the early years of schooling with a range of mathematical abilities (Houssart, 2001). Without exposure to effective pedagogical practices, students exhibiting delays in their knowledge often fall behind the rest of their cohort for the duration of their formal schooling (Morgan, Farkas, & Wu, 2009; Princiotta, Flanagan, & Germino Hausken, 2006). Other studies have confirmed the importance of developing core mathematical competencies in the early years of schooling, as these competencies have been found to predict both current and future mathematics achievement (Duncan & Magnuson, 2011; Jordan, Kaplan, Ramineni, & Locuniak, 2009). Thus, the early years of learning, including Kindergarten and the lower primary years, are an important focus for the implementation of pedagogical practices to promote student learning and achievement in mathematics.

More positive findings have been reported in the science domain with reform efforts in international science education advocating the implementation of constructivist learning and teaching approaches, that employ authentic, inquiry-based pedagogical practices to make connections between student's existing knowledge and currently accepted scientific knowledge (NGSS, 2013). Research indicates that when students actively engage in authentic science inquiry in collaborative groups, they are afforded opportunities to act like scientists (Bricker & Bell, 2008; NRC, 2012). As a consequence of engagement in meaningful science experiences aligned with authentic science practices, students have been found to display increased motivation and interest in science, and improvements in student achievement (Fang & Wei, 2010; Herrenkohl & Guerra, 1998). In particular, pedagogical practices utilising inquiry-based science curricula have been found to improve student achievement by enhancing their science conceptual knowledge (Sandoval & Morrison, 2003) and improving their ability to effectively engage in inquiry-based activities such as scientific reasoning and data analysis (Ebenezer, Kaya, & Ebenezer, 2011). Clearly, the implementation of effective pedagogical practices requires high quality teachers who have the requisite knowledge and skills to create learning environments to facilitate student learning and achievement. A consideration of the role of the teacher in STEM education is discussed in the following section.

THE ROLE OF THE TEACHER IN STEM EDUCATION

Teachers are considered to play a pivotal role in students' learning and achievement via the provision of a safe and supportive learning environment, engagement in effective pedagogical practices, and the provision of adequate time to engage in the learning process (Elster, 2014; Lasley, Siedentop & Yinger, 2006; Rivkin, Hanushek & Kain, 2005). The following subsections will discuss the influence of the teacher on student achievement; the role of teacher competence, beliefs and self-efficacy on their practice; and the importance of teacher professional development.

Teachers and achievement

The influence of the teacher on student achievement has been the focus of extensive research over the past 40 years (e.g., Darling-Hammond, 2000; Goldhaber & Brewer, 1997; Hanushek, 1971, 1997), and has predominantly been conducted in the areas of mathematics and science education. The majority of this research has explored the assumed relationship between aspects of teacher quality (e.g., subject matter knowledge, pedagogical knowledge, teaching experience, classroom practice, academic qualifications) and student achievement, however the results of empirical studies have reported mixed findings (e.g., Ball, Lubienski & Mewborn, 2001; Brophy, 1986; Wenglinsky, 2002). For example, in science education, some studies have identified a relationship between student achievement and teacher experience and qualifications (e.g., Darling-Hammond, 2000; Kaya & Rice, 2010), with others finding no relationship (e.g., Goldhaber & Brewer, 2000; Xu & Gulosino, 2006). Interestingly, very little research has been conducted on the relationship between science teacher content knowledge and student achievement, or classroom practice (Chinnappan & Lawson, 2005). As such, this is an important area for future research.

Conversely, a large body of research has been conducted on the influence of mathematics teachers on student learning and achievement, with the majority of this research highlighting the critical role of the teacher in this process (e.g., Boaler, 2002; Nye, Konstantopolous, & Hedges, 2004). Many studies have examined the influence of teachers' classroom instruction on student achievement (e.g., Pianta & Hamre, 2009), with results generally showing a positive relationship between high-quality classroom instruction and student achievement. Importantly, future studies are needed to determine the nature of the role of technology and engineering teachers on student achievement.

Teacher competence, beliefs and self-efficacy

Although there is agreement in the wider teacher education community that teacher competence is enhanced when teachers possess strong content knowledge (Grossman & Schoenfeld, 2005; Shulman, 1986), the relationship between teacher content knowledge and student achievement has been found to be complex, and mediated by other factors including teacher academic qualifications and discipline majors (Goldhaber & Brewer, 2000). A significant body of research in mathematics education has focused on the relationship between teachers' content knowledge and student learning. In mathematics education, mathematical knowledge for teaching (MKT) is conceptualised as an integration of content knowledge and pedagogical content knowledge (Ball, Thames, & Phelps, 2008; Hill, Ball, & Schilling, 2008). MKT is considered to be an essential prerequisite for effective teaching and learning in mathematics, with research indicating that teachers with higher MKT provide higher quality mathematics instruction in their classrooms, via more effective presentation of concepts, ability to help connect student ideas, and the implementation of effective questioning techniques (Boaler, 2002; Borko & Putnam, 1995; Hill, Kapitula, & Umland, 2011). In addition, MKT has been found to positively influence student achievement (Baumert et al., 2010; Hill, Ball, Blunk, Goffney, & Rowan, 2007).

Studies have been more unanimous in their support of a relationship between teachers' beliefs and their classroom practice (e.g., Haney & Lumpe, 1995; Pajares, 1992). For example, Bandura (1977) highlighted the critical role of teachers' self-efficacy beliefs on their practices in the classroom. Teacher beliefs have been shown to influence their implementation of new pedagogical practices, classroom planning activities, and involvement in professional decision-making (Dixon & Wilke, 2007; Lee, Hart, Cueves & Enders, 2004). Thus, a consideration of teacher beliefs is an important focus for administrators wishing to implement innovative pedagogical practices and reforms in STEM education.

For example, in the technology domain, a necessary prerequisite for successfully utilising technology pedagogical practices is an understanding of the underlying conceptual workings of the pedagogical tools to be implemented. Importantly, this technical competency is a necessary, but not sufficient, condition for effective integration, as the teacher must then develop the relevant pedagogical content knowledge to successfully integrate the technological tool in the classroom (Murcia, 2012). Research indicates that when teachers have developed this technology pedagogical content knowledge they will be more likely to change their beliefs and practices in the classroom, to effectively engage students in technology learning environments (Hall & Hord, 2006).

As a relatively new focus in school education, a paucity of research exists that examines the role of the teacher in engineering education. Clearly, as a new discipline area, many teachers have little or no experience in teaching engineering. This has obvious consequences as a lack of discipline-specific content knowledge, pedagogical practices and experience has been shown to affect teacher competence (Shulman, 1986). Bamberger and Cahill (2013) highlight some of the challenges teachers encounter when attempting to teach engineering in their classrooms, including the adoption of new pedagogical practices needed to support engineering instruction. For example, engineering teachers are required to focus on design-based issues that have multiple solutions. These types of tasks are open-ended and can be viewed from differing perspectives. Although these types of tasks encourage creativity, teachers are required to adopt student-centred instructional strategies, which may present challenges for more traditional teachers (Burghardt & Hacker, 2004). Thus, professional development is essential to provide engineering teachers with the requisite content and pedagogical knowledge needed to effectively scaffold these new types of pedagogical practices in the classroom.

Research indicates that the successful implementation of recent reform efforts in the global education community promoting inquiry-based approaches to learning are mediated by teachers' beliefs about effective instructional approaches. For example, in science education, many studies have reported that teachers commonly adopt a transmissive, teacher-centred instructional approach instead of an inquiry-based, student-centred instructional approach in their science classes (e.g., Lumpe, Haney, & Czerniak, 2000; Thomson, Turner, & Nietfeld, 2012). Their adoption of these traditional approaches is thought to be due to a perception of inquiry as lacking structure, and more difficult to implement effectively. Thus, an important focus for the successful implementation of educational reform initiatives may involve changing teachers' beliefs about effective instructional approaches.

Other research conducted in technology education indicates that the successful integration of technology in the classroom is highly dependent on teachers' beliefs about technology (Hsu & Kuan, 2013). Research has indicated that teachers' attitudes and perceptions of technology significantly predict how they adopt, and the extent to which they adopt, technologies in their classrooms (Capo & Orellana, 2011). If teachers do not feel confident in utilising technologies themselves, they are often reluctant to adopt them in their classrooms. Teachers' level of experience with technologies, and perceptions of usefulness have also been shown to influence adoption (Miranda & Russell, 2012).

Teacher professional development

Research has shown that high-quality professional development programs lead to positive changes in classroom practice (e.g., Desimone, 2009; Desimone, Porter, Garet, Yoon & Birman, 2002; Garet, Porter, Desimone, Birman & Yoon, 2001), and improved student achievement (e.g., Blank, de las Alas, & Smith, 2007; Borko, 2004; Yoon, Duncan, Lee, Scarloss & Shapley, 2007) in STEM disciplines. However, not all professional development programs are the same, with wide variance reported between programs (Shulman, 2005), although some consensus has been reached on important features of effective professional development programs (Darling-Hammond & McLaughlin, 1995; Garet, Porter, Desimone, Birman, & Yoon, 2001; Penuel, Fishman, Yamaguchi, & Gallagher, 2007). These features include a focus on conceptual knowledge, active learning strategies, and coherence with curriculum goals (Garet et al., 2001). In addition, effective professional development should be conducted over a sustained time-period, and embedded within the school context (Desimone, 2009).

The majority of research on professional development in STEM disciplines has been conducted in science and mathematics, with findings indicating that engaging in professional development has been shown to be beneficial to teachers (Banilower, Heck, & Weiss, 2007; Capps, Crawford & Constas, 2012; Goldhaber & Brewer, 1997; Suppovitz & Turner, 2000). Professional development programs have been found to be especially important to primary science teachers who exhibit a general lack of science content knowledge (Appleton, 2002; Kikas, 2004; Garbett, 2003), low confidence in teaching science (Cobern & Loving, 2002; Pell & Jarvis, 2003), limited science teaching pedagogy (Garbett, 2003; Tu, 2006), lack of science-specific qualifications (Epstein & Miller, 2011), and limited time available to teach science (Silvertsen, 1993). Thus, it is crucial for these teachers to engage in professional development programs to improve their science content knowledge, science pedagogical knowledge, and confidence in teaching science.

Research conducted in technology and engineering has also promoted the benefits of engaging teachers in professional development, particularly for the development of technological pedagogical content knowledge (TPACK) and design-based learning approaches (DBL) (Burghardt & Hacker, 2004; Burns 2002; Culp, Honey, & Mandinach, 2005). Importantly, this professional development is needed not only prior to the implementation of new practices, but also during the implementation in the classroom. On-going support has been shown to be critical to the success of technology and engineering integration in the classroom (Wood, Mueller, Willoughby, Specht, & Deyoung, 2005). Other features of effective technology and engineering professional development include technology- and engineering-specific information, extended periods of time to engage in professional development, implementation of student-centred instructional strategies, and a focus on technologies/pedagogies that are available to teachers (An & Reigeluth, 2011).

CONCLUSION

The implementation of STEM initiatives is a challenging endeavor. Central findings from this review of 237 papers highlight three key factors to consider when attempting to successfully integrate STEM teaching and learning in schools. First, disengagement in STEM subjects is pervasive throughout junior secondary school. A focus on maintaining student interest and motivation to engage in STEM in this phase of schooling is vital to ensure students are encouraged to consider post-compulsory STEM courses, and remain in the STEM pipeline. Second, implementing effective pedagogical practices has been shown to increase student interest and motivation, develop 21st century competencies, and improve student achievement. The implementation of inquiry-based practices that value active learning, immersion in authentic settings, engagement in reasoning and problem-solving, and the development of creativity, have been shown to facilitate effective student learning. Finally, and perhaps most importantly, the role of the teacher is critical in this process. Evidence strongly suggests that high-quality teachers are instrumental in positively affecting students' attitudes and motivation, and in many cases, student achievement. Providing teachers with adequate support (particularly primary teachers) via effective professional development is vital to ensure our students are adequately prepared to enter our increasingly technologically-driven world as "STEM literate" citizens.

Importantly, this paper has examined the contributions of the four disciplines – Science, Technology, Engineering, and Mathematics – to the field of STEM education. This disciplinary perspective to examining the field has inherent limitations which are acknowledged in this paper including a recognition that 'the whole is more than the sum of the parts,' and the contribution of interdisciplinary and transdisciplinary approaches to STEM in future research. However, the strength of this paper lies in the identification of common themes, practices and approaches drawn from empirical research in each of the STEM disciplines, which can inform future evidence-based approaches to STEM education in school settings.

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