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Numeracy and Digital Learning: Use of Digital Technologies as Tools for Numeracy Development

A Review of the Literature

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Recommendations

- The centrality of the role of the teacher must be foregrounded; this requires that teachers are supported to develop deep understanding of what is meant by the development of mathematical numeracy, understand what pedagogical approaches to use and how to leverage the use of digital tools when designing learning experiences and assessment of and for learning (Bray & Tangney, 2017; Geiger et al., 2010; Laborde et al., 2006; Olive et al., 2010; Swan, 2007).
- Dynamic Geometric Software (DGS), Virtual Manipulatives (VM) should be integrated into mathematics teaching to provide students with opportunities to gain access to mathematical representations and visualisations and to interact with complex phenomena in ways that would not otherwise be possible (Aliyu et al., 2021; Ayub et al., 2012; Beauchamp & Kennewell, 2013; Chan & Leung, 2014; Costică, 2015; Juandi et al., 2021, Tamur et al., 2020). Further research needed to examine the comparative effectiveness of virtual /physical manipulatives (Holmes, 2013; Kul et al., 2018).
- Educational robots/robotics should be used to (i) promote active learning pedagogy and enhance the learning experience through inquiry, exploration; (ii) make cognitive associations with prior experience thus allowing students to improve their conceptual understanding of the content and understand abstract concepts (e.g., Krishnamoorthy & Kapila, 2016; McGrath et al., 2008; Shankar et al., 2013; Williams et al., 2011).
- Digital game-based learning can be as a pedagogical approach for student motivation and to enhance student interest /attitude in mathematics but further research is needed to investigate the range of possibilities for mathematical development.
- Computational thinking should be embedded integrated curricula across subjects (e.g. computer science, mathematics, science) (Ingram, 2014; Tanaka et al., 2016).
- To maximise the opportunities of mathematical developmental potential, further research is needed to explore the relationship and possibilities between computational thinking/ programming / coding / robotics and mathematical development. Research is also needed to explore the developmental progression of computational thinking and how best to design for this. This is particularly pertinent considering the new Primary Curriculum Framework (NCCA, 2020), the new digital strategy for schools (2021-2027) (DE, 2022) as well as the STEM Education policy statement (2017 - 2026) (DES, 2017).
- Technology-assisted systems for mathematics instruction should be developed in line with mathematics learning trajectories to ensure that learning tasks / assessment utilised by these systems are informed by research grounded in mathematical learning.
- Teacher professional learning must be provided to support teachers leverage the use of digital tools when designing learning experiences and assessment of and for learning in mathematics. Professional learning opportunities relating to the use of DGS, VM, mobile devices and other and technologies in mathematics education are required so that teachers are required to enable teachers to develop the necessary skills to employ them in the most appropriate way to develop students' mathematical thinking and in particular, higher-order cognitive and metacognitive competencies (Wong et al., 2020).
- Given the dearth of studies focussing on the use of digital technologies on mathematical development kindergarten and prekindergarten level, further research is required in this area.
- Considering the predominant influence of AI in our daily lives, it is crucial that attention is accorded to the development of data literacy. Teachers not only need to possess excellent statistical skills but also have the ability to critically select appropriate materials and digital tools, to design learning that captures the interest of the students (Weiland, 2017).

Summary of Findings

- This paper focuses on how the use of digital tools can support numeracy development in early childhood, primary and post-primary mathematics education. It concludes that lasting significant change requires teachers to have a deep understanding of what is meant by the development of mathematical numeracy as well as an understanding of what pedagogical approaches to use, including how to leverage the use of digital tools, when designing learning experiences and assessment of and for learning. Central to any change in pedagogical approaches is the teachers' values, beliefs and attitudes.
- The use of digital technologies to support numeracy development is a complex issue and a "wicked challenge" to disentangle. While reviews (Harskamp, 2014; Slavin, 2019) indicate a positive effect of digital technologies on mathematics achievement, this is dependent on other factors such as pedagogical approaches and strategies used. Other factors to consider include the impact of technology use on student achievement, motivation, and attitudes in the context of mathematics and if/how results vary based on the different aspects of the intervention examined (e.g. Higgins et al., 2019)
- Digital technologies such as Dynamic Geometric Software (DGS), Virtual manipulatives (VM) provide students with opportunities (i) to gain access to mathematical representations and visualisations that would not be possible to explore on paper or using concrete manipulatives and (ii) to experiment with complex ideas that would otherwise be inaccessible (Aliyu et al., 2021; Ayub et al., 2012; Beauchamp & Kennewell, 2013; Costică, 2015; Donnelly-Hermosillo et al., 2020). The use of these technologies can positively impact student achievement (Chan & Leung, 2014, Juandi et al. 2021a, Moyer-Packenham and Westenskow, 2013) and can promote higher-order thinking skills such as critical thinking, deductive thinking, and visualisation skills (Aliyu et al., 2021; Browning et al., 2011).
- Robotics can play an active role in mathematics education at pre-school, elementary and secondary school levels (Bers, 2010; Bers & Horn, 2010; Kazakoff & Bers, 2011; Rogers & Portsmore, 2004, Zhong & Xia, 2020). The use of robotics promotes active learning pedagogy and helps to improve the learning experience through inquiry, exploration, and making the cognitive association with prior experience; allows students to improve their conceptual understanding of the content and understand abstract concepts better (e.g., Krishnamoorthy & Kapila, 2016; McGrath et al., 2008; Shankar et al., 2013; Williams et al., 2011). Using educational robots also facilitates students' ability to apply and transfer mathematical skills in programming (Sánchez-Ruíz & Jamba, 2008).
- Computational thinking processes of abstraction, algorithmic processing, and systemic thinking can aid students' understanding of many academic domains such as mathematics, science and language (Grover & Pea, 2013). Students learning via integrated curricula across subjects (e.g. computer science, mathematics, science) are more likely to have knowledge and skills acquired in one subject affect their learning outcomes in other subjects compared to students learning via fragmented curricula with segregated subjects (Ingram, 2014; Tanaka et al., 2016). This link is likely strongest in primary school (Lei et al., 2020). Reviewing the similarities and differences between programming as a part of computational thinking and mathematical thinking, skills such as problem solving and modelling are involved in both (Shute et al., 2017). Both also require the abstraction of real-world problems (Zong & Zia, 2020), the formulation as computational models, the application of strategies and algorithms to solve them, and the interpretation of a solution. These shared sub skills may explain the strong and positive

transfer effects on mathematical skills (Scherer et al., 2019; Popat & Starkey, 2019, Sun et al., 2021b; Fidai et al., 2020).

- Technology-assisted systems for mathematics instruction can have a positive impact on students' achievement in mathematics (e.g. Cheung and Slavin, 2013; Deunk et al., 2018; Ran et al., 2021). However, they must be used alongside other forms of instruction and cannot be used in isolation. Further research is required to identify the instructional design features that are required to optimise their effects on mathematics learning. Transparency is required relating to how learning pathways are determined e.g. what metrics are utilised in assessments to measure their 'effectiveness'. This information would enable researchers /teachers to understand the mathematics underpinning these systems and to evaluate their potential impact prior to implementing them within their classrooms.
- Only one systematic review (Aziz & Rosli, 2021), focused on statistical literacy skills (i.e. critically understand, interpret, evaluate, and communicate statistical data through various forms of media) which is crucial in a society that is continuously bombarded with a myriad of information that involves statistical data-based arguments (Weiland, 2017).
- Professional learning opportunities for teachers to leverage the use of digital technologies for mathematical development is a key factor in their effective use (Bray & Tagney, 2029; Talib et al, 2019; Ugolini, 2019; Sun et al., 2021b Wong et. al., 2020).

Numeracy and Digital Learning: Use of Digital Technologies as Tools for Numeracy Development

This paper focuses on trying to understand if and how the use of digital tools can support numeracy development in early childhood, primary and post-primary mathematics education. This question is, of course, very dependent on how numeracy is understood and how its development can be measured or accessed. There is also the complex issue of considering, if mathematical achievement/attainment only should be taken as evidence of the effective and appropriate use of digital tools (which in itself throws up the question of what should be considered as mathematical achievement) or if the use of digital tools is to be regarded as an integral component of the development of mathematical thinking, knowledge, skills and dispositions.

The use of digital tools to support numeracy development is a complex issue and a "wicked challenge" to try to disentangle. For example, the meta-analysis conducted by Harskamp (2014) indicates an overall medium positive effect (0.48 SD) of digital technologies on mathematics achievement in primary education. Findings from Hardman's review (2019) of 37 studies also indicate that the impact of digital technologies on mathematical attainment at primary school level impact positively on student mathematical outcomes. However, this is provided that a constructivist pedagogy is used rather than a traditional transmission based pedagogy. Similarly, Slavin's review (2013) indicates that technology innovations had their largest effects in primary mathematics (ES = +0.19), but only when combined with instructional process programmes that enabled teachers to use multiple strategies (e.g. cooperative learning and metacognitive development) (ES = +0.33). The role of the teacher and how their values, beliefs and assumptions about both numeracy and the use of digital tools are central to any discussion as this determines what learning experiences are designed for students and whether the use of digital tools support numeracy development. Other factors to be considered include students' attitudes, motivation and achievement in mathematics and whether these should be considered separately or if using technology can increase these aspects of learning in the context of mathematics. Findings from a meta-analysis of 24 articles (4,522 subjects) by Higgins et al. (2019) indicate a significant overall impact of technology on student achievement, motivation, and attitudes. Overall, the mean weighted Cohen's *d* between groups for the technological intervention on mathematics achievement was 0.68; it was 0.30 for motivation, and 0.59 for attitudes. However, results varied based on the different aspects of the intervention examined such as the technologies used, duration and content area. Education level may also be a factor.

These examples serve to indicate that the use of digital tools to support numeracy development is a complex issue and a "wicked challenge" to try to disentangle. The focus of this paper is to gain insight into if and how the use of digital tools can support numeracy development. In order to structure this report, we present the findings of our review of 65 systematic reviews, according to the different categories of digital tools that were predominantly identified in the studies used in relation to numeracy development and mathematics education. We discuss the use of these digital tools and the pedagogical implications in relation to students' numeracy development.

Research Question

In what ways can the use of digital tools support numeracy development in early childhood, primary and post-primary education?

Narrative Report

Dynamic Geometry Software

Dynamic geometry software (DGS) enables students to construct, manipulate, measure, simulate, hypothesise, and verify mathematical relations and geometric figures in a computer-based learning environment (Drigas & Pappas, 2015; Olivero & Robutti, 2007; Straesser, 2002). In their systematic review, Chan and Leung (2014) analysed nine studies and found that the use of DGS has a positive impact on student's mathematics achievement, producing a positive and large effect size (d = 1.02). They concluded that this supports the implementation of DGS interventions and they posit that the use of DGS has the potential to transform traditional teaching practices. The findings of a meta-analysis conducted by Juandi et al. (2021a). Their review of 50 studies, involving 57 effect sizes, also produced a positive and large effect size (d = 1.07). The studies included across the systematic reviews identify a number of reasons for the positive impact of DGS. For example, DGS enables students to access geometrical tools that would otherwise be unavailable using traditional approaches and also to experiment with complex ideas that would otherwise be inaccessible (Aliyu et al., 2021; Ayub et al., 2012; Beauchamp & Kennewell, 2013; Costică, 2015). In addition, studies highlight that DGS can promote higher-order thinking skills such as critical thinking, deductive thinking, and visualisation skills (Aliyu et al., 2021; Browning et al., 2011). In particular, GeoGebra, which offers a combination of 2D and 3D dynamic geometry software, provides opportunities for children to manipulate and visualise 2D and 3D geometric representations that would not be possible using traditional methods. In their analysis of 51 studies Tamur et al. (2020) revealed that GeoGebra was more effective than any other mathematical software.

The conditions under which the use of DGS is most effective have been explored in a number of studies. In a systematic review of 13 papers regarding a particular DGS, namely Geometer's Sketchpad, Wong et al. (2020) identified the professional development of teachers as a key factor in the effective use of DGS. They found that preparing materials for use with DGS is challenging and requires in-depth knowledge of the software and deep pedagogical understandings. Chan and Leung (2014) found that shorter DGS interventions were more effective than longer programmes of implementation. They attributed this to the novelty effects of implementing a new technological approach and to the instructional design of such interventions (Erbas & Yenmez, 2011; Hannafin & Scott, 2001). The number of students in the classroom and the availability of a computer for each child were reported by Juandi et al. (2021a) as factors that contributed to the effectiveness of the use of DGS.

There was a lack of agreement across the systematic reviews regarding the age group that may benefit most from using DGS. Drawing on research involving students in primary and secondary schools, Chan and Leung (2014) suggest that students in primary education may benefit most from the use of DGS. Indications were that this was because (i) geometric properties could be kept consistent when using DGS thus leading to better recognition of geometric shapes and figures and (ii) the concrete and hands-on nature of DGS may facilitate younger children in acquiring geometrical knowledge. In contrast, an analysis of previous studies conducted by Juandi et al. (2021a) which focused on students in junior high schools, high schools and higher institutions concludes that the use of DGS is most effective in the upper-end of secondary schools and universities. However, another study by Juandi et al. (2021b) in which they examined the impact of GeoGebra[1] on mathematics learning indicates that differences in class level do not influence the size of the effect of using GeoGebra software on students' mathematics achievement. These findings lead us to conclude that further research is required to identify the conditions required across various settings to maximise the impact of DGS on mathematics teaching and learning.

Virtual Manipulatives

Virtual manipulatives are computer applications that enable students to explore and manipulate virtual models of physical manipulatives (Reimer & Moyer, 2005). They were designed to provide opportunities for students to make connections between pictorial and symbolic representations and to perform a variety of actions on these representations, thereby developing their understanding of mathematical concepts (Moyer-Packenham & Westenskow, 2013).

There is widespread availability and use of virtual manipulatives in mathematics classrooms and extensive research has been conducted into their effects on student learning (Holmes, 2013; Moyer-Packenham & Westenskow, 2013). However, it was not until 2013 that attempts were made to synthesise this research base. Meta-analyses were conducted by Holmes (2013) and Moyer-Packenham and Westenskow (2013) in an effort to produce findings that could influence teachers, policy makers, scholars, and researchers.

In their meta-analysis of 17 studies, Holmes (2013) found that students who used virtual manipulatives during mathematics lessons performed one-fifth of a standard deviation higher than those who used physical manipulatives. However, due to insufficient reporting from the primary studies and the small number of studies reviewed, Holmes concludes that further research is required to investigate the impact of virtual manipulatives in comparison to physical manipulatives. Moyer-Packenham and Westenskow (2013) conducted a larger-scale meta-analysis of 66 studies and produced positive results in relation to the effect of virtual manipulative on student achievement, identifying a moderate effect size (d = 0.35). Their comparison of the use of virtual manipulatives to

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[1] GeoGebra offers a combination of 2D and 3D dynamic geometry software.

physical manipulatives echoes the results of Holmes (2013), producing a small effect size (d = 0.15). Finally, a more recent meta-analysis by Kul et al. (2018) reports that available studies shared inconsistent findings in relation to the impact of manipulatives (both physical and virtual) and they conclude that there is a need for further systematic investigations to examine their effects on mathematics achievement. To conclude, while studying these effects, sizes alone suggests that virtual manipulatives may only have a small to moderate impact on mathematics learning, these virtual platforms offer the potential for supporting students to interact with complex phenomena in ways that would be difficult to achieve without technology (Donnelly-Hermosillo et al., 2020).

Programming and Computational Thinking

The limitations of a word count for this paper prevents a full discussion of the development of and the complex inter-relationships between Computational Thinking (CT) and programming which is often referred to as coding. For example, an analysis carried out by Tikva & Tambouris (2021) recorded more than 60 different CT elements proposed by frameworks and definitions in empirical studies. What is outlined here is a brief overview of how CT and programming / coding relate to the development of numeracy.

Computational thinking processes of abstraction, algorithmic processing, and systemic thinking can aid students' understanding of many academic domains such as mathematics, science and language (Grover & Pea, 2013). Indeed, students learning via integrated curricula across subjects (e.g. computer science, mathematics, science) are more likely to have knowledge and skills acquired in one subject (computer science) affect their learning outcomes in other subjects (mathematics), compared to students learning via fragmented curricula with segregated subjects (Ingram, 2014; Tanaka et al., 2016). As computational thinking is more likely to influence learning outcomes in integrated curricula, this link is likely strongest in primary school, especially when each student only has one teacher (Lei et al., 2020).

Focusing on the transferability of learning computer programming to cognitive skills, Scherer et al. (2019) adopted a three-level random-effects, meta-analytic approach (105 studies; Pre K- 12 and tertiary education), and identified a positive, overall transfer effect. Of the cognitive skills examined for far transfer, the transfer effects were large for creative thinking, mathematical skills, and reasoning. Reviewing the similarities and differences between programming as a part of computational thinking and mathematical thinking, Shute et al. (2017) concludes that skills such as problem solving and modelling are involved in both. More specifically, both programming and mathematical modelling require the abstraction of real-world problems, the formulation as computational models, the application of strategies and algorithms to solve them, and the interpretation of a solution. These shared sub skills may explain the strong and positive transfer effects on mathematical skills. Another explanation refers to the tasks used to assess mathematical thinking (Scherer et al., 2019) as in several studies, the understanding of geometric concepts and shapes was assessed following an intervention that used the Logo programming language with geometric objects. In this sense, the transfer of skills needed to program geometric objects to mathematical skills seems obvious (Clements & Sarama, 1997). Regardless, the transfer effects on mathematical skills (g = 0.57) were larger than those found in similar meta-analyses that focused on the transfer effects of chess instruction, technology-based instruction, music education, or working memory training (Scherer et al., 2019). The effect size was comparable to that of direct training studies. Thus, learning computer programming might be an effective approach to developing students' mathematical skills.

Popat & Starkey's (2019) review of 10 studies with students aged 5 – 17 years illustrates evidence of educational outcomes beyond coding that are influenced by learning to code. These include mathematical problem-solving, critical thinking, social skills, self-management and academic skills. However, a key finding is the importance of instructional design for developing these educational outcomes through coding. In other words, unless a teacher is aware of the possibilities and consciously designs for the development of particular mathematical knowledge, skills and dispositions while engaged in coding, the potential for development will not be maximised. For example, while mathematical skills, such as the use of geometry to solve problems, may be enhanced by learning coding, other programmes of learning can yield better or the same improvement (Hayes & Stewart, 2016; Kalelioğlu & Gülbahar, 2014). Therefore, if the academic aim is for students to learn mathematical problem solving, Popat & Starkey (2019) indicate that teaching these skills directly is often more effective than learning them through coding. However, as outlined in Scherer et al. (2019), this may also be a factor of the tasks used to assess mathematical thinking as well as the teacher's understanding of the relationship between CT, coding/programming and the development of mathematical thinking. In addition, consideration also needs to be taken of how best to design programming activities to promote computational thinking skills. Through the analysis of 86 quantitative empirical studies (K-12) with 114 effect sizes, Sun et al. (2021b) conclude that programming has a moderate positive influence on K-12 students' CT skills (Hedges' g = 0.601). They report that the use different programming instruments (e.g. Scratch, robotics) has a significant impact on K-12 students' CT skills. Fidai et al., (2020) find that the use of a combination of digital tools (e.g. Arduino and Scratch) similarly has an overall positive effect (d = 1.03, CI = [0.63, 1.42]) on students' CT skills (2020). However, the design of the learning activities is of critical importance and Kakavas & Ugolini (2019) point to the importance of designing coherent classroom tasks that have the potential to integrate computational perspectives in effective ways into mathematics curricula and that occur in interdisciplinary ways. For example, if graphic calculators are effectively integrated into STEAM education, they will help students build computational thinking skills as well as computer science skills beyond sorting and searching (Talib et al, 2019). How the learning is organised is also identified as a factor as the effect of collaborative programming activities on students' CT skills is higher than that of solo programming activities (Sun et al. 2021b).

Findings from Zhang & Nouri's (2019) systematic review of learning CT (55 studies, K-9) suggest that the learners' age and their cognitive development are positively correlated with their level of understanding of CT skills. The CT learning progression revealed in this systematic review (c.f. Zhang & Nouri, 2019, Table 8, p.19) can support curriculum planning and assessment of CT education. It can also be used to inform the CT skills that teachers on different educational levels need to develop.

Robotics

The systematic review of 45 studies conducted by Anwar et al. (2019) unanimously suggests that robotics promotes active learning pedagogy and helps to improve the learning experience. Their use also enables educators to design socially and culturally relevant learning activities which can enhance students' motivation and creativity. However, as suggested by Jung & Won (2018), careful attention needs to be paid to children's historical, cultural, social, and institutional contexts in understanding young children's engagement in robotics education. Through the use of robotics, students can be engaged in an active-learning process, where they will construct new knowledge based on hands-on experience and by engaging with certain tasks. In the process of using robotics, students learn and construct new knowledge through inquiry, exploration, and making the cognitive association with prior experience; this allows students to improve their conceptual understanding of the content and understand abstract concepts better (e.g., Krishnamoorthy & Kapila, 2016; McGrath et al., 2008; Shankar et al., 2013; Williams et al., 2011). While many of the studies, reviewed by Anwar et al. (2019), focused on the idea that there is a broad benefit to using educational robotics with K–12 students without referring specifically to discrete disciplines, there is evidence to indicate that students show increased interest in and motivation to learn mathematics through these team activities. Benitti & Spolaôr's review (2017) includes a summary of the mathematical topics covered in educational robotics completed by Karim et al. 2015. It includes:

- Geometric primitives
- Counting
- Multiplication
- Decimals
- Fractions and ratios
- Coordinate system
- Recognition of quantities

- Problems with operator
- Graph construction and interpretation
- Angles

The 20 studies analysed by Zhong & Xia (2020) also suggest that robotics can play an active role in mathematics education at elementary and secondary school level particularly in relation to:

- graphics and geometry: measurement, distances, angles, lengths, vectors, etc.
- number and algebra: counting, computation, proportion, function, etc.
- practice and synthesis application: mathematical problem solving, metacognitive skills,
- statistics and probability: data collection and analysis, likelihood, etc.

Encouraging results in Çetcin & Demircan’s (2020) review of 23 studies similarly indicate that through the use of robots, younger children (up to age 8 years) can acquire interdisciplinary skills and knowledge, and engage with mathematical concepts, such as sequencing, scientific inquiry and problem solving (Bers, 2010; Bers & Horn, 2010; Kazakoff & Bers, 2011; Rogers & Portsmore, 2004).

Using educational robots facilitates students’ ability to apply and transfer mathematical skills in programming (Sánchez-Ruíz & Jamba, 2008). Moreover, these activities expose students to real-world applications of mathematics outside the classroom (Williams et al., 2011; Zhong & Xia, 2020). Enabling real-world applications helps to remove the abstractness of mathematics (Benitti & Spolaoôr, 2017, p.104), and can be especially effective if an integrated STEM approach is used. For example, Benitti & Spolaôr (2017) highlight the possibility of exploring the engineering design process (illustrated by papers such as McKay et al., 2015). When defining the problem, planning solutions, making a model, testing the model, and reflecting and redesigning robots, students not only learn how technology works, but they also apply the skills and content knowledge learned in a meaningful way.

Finally, the analysis by Sullivan & Heffernan (2016) of 21 studies (Pre K – 12) supports a computational thinking learning progression in the robotics domain that begins with sequencing abilities, advances to reasoning abilities (causal inference and conditional reasoning), and results in improved systems understanding; all of which is aided by problem solving activity. Over time, students move beyond the trial-and-error method and begin to develop more sophisticated approaches to problem solving that support the development of student reasoning.

Mobile Devices

Across a review of the systematic reviews, mobile learning (mlearning) is conceptualised as the use of mobile devices/technologies and digital applications for learning, and which can be underpinned by four central constructs: pedagogy, technological devices, context, and social interactions (Crompton, 2013). Using these constructs, mobile learning may be defined as the “learning across multiple contexts, through social and content interactions, using personal electronic devices” (Crompton, 2013, p. 4). Some of the systematic reviews investigate the use of mobile learning in mathematics education (Verbruggen et al, 2021; Xie, 2021; Svela et al., 2019; Lakhan & Laxman, 2018; Crompton & Burke, 2017), however, there were more studies which investigated the integration of mobile devices in mathematics along with another subject discipline such as science and/or language studies (Boon et al, 2021; Bano et al. 2018; Crompton, Burke & Lin, 2019; Herodotou, 2018; Zhang & Nouri,. 2018; Tingir et al, 2017; Zheng et al., 2016). From these studies, it can be inferred that the accessibility and the mobility of devices, along with the multimodal design features of the devices and apps tend to promote student engagement in mathematics, as well as influence the pedagogies associated with mathematics teaching and learning. The multimodal affordances of mobile device features such as immediate feedback and adaptivity give rise to the capacity of devices to adapt to the differing abilities and needs of individual students (Boon et al., 2021; Benavides-Varela et al., 2020; Verbruggen et al., 2020; Svela et al., 2019; Zhang, & Nouri, 2018). The flexibility of the mobile devices and their applications enables autonomous and individualized learning, meaning students can learn in accordance to their own pace and needs, contributing to their motivation and engagement. Software or apps which provide well-designed learning based on repeated drill-and practice, transmissive instruction are found to be more frequently employed in kindergarten (Svela et al., 2019; Verschaffel et al., 2019). This is in comparison to collaborative learning and project/problem-based learning which are frequently identified as teaching practices that advance mobile learning in primary and secondary mathematics education (Svela et al., 2019; Verschaffel et al., 2019; Bano et al., 2018; Zhang & Nouri, 2018).

In their systematic review of 49 studies, Bano et al. (2018) corroborate that secondary students not only work together in groups, share goals, understandings and discussions to achieve agreed objectives but also demonstrate critical thinking through questioning, investigating and problem solving when using mobile devices in science and mathematics education. While the majority of the studies in mathematics did not specify the subdomains of investigation, in those that did, geometry and algebra were the subdomains most frequently investigated. Similarly, Svela et al. (2019) found arithmetic, computation, and geometry to be the subdomains most predominantly deployed. In particular, the teaching of geometry is seen to be supported by mobile devices, which facilitate interaction with the environment; for example, utilising camera and navigation/compass features to apply to real-world learning contexts. Bano et al. (2018) draws comparison to the pedagogical approach of the Realistic Mathematics movement (Freudenthal, 2006) and the situated, authentic and context-aware ubiquitous learning that mobile learning affords in terms of "locating students in virtual contexts that are easily imagined and understood as real" (p.52). The pedagogical use of mobile devices is further highlighted in Boon et al.'s (2021) systematic review which suggests that the use of the iPad does not consistently enhance mathematical learning outcomes. Out of 43 studies included in the review, the nine studies which included mathematics education for 9-14 year olds reveal mixed results. These studies generally reported that iPad intervention supported mathematics learning, with an increase in the number of students' obtaining correct answers, improved student motivation and improved students' mathematical self-perceptions. However, other studies found there was either no significant difference or that inconsistent results were found in mathematical learning outcomes for those students using iPads. Boon et al. (2021) also refers to Perry and Steck's (2015) study which found that the 110 secondary level students involved in the iPad intervention in a geometry course scored lower than the control group and had higher levels of off-task behaviours. Differences in teachers' instructional style was proposed as one of the limitations of this intervention.

Crompton & Burke's (2017) review of 36 studies investigating the use of mobile learning in mathematics educational levels from pre-K-higher education does not include studies using laptops, netbooks or calculators. 71% of the studies reported improved student mathematical learning, 10% reported neutral learning outcomes, where there was neither a positive nor negative impact on the student's' learning. No study reported negative learning outcomes when using a mobile device and 18% reported outcomes that were not related to effects on student learning. Crompton & Burke (2017) also highlight that the mathematical concepts of data analysis, probability, and measurement were not referenced when using mobile devices such as mobile phones, iPads and iPods in mathematics teaching and learning. They also found that no studies reported the use of mobile learning in mathematics in Pre-K settings but conclude that when the focus is on mathematics, the research indicates that mobile learning is most frequently present in elementary mathematics settings (34%) followed by middle school (29%) and high school (21%) with the mobile phone the most frequently used mobile device. In Bano et al.'s review (2018), 36% of the studies included identified algebra, numbers and operations as the subdomains most frequently referred to with numbers and operations dominating the mathematical concepts being taught from Grade1-4. Finally, while Crompton & Burke's (2017) systematic review did not include the use of laptops as a mobile device, Zheng et al.'s (2016) meta-analysis investigates the impact of laptop programs on K-12 students' academic achievement, finding a positive average effect size in mathematics ($d = 0.17$, $p < 0.05$). This said, further explanation is warranted in regard to the specific use of the laptops in mathematics education.

Verbruggen et al, (2020) and Herodotou's (2018) reviews go some way in addressing the impact of mobile devices on the young children's mathematical learning and development. Herodotou's (2018) review of eight studies examined effects of touch screen devices on STEM development, in particular, mathematics and science. Positive learning outcomes were recorded for older children finding that learning is transferred from one context to another with similar structure and with or without different task characteristics on mathematical concepts of time, non-standard units of measurement and counting. Based on an analysis of Schacter and Jo's (2016) study which found improvements in the early number skills of a treatment group after interacting with a mathematics application on a mobile device, Herodotou (2018) highlights the potential of mobile devices in improving mathematical attainment of young children from a low socio-economic status.

Finally, (Boon et al., 2021) conclude that the efficacy of mobile learning is very much dependent on a range of factors such as teachers' digital literacy, the level of digital competency and skills of the students, the pedagogical approaches used in the educational setting, in conjunction with the mobile devices and other technologies used

Digital manipulatives hosted on mobile devices are found to be as beneficial to young children as traditional manipulatives in facilitating more complex reasoning about mathematical concepts. as the affordances of the design features support the open-ended nature of tasks, variety of representations, and degrees of challenge (Herodotou, 2018). Of the 54 studies in Verbruggen et al. (2020) systematic review, the vast majority of the studies (n = 48) investigating the effectiveness of digital tools and game-based applications in terms of enhancing mathematical cognitive learning outcomes in pre-K children, focused on the subdomain of number and operations, with 10 studies addressing geometry, 7 examining patterns, 5 focusing on measurement and 2 related to data analysis. Contrary to the findings that the mobile learning features of interactivity, meta-cognitive guidance, and the instructional principles that are found to contribute to the effectiveness of mobile devices for enhancing mathematics learning in older children, Verbruggen et al. (2020) noted that none of these features were found to be associated with the effectiveness of digital technology in early mathematics education. Interesting also that while many of the systematic studies credits the positive effects of using mobile technologies on facilitating student cooperation and collaborative learning, Verbruggen et al. (2020) found that the use of such devices were more effective for learning when the children were provided with support by the teacher during their use and when used individually rather than cooperatively. The authors deduce that a plausible explanation for this finding may relate to young children's varying metacognition coordination and communication abilities when collaborating with a peer. Students learning mathematics with mobile devices may find the process challenging due to the additional knowledge and skills that students need to use technology effectively in their learning or the inequalities in provision and access to mobile devices (Verbruggen et al., 2020; Svela et al., 2019; Herodotou, 2018; Lakhan & Laxman, 2018; Tingir et al., 2017).

Crompton et al. (2019) report on 8 studies which focus on the use of mobile learning in PK-12 mathematics settings as it relates to levels of student cognition. The highest number of pedagogical opportunities reported were given to students PK-12 mathematics settings involved learning how to apply the mathematical skills and concepts. However, as digital technologies do provide opportunities for students to learn in new ways, it is essential that educators understand and utilise digital technologies as a means of promoting higher cognitive processes in mathematics. Verschaffel et al., (2019) proposes embedding metacognitive pedagogy in digital learning environments or the reverse; the use of digital technology to promote metacognitively orientated mathematics learning environments, to develop students' higher-order cognitive and metacognitive competencies by means of more advanced learning technologies such as those referred to in this report like intelligent tutoring systems, programming, game-based learning, collaborative learning environments, and virtual reality. The metacognitive strategies taught to the kindergarten children were basic forms of planning, monitoring, and reflection, which were provided by means of instructional techniques such as providing cues and questions, demonstrations, and explanations; while the learning environment in elementary settings essentially involved individual tutoring in and practicing of the targeted content and skills, and computer-supported collaborative learning with an emphasis on mathematical word problem-solving, arithmetic computation, geometry and algebra.

Digital Games

Mobile device applications, or third party apps, are often referred to as digital games, whereby Hainey et al. (2016) distinguishes the genres of digital games in accordance to the game features whether the games are establishing on role play, strategy, adventure, simulations; or the platform used or method of delivery such as personal computer, video game console, mobile, online; and the subject discipline or curricular areas that the game addressed. As indicated in the previous section of this report, the affordances of mobile devices promotes the use of digital games and particularly, game-based learning, as a pedagogical approach in mathematics education (Svela et al., 2019; Zhang & Nouri, 2018; Bano et al., 2018; Hainey et al., 2016). This is where students engage with mathematical content by playing digital games and have access to immediate, built-in feedback in the form of results, points, rewards, progress or positive reinforcement through virtual tutoring. Digital games are found to enhance student interest and motivation due to the fun and novelty element (Chen et al., 2020; Svela et al., 2019; Byun & Joung, 2018) but the effects of game-based learning on student mathematical achievement is limited (Tingir et al., 2017). To this end, Byun and Joung (2018) calculated an overall small effect size ($d = 0.37$) of the use of digital games within the context of K-12 mathematical cognitive learning for 17 out of 33 studies. Number and operations, followed by algebra, geometry, and measurement were the subdomains most addressed in these digital game-based learning studies, whereas data analysis and probability were less frequently the focus. Byun and Joung (2018) noted that most of the games in the studies tended to examine students' procedural fluency only, neglecting the other strands of mathematical proficiency in mathematics learning i.e. conceptual understanding, strategic competence, adaptive reasoning and productive disposition (Kilpatrick et al., 2001). This may be due to the drill and practice nature of the games that were most predominantly used in the studies, thus limiting the opportunity for higher level thinking skills required for solving complex problems.

Chen et al. (2020) meta-analysis of 25 studies on digital game-based learning (including the genres of role-play games, puzzle, simulation, strategy and action) reported a moderate effect on mathematics learning outcomes ($g = 0.634$, $p <0 .10$). Additionally, the authors found that the effects of competition as an essential element of game-based learning was significantly stronger in mathematics than in other disciplines ($p < 0.10$) which may be potentially due to the problem based and structured nature of the mathematical games. While both individual and peer games had a significant effect ($g = 0.453$, $p < 0.10$; $g = 0.324$, $p < 0.10$), no significant effects were found between the two learning settings or between elementary and secondary school students ($p >0 .10$).

Tokac et al. (2019) report that the empirical research on comparing video games learning with traditional instructional methods remains limited. Their meta-analysis found that video games contribute to slightly higher mathematical learning gains compared to transmissive instructional methods with a small but marginally significant overall effect size ($d. = 0.13$; $p = 0.02$). With regard to grade level, results suggest that mathematics video games were similarly beneficial for students from various grade levels, a finding that also resonates with Benavides-Varela et al. (2020) review. Tokac et al. (2019)'s analysis reveals that a high percentage of the empirical research was conducted in 1st-12th grade, as the empirical research in pre-K settings was limited and therefore, the findings should be interpreted with caution when generalising to students of all levels. The length of game-based interventions did not have significant consequences on mathematical learning outcomes where some of the length of game-based intervention consisted of a single game session of 33 minutes as the shortest and multiple game sessions with a total of 10,080 minutes as the longest. Therefore, the duration of the intervention only had a small impact on students' academic achievement in both primary and secondary schools (average effect size = 0.12–0.19). As most of the identified mathematics video game studies only provided partial information about the video games and game-based instructional interventions, the ability to systematically examine the effects of various factors that could affect the relationship among video games and mathematical achievement, including student individual differences, game design characteristics, and attributes of video game-based interventions.

Computer as Tutor

In this section, we aim to present findings pertaining to the use of technology as *tutor* in the mathematics classroom. We identified nine systematic reviews which examined the use of various computer-assisted teaching and learning systems. This is a complex area and a variety of systems and programs exist that can be categorised under this topic of *computer as tutor*. However, a range of terms are used to describe the wide array of systems that are available and these are used interchangeably and inconsistently across existing research. In a number of the papers that we examined, terms such as intelligent tutoring systems, computer assisted instruction, computer managed learning, computer-based scaffolding, and technology-mediated mathematics were utilised but in most cases, these terms were not defined.

Cheung and Slavin (2013) conducted a systematic review of 74 studies pertaining to technology-based programs that support mathematics instruction. They categorised these applications into supplemental computer assisted instruction, computer-managed learning systems and comprehensive models. They reported that supplemental computer assisted instruction, which they defined as programs that supplement traditional classroom instruction by providing additional instruction at students' assessed levels of need, had the largest effect on mathematics achievement (ES = 0.18). Comprehensive models which were defined as an approach to learning that uses computer-assisted instruction in tandem with non-computer activities, were found to have a minimal effect on student mathematics achievement (ES = 0.06). The final category relates to computer-managed learning systems and the findings of this systematic review also indicated that these systems have a minimal effect on mathematics achievement (ES = 0.09). The term computer-managed learning systems was not defined in the paper, but *Accelerated Math* was identified as an example. In their systematic review of 101 studies, Deunk et al. (2018) also referred to this specific program, analysing work by Ysseldyke and colleagues pertaining to its potential to support differentiated mathematics instruction. In one particular study by Ysseldyke et al. (2003), implementing Accelerated Math in maths lessons in Grade 3, 4, and 5, was found to have a small to medium positive effect on student achievement.

Intelligent tutoring systems are computer-assisted learning environments which provide self-paced, adaptive, and interactive instructional guidance suited to the learner's individual needs (Shute & Zapata-Rivera, 2007; Steenbergen-Hu & Cooper, 2013; Tsuei, 2012). Intelligent tutoring systems track students' responses to document their knowledge in relation to a particular topic, their learning strategies and pace, their emotions, and their motivation at a level of detail which Graesser et al. (2011) posit is beyond the capabilities of human tutors. Intelligent tutoring systems are also considered superior to computer assisted instruction due to the level of interaction they facilitate between the systems and the learners (Graesser et al., 2011). Steenbergen-Hu and Cooper (2013) conducted a meta-analysis of 26 studies to explore the impact of ITS on K-12 students' mathematical learning. Their examination of the effect sizes reported in these studies illustrates that intelligent tutoring systems had "no negative and perhaps a very small positive effect on K–12 students' mathematical learning relative to regular classroom instruction" (p. 982). They also compared the impact of the use of intelligent tutoring systems to the assignment of homework or access to human tutoring, finding that the effect sizes were small to modest, ranging from 0.20 to 0.60. However, this finding is limited by the small number of studies included in their meta-analysis which focused on this comparison. A systematic review by Ran et al. (2021) also concluded that computer-based tutoring had a positive effect on the mathematics achievement ($d = 0.80$) but their focus was on low-performing students. The systematic review of 92 studies conducted by Hillmayr et al. (2020) indicated that the impact of intelligent tutoring systems was greater when they were used alongside other instruction methods rather than as a substitute.

Belland et al. (2017) focused on computer-based scaffolding in their meta-analysis of 56 studies. In their review, the authors stated that computer-based scaffolding is intended to assist students in addressing problems, identify strategies for solving problems, provide opportunities for students to question their understanding and improve confidence, interest, motivation and autonomy. They reviewed studies across STEM (Science, Technology, Engineering and Mathematics) disciplines and they reported that computer-based scaffolding had a strong effect across all STEM discipline, with the highest effect size in mathematics ($\bar{g} = 1.29$).

Kiru et al. (2018) reviewed 19 studies relating to Technology-Mediated Mathematics (TMM) Interventions. However, in their systematic review, they did not define TMM or describe the types of interventions that they have classified under this term. The review focused on the impact of TMM on students with or at risk for mathematics learning difficulties. Their investigation suggested that TMM interventions have mostly positive effects on the mathematics outcomes of these students. This beneficial impact was demonstrated across a range of mathematical concepts and skills.

Socially-Assistive Robots (SARs) have emerged as a computer-assisted teaching and learning system due to rapid advances in artificial intelligence over the past decade. SARs are robots that take the form of humans, pets or toys and may be utilised to interact with students through the use of speech, emotional expression, gestures, and other actions (Papadopoulos et al., 2020). A dearth of research exists into the use of SARs in education and a systematic review by Papadopoulos et al. (2020) revealed that of this limited research base, the use of SARs in mathematics is particularly under-represented. They attributed this to the assumption that SARs may be viewed as more appropriate in language learning due to their interactional skills while non-socially interactive robots may be more suited to the learning of mathematics. However, they conclude that further research is required to explore the potential impact of SARs on mathematics-learning rather than being influenced by these assumptions.

Assessment and Learning in Knowledge Spaces (ALEKS) is the final type of computer-assisted teaching and learning system that was identified during our systematic review. ALEKS was the focus of a meta-analysis of 33 research studies by Sun et al. (2021a). In their analysis, ALEKS was described as an artificially intelligent learning and assessment system that “employs adaptive questioning to establish a student’s knowledge state and provide a summary of what knowledge the student possesses and what knowledge the student has yet to learn” (p. 2). The results of the study indicated that ALEKS can significantly enhance mathematics learning when used to supplement traditional instruction but that such benefits do not arise when ALEKS is used as a replacement for traditional instruction.

Overall, the systematic reviews that we identified in this study, indicate that the use of technology-assisted systems for instruction such as computer assisted instruction, computer-managed learning systems and comprehensive models, intelligent tutoring systems, computer-based scaffolding and technology-mediated mathematics interventions, can have a positive impact on students’ achievement in mathematics. However, further research is required to identify the instructional design features that are required to optimise their effects on mathematics learning. While these systems may offer benefits to mathematics teaching and learning, they must be used alongside other forms of instruction and cannot be used in isolation.

Teacher Knowledge and Pedagogical Orientation

Although there is great diversity in the empirical research into the use of technology in mathematics education outlined in this report, the authors would agree with Bray and Tangney’s (2017) conclusion that for the most part, the outcomes described do not live up to their perceived potential to transform the learning experience (Geiger et al., 2010; Hoyles, 2016; Reed et al., 2010; Selwyn, 2011). Digital technologies can support computations and representations (e.g., geometric figures, graphs of functions, or animations), provide interactive tools and makes key relations for mathematical understanding more transparent and tangible technologies, as well as open up new possibilities for dynamically expressing a problem’s contents and extending its analysis (Sokolowski et al., 2015) and enable complex computations and dynamic modelling that lead to more experimental forms of teaching and learning mathematics (Joyce et al. 2009; Li & Li 2009; Passey 2012). Unfortunately, the usage of technology is often confined to “augmentation” of existing classroom practice (Puentedura, 2006). For example, as illustrated by Bray and Tangney (2017), the majority of interventions (61%) were classified as augmentation whereby the technology was used as a direct substitute for traditional approaches. Another worrying concern is just one systematic review focused on the development of statistical literacy skills (Aziz & Rosli, 2021). Defined as the ability to critically understand, interpret, evaluate, and communicate statistical data through various forms of media, the development of statistical literacy in school is crucial for preparing students to become part of a 21st-century society that is continuously bombarded with a myriad of information that involves statistical data-based arguments (Weiland, 2017). .

However, moving beyond "augmentation" and focusing on the development of particular aspects of numeracy to meet the requirements of living in a digital age (e.g. statistical literacy), requires more than just focussing on using particularly digital tools. Instead, it is strongly linked to a teacher's understanding of what mathematical competence is and how this influences why, how and what digital tools are utilised and by who (teacher and/or student). Perhaps as Bray and Tangney (2017) indicate, teachers view mathematics as a collection of unrelated facts, rules, and 'tricks' that are "hard, right or wrong, routinised and boring" (Noss & Hoyles, 1996, p. 223), and that mathematics education is about memorisation and execution of procedures that should lead to unique and unquestioned right answers (Ernest,1997; Hoyles, 2016; Maaß & Artigue, 2013; Schoenfeld, 1992, 2004). This by definition can result in a use of digital tools that is restrictive, and confined to consolidating practice.

In contrast, if a teacher embeds mathematics within a meaningful context, digital technology has the potential to open up new routes for students to construct and comprehend mathematical knowledge, returning the agency to create meaning to the learner, as well as using a range of approaches to problem-solving. It can help increase collaboration and bring about more of an emphasis on practical applications of mathematics, through modelling, visualisation, manipulation and the introduction of more complex scenarios and can enable learners to perform tasks that would not previously have been possible (Bray & Tangney, 2017; Geiger et al., 2010; Noss & Hoyles,1996; Olive et al., 2010).

In addition, rather than considering mathematics as a standalone subject, designing STEM focused programmes can contribute to student mathematical achievement. Siregar et al. (2019) meta-analysis points to an overall weighted average effect size of 0.242 with a corresponding p-value of 0.023 demonstrating that STEM impacts on student mathematics achievement. When examining individual studies, the analysis shows the majority, 10 of 17 studies yielded statistically significant positive effect sizes between 0.118 and 1.571. These findings illustrate that the STEM program approach utilised in these ten studies might have improved students' achievement in mathematics in some way.

However, an essential question to examine is what is considered as mathematical achievement/ attainment and how achievement is measured. Many of the reviews considered in this paper used traditional measures of achievement (often these were not specified in detail). For example, Akar's (2020) meta-analysis of 47 experimental studies examining the effect of smart board use on academic achievement, found that the effect size of smart board use on academic achievement was positive, large, and significant (ES(d) = 0.94, $p < 0.05$). The calculated effect size does not differ according to the type of publication, school level, and field of science (course), publication year, sample size and duration of experiment implementation. However, what is not clear is what was used as the measure for mathematical achievement. Similarly, is what is measured only what is easy to measure? It stands to reason that if the purpose of a task is to increase student attainment in an existing form of assessment, then the purpose of the technology is to achieve an improved, and not necessarily different, version of what went before (Bray & Tangney, 2017). This brings into focus the argument that in order to radically change the dominant pattern of augmentative technology usage in classrooms, there needs to be a swing away from the prevalent high-stakes assessment practises in education systems (Dede, 2010; Fullan & Langworthy, 2014; Schoenfeld, 1992) towards forms of assessment that capture the kinds of mathematical problem-solving, creativity and decision-making skills that can be facilitated by the interactive, communicative and accessible nature of technology (Conole, 2008; Dede, 2010; Fullan & Langworthy, 2014; Star et al., 2014). They also highlight the issue of using digital technologies for formative assessment. See et al. (2021) suggest promising evidence that digital formative assessment could facilitate the learning of mathematics for young children. However care has to be taken in interpreting the results because the implementation of these digital feedback tools varied considerably. Some involved generic feedback, some provided contextualised and elaborated feedback, delivered in real-time and delayed; which has implications for the results.

A culturally responsive pedagogy which leverages digital technologies could promote increased interaction between students and teachers and with other students and this means attending to individual student's learning needs in better ways (Lakhan & Laxman, 2018). For example, the pedagogical approach of the flipped classroom enables the teacher to "bring technology more into the classroom, help develop students' digital competencies, increase higher order thinking skills and active learning time, promote problem solving, teamwork and collaboration skills and has the potential to enhance both parent and student engagement" (Bond, 2020, p. 1) Both Bond (2020) and Lo & Hew (2021) systematic reviews discuss flipped learning in benefitting aspects of the behavioural, affective and cognitive dimensions of student engagement in K-12 mathematics education. In addition, Sokolowski et al. (2015) (20 studies, Grades 1-8) found a moderate positive effect size (ES = 0.59) associated with exploratory computerised environments. However, the availability of technology in a classroom environment will not on its own, ensure the development of a collaborative and explorative classroom (Geiger et al., 2010; Olive et al., 2010). Technology and curriculum innovations can support or supplement changes in teaching practises, but they do not have important effects on learning in themselves (Slavin, 2013). As Bray and Tangney (2017) outline, the role of the teacher, appropriate task design and consideration of the learning environment, are fundamental for the facilitation of a discursive, inquiry-focused atmosphere in the mathematics classroom (Geiger et al., 2010; Laborde et al., 2006; Olive et al., 2010; Swan, 2007). Ensuring all teachers can design such learning environments will require structured support for teachers (including professional learning workshops, coaching and follow up help) based on sustained and reliable research (Bray & Tangney, 2017; Donnelly et al., 2011; Drijvers et al., 2010; Fullan & Langworthy, 2014; Lameras & Moumoutzis, 2015; Noss et al., 2009) to help teachers make effective and lasting changes in their daily classroom practice.

For lasting significant change to occur requires teachers to have a deep understanding of what is meant by the development of mathematical numeracy as well as an understanding of what pedagogical approaches to use, including leveraging the use of digital tools, when designing learning experiences and assessment of and for learning. Central to any change in pedagogical approaches is the teachers’ values, beliefs and attitudes.

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**denotes literature included in the tabulation (Appendix B)*

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Appendix A: Search Strategy

Research Question

In what ways can the use of digital tools support numeracy development in early childhood, primary and post-primary education?

Key Search Terms in Relation to Research Question

In searching for relevant systematic reviews, meta-analyses and other literature to answer the research question, three databases (EBSCO Education Research Complete, EBSCO ERIC, Scopus) were searched using the key terms and strategy detailed below. 'Grey' literature was identified through hand searches via Google Scholar.

S1. DE: STEM education or STEAM education or integrated STEM or emergent math* or early numeracy or early math* or numeracy or math* or math* education or math* literacy or computational thinking

S2. "STEM education" or "STEAM education" or "integrated STEM" or "emergent math*" or "early numeracy" or "early math*" or numeracy or math* or "math* education" or "math* literacy" or "computational thinking"

S3. S1 OR S2

S4. S3 AND: "digital tools" or "digital technolog*" or technology or "educational technology" or "mobile learning" or "digital competenc*" or "digital learning" or "digital fluency" or "information technology" or ICT or "computer literac*" or information or "data literac*" or "data visualisation*" or "digital literac*" or "artificial intelligence" or "algorithmic thinking" or algorithm* or "digital media" or computer* or "mind tools" or coding or robotics or robots

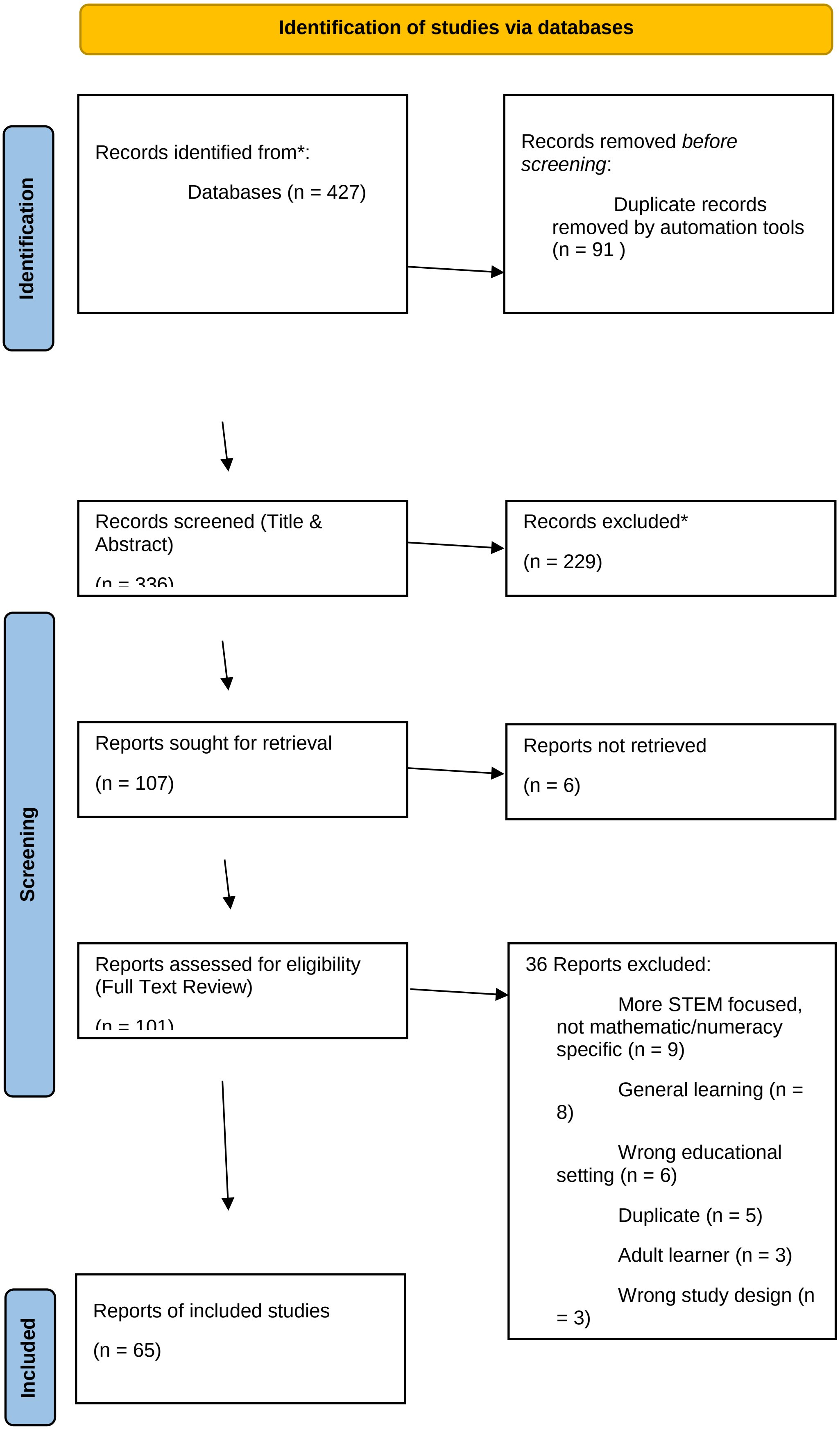
S5. S4 AND: "systematic review" or "meta-analysis" or "systematic literature review" or "systematic research review" or "meta-review" or "international review" or "research synthesis" or "best evidence" or "review of the literature" [ABSTRACT]

S6. S5 AND: "school student" or teacher or practitioner or educator or post-primary or "middle school" or "high school" or secondary or K-12 or "primary school" or "elementary school" or "primary education" or "elementary education" or "national school" or K-6 or elementary or "primary Grade 6" or "early childhood education" or preschool or kindergarten or child* or "early years" or pre-k or "key stage 1" or "key stage 2" or "foundation stage"

Exclusion Criteria

Date limit 2011 onwards, limited to 'peer review' and limited to English language where necessary. As indicated in the PRISMA diagram (Figure 1) an initial search yielded 336 articles when duplicates were removed. The exclusion criteria that were applied to the screening of the Title and Abstract of articles were the following: pre-2011

not systematic review or meta-analysis, not applicable if solely focusing on higher education, pre-service teachers, initial teacher education, undergraduate or not relevant if reference to nurse, patient, medical, medicine, health, post-secondary, non tertiary, military, surgery, logistics, financial market, oil, tourism, construction, job performance, employee attitude, genetics, genome, quantum, manufacturing, disease, antibiotics. 101 full text articles were found to be accessible and reviewed to satisfy the inclusion criteria being a systematic review or meta-analysis and referred to the use of digital tools support numeracy development in early childhood, primary and post-primary educational settings.



*Records excluded following blind review by two reviewers using Covidence.

Figure 1. PRISMA diagram summarising the review process

Appendix B: Tabulation of Findings

Author	**Review**	**No. of Studies**	**Age Range**	**Effect Size**	**Relevant Themes/ Ideas**	**Digital Tools**	**Key Findings**
Akar (2020)	The Effect of Smart Board Use on Academic Achievement: A Meta-Analytical and Thematic Study	47	Primary to University (majority of papers had post-primary focus)	0.94 effect size of smart board use on academic achievement was positive, large, and significant (ES(d) = .94, p < .05). The calculated effect size does not differ according to the type of publication, school level, and field of science (course), publication year, sample size and duration of experiment implementation.	Impact on achievement	Smart Boards	● Most of the studies were conducted within the scope of science and mathematics courses. ● Positive and negative aspects of smart board use identified ● Recommendations for smart board use shared.

Aliyu, Osam, Daud, & Kumar (2021)	Mathematics Teachers’ Pedagogy through Technology: A Systematic Literature Review	28	Primary to university / Primary 4 Post Primary 17 University 7		Mathematics teachers' pedagogy (MTP); TPACK framework	GeoGebra	● The findings reveal the intervention impact of MTP with GG and other technologies such as matrix laboratory (MATLAB); an interactive whiteboard (IWB) and computer algebra system (CAS); wxMaxima, which is a CAS; information and communication technologies (ICT); concrete materials as well as other resources in developing students’ performances in mathematics which were generally effective too. ● The implication of MTP to educational practice and research is dynamic and significant to the learners’ logical thinking ability and may foster a good understanding of content knowledge. ● MTP is a catalyst that sustains best practice through critical thinking, technology, communication, and confidence.
Anwar, Bascou, Meneske, & Kardgar (2019)	A Systematic Review of Studies on Educational Robotics	147	K-12		Benefits of robotics - more general than related to mathematics but maths is mentioned in a few of the studies reviewed.	Robots	● 45 of the studies reviewed focused on the idea that there is a broad benefit to using educational robotics with K–12 students, but they typically did not highlight a particular focus. ● These studies unanimously suggested that robotics promotes active learning pedagogy and helps to improve the learning experience.

Aziz & Rosli (2021)	A systematic literature review on developing students' statistical literacy skills	36	Primary to university/ adult learners; 20 = university /adult students; 11 =secondary school students, and 5 = primary schools.		Statistical literacy	Robot Bioglyphs, computer and internet, Mturk application	● Four dominant factors influence the development of statistical literacy among students: the learning environment, students' attitude, teaching method, and students' basic knowledge. ● Materials-based teaching was the most commonly used to develop statistical literacy among students ● Student-centered learning environment provides students with an opportunity to develop their understanding of statistical concepts and practice critical thinking in solving problems related to real-life situations.
Bano, Zowghi, Kearney, Schuck & Aubusson (2018)	Mobile learning for science and mathematics school education: A systematic review of empirical evidence.	49	Secondary school		Impact on achievement	Mobile devices and apps	● The majority of studies investigated processes associated with teaching and learning, for example, collaboration, constructivist learning or investigated the design and features of apps used to enhance learning. ● There was a gap in the literature concerning discipline knowledge. When using mobile devices, students were found to be working together in groups, sharing goals, understandings and discussions to achieve agreed objectives. ● Given that previous research has identified the proliferation of drill and practice and transmissive apps in the app stores (Goodwin

							& Highfield, 2013; Murray & Olcese, 2011), the findings in this SLR possibly point to a change in approaches of software designers.
Belland, Walker. & Kim (2017)	A Bayesian Network Meta-Analysis to Synthesise the Influence of Contexts of Scaffolding Use on Cognitive Outcomes in STEM Education.	56	Early elementary to adults	3.13	Computer-based scaffolding		● Computer-based scaffolding is highly effective at improving cognitive learning ● Mathematics and technology had the highest pre–post effect sizes: $\bar{g} = 1.29$ and $\bar{g} = 1.06$, respectively ● Not surprising, since much work on intelligent tutoring systems is done in mathematics (Steenbergen-Hu & Cooper, 2013; VanLehn, 2011) and it has long benefitted from more synthesis of research results and systematic refinement (Murray, 1999; Steenbergen-Hu & Cooper, 2013, 2014; VanLehn, 2011) than other scaffolding types.

Benavides-Varela, Zandonella Callagher, Fagiolini, Leo, Altoe, & Lucangelli (2020)	Effectiveness of digital-based interventions for children with mathematical learning difficulties: A meta-analysis.	15	5.6 - 16.3 years	0.55 A random effects meta-analysis indicated that digital-based interventions generally improved mathematical performance (mean ES = 0.55]	Digital-based interventions; Mathematical learning difficulties; Impact on academic achievement	Variety of tools including video games and digital-based tutorials	● Evidence of a moderate but significantly positive effect of digital-based interventions on mathematics achievement (mean ES = 0.55). ● The random effects meta-analysis showed a medium mean effect size, dppc2 =0.55, 95%CI (0.19 0.90), p =0.002, meaning that children in the treatment groups showed a greater improvement in mathematical ability than children in the control groups ● The findings of the present study suggest that school level has no significant moderating effects. Thus, digital-based interventions provide promising results for both young and older children.
Benitti & Spolaor (2017)	How have robots supported STEM teaching?	60	Across school levels		Impact on achievement	Robots	● Educational robotics is still frequently associated with teamwork and problem-solving development, extracurricular activities, and LEGO robots. ● Although technology and engineering are more frequently associated with robots, science and mathematics also benefit from these powerful machines. ● These findings indicate the flexibility of robots as a supporting tool for learning.

Bond (2020)	Facilitating student engagement through the flipped learning approach in K-12: A systematic review.	107	Year 4 - Year 12		Flipped classroom	Google classroom, Edmodo	● The flipped learning approach positively affected at least one dimension of student engagement (behavioural, affective or cognitive engagement) in 93% of studies. ● Positive collaboration, as well as peer teaching and learning, were particularly encouraged through the approach, as were increased enjoyment, participation, and improved student-teacher relationships. ● However, 50% of studies did show at least one facet of disengagement. ● Although student grades may not have improved, student attitudes, motivation, interest, self-efficacy and overall engagement were nonetheless positively affected as a result of the flipped learning approach.
Boon, Boon & Bartle (2021)	Does iPad use support learning in students aged 9–14 years? A systematic review.	43	9-14 years			iPads	● A majority of teachers and students are positively disposed towards the use of iPads in educational settings. ● In relation to mathematics, the results were mixed. Participants generally reported that iPad intervention supported mathematics learning - some researchers found that iPads could motivate student learning, increase the number of students’ correct answers, and improve students’ mathematical self-perceptions (Hilton 2018). ● However, other studies showed either no significant difference in learning outcomes in mathematics for those students using iPads

							compared to those using other non-technology-based methods. ● Some studies found that iPads are a useful tool in the classroom, promoting collaborative learning, communication, and access to information. On the other hand, the potential for iPads to be a distraction in the classroom has also been frequently reported.
Bray & Tangney (2017)	Technology usage in mathematics education research – A systematic review of recent trends	139	Post-primary and upper primary		Good practice in technology-enhanced mathematics education.		● Although there is great diversity in the empirical research into the use of technology in mathematics education, the outcomes of its utilisation do not in the main, live up to their perceived potential to transform the learning experience ● Digital technology has the potential to open up new routes for students to construct and comprehend mathematical knowledge and new approaches to problem-solving. This does however require a change in the pedagogical approach in the classroom. which in turn requires support for teachers, and a structured approach based on sustained and reliable research.

Browning, Edson, Kimani, & Aslan-Tutak (2011)	Geometry and Measurement Content Knowledge of Preservice K-8 Mathematics Teachers: A Synthesis of Research	13	3-12 years		Pre-service teachers MCK	Dynamic geometry software	● Studies that explored alternative methods of instruction with the use of technology, such as dynamic geometry systems and virtual manipulatives, provided encouraging results related to improving deductive thinking and 2D visualization skills
Byun & Joung (2018)	Digital game-based learning for K–12 mathematics education: A meta-analysis.	33 (only 17 used to calculate effect size)	K-12	0.37	Game-based learning	Digital games	● It is hard to say that DGBL has had a large effect on learning mathematics since the calculated overall effect size value (0.37) is quite small. This result implies that there may be other ways for students to learn mathematics more effectively than DGBL, although the DGBL studies have shown statistically positive effects on students' learning mathematics. ● More empirical studies are needed to discover more accurately how much digital games affect learning mathematics. ● Two-thirds of the DGBL studies were conducted with elementary school-aged students.

							- Research into the effects of DGBL focused mainly on students' learning number and operations, algebra, geometry, measurement, and data analysis and probability. - Although interest in using digital games for mathematics learning has consistently increased, there have been relatively few attempts to examine their effectiveness empirically.
Cetin & Demircan (2020)	Empowering technology and engineering for STEM education through programming robots: a systematic literature review.	23	0-8 (and preservice and inservice teachers of this age range)		Programming	Robots	- Through the use of robots, children can acquire interdisciplinary skills and knowledge, and engage with mathematical concepts, such as sequencing, scientific inquiry and problem solving (Bers, 2010; Bers & Horn, 2010; Kazakoff et al., 2013; Kazakoff & Bers, 2012, 2014; Rogers & Portsmore, 2004).

Chan & Leung (2014)	Dynamic Geometry Software Improves Mathematical Achievement: Systematic Review and Meta-Analysis.	9	Primary and secondary	SMD, 1.02; 95% CI: 0.56–1.48	Impact on achievement	Dynamic geometry software (DGS)	● DGS-based instruction was found to have a significantly positive influence on students' mathematical achievement in all levels of education. ● The effect is greater in primary education.
Chen, Shih, & Law (2020)	The Effects of Competition in Digital Game-Based Learning (DGBL): A Meta-Analysis	25	Elementary, secondary and college	0.386	Digital game-based learning	Games (including role-play games, puzzle games, simulations and virtual worlds)	● Competition in DGBL was effective for math, science and language, but not for social science and other subjects. ● It was effective for K12 students and college students. It was effective for puzzle, strategy, role-playing, and simulation, but not for action games. ● Finally, competition in DGBL was equally effective for cognitive and non-cognitive outcomes. ● The results suggested that the effects of competition in GBL in the math domain were significantly stronger than those of the language learning and science domains (p<.10). ● No significant differences were found in other subjects.

Cheung & Slavin (2013)	The effectiveness of educational technology applications for enhancing mathematics achievement in K-12 classrooms: A meta-analysis	74	K-12	Small studies = +0.26, large studies = +0.12	Impact on achievement	Applications - supplemental CAI, computer management learning and comprehensive programs	● Educational technology applications generally produced a positive, though modest, effect on mathematics achievement (ES = +0.16) in comparison to traditional methods. ● However, the effects may vary by educational technology type. Among the three types of educational technology applications, supplemental CAI had the largest effect with an effect size of +0.18. The other two interventions, computer-management learning and comprehensive programs, had a much smaller effect size, +0.08 and +0.07, respectively. ● The use of educational technology had a bigger effect on elementary students than secondary students
Crompton & Burke (2016)	Research trends in the use of mobile learning in mathematics	36	Pre-K to Higher Education		Mobile learning; Impact on achievement	Mobile devices	● From the 36 studies, 27 presented positive learning outcomes. ● Mobile learning is most frequently used in elementary mathematics settings (34%) followed by middle school (29%). ● Mobile phones are currently the most widely used device for mobile learning in mathematics

Crompton, H., Burke, D., & Lin, Y. C. (2019).	Mobile learning and student cognition: A systematic review of PK-12 research using Bloom's Taxonomy.	101	PK-12		Mobile learning	Mobile devices	●Studies of the use of mobile learning in PK-12 mathematics settings composed 7.9% of the total data set. ●The highest number of pedagogical opportunities given to students in the math research studies (37%) involved applying their knowledge (level 3 bloom's taxonomy). As much of mathematics instruction in PK -12 ●classrooms typically can involve learning how to apply the mathematical skills and concepts this is perhaps an expected outcome.
Deunk, Smale-Jacobse, de Boe, Doolard & Bosker (2018)	Effective differentiation Practices:A systematic review and meta-analysis of studies on the cognitive effects of differentiation practices in primary education.	21	6-12		Differentiation	Varied	●Overall, differentiation practices in primary education have a small significant positive effect on students' academic performance. ●The findings reveal a small significant negative effect of differentiation for low-ability students, but no significant effects for the other ability groups

Donnelly-Hermosillo, Gerard, & Linn (2020)	Impact of graph technologies in K-12 science and mathematics education.	42	K-12		Graphing technologies	Graphing software	● Graphing technologies provide immediate, visual feedback about complex phenomena and support autonomous investigations that are difficult to achieve without technology. ● Technology has benefits over non-technology approaches in helping students connect physical phenomena with the representations displayed on graphs by directly linking sensors measuring temperature, motion, or chemical concentrations to scientific phenomena
Fidai, Capraro, & Capraro (2020)	"Scratch"-ing computational thinking with Arduino: A meta-analysis.	11	K-12 and post-secondary classrooms	RQ1 Effect size: d=1.03 RQ2 Effect size: d=1.16, d=0.72 and d-1.68		Scratch and Arduino	● The findings indicate that the combination of Arduino and Scratch had an overall positive effect on students' CT skills and that these skills were improved in a number of areas including problem-solving and creative thinking. ● Arduino- and Scratch-enabled interventions had the largest effect on students' CT perspectives skills; this was followed in magnitude by the effect on students' CT concepts skill, then CT practices skills.

Hainey, Connolly, Boyle, Wilson, & Razak (2016)	A systematic literature review of games-based learning empirical evidence in primary education.	105	Primary education		Game-based learning	Strategy, puzzle, simulation, role-play, adventure and generic games. PC, video game console, online games and mobile games.	● The most popular delivery platform overall was the PC, followed by the video game console, online games and mobile games. In terms of the subject disciplines that the games in the studies were applied to, the majority of the games were in the areas of mathematics, science, languages and social areas which is not really particularly surprising in PE as there is a strong emphasis placed on these subjects at this level of education.
Hardman (2019)	Towards a pedagogical model of teaching with ICTs for mathematics attainment in primary school: A review of studies 2008–2018	37	Elementary schools		Pedagogy in ICT based classrooms Impact on achievement		● Findings from this review indicate that ICTs can impact positively on primary school mathematics performance provided that a constructivist pedagogy is used as opposed to a traditional transmission based pedagogy. ● While the evidence suggests that pedagogy does indeed change with ICTs, the exact nature of this change remains opaque. ● The research regarding the impact of ICTs on mathematical attainment points clearly to the fact that ICTs, at a primary school level, do indeed impact positively on student outcomes

Harskamp (2014)	The effects of computer technology on primary school students’ mathematics achievement: A meta-analysis	16	Primary education	0.48	Impact on achievement (across different sub-domains of mathematics)	Varied (Building Blocks, Merlin’s Math Mill, Spatial-Temporal maths software games, and virtual manipulatives.)	● This meta-analysis indicated an overall medium positive effect of computer technology on mathematics achievement in primary education. There was an overall extra effect for ‘type of student’. For low achieving students the overall effect of computer programs versus traditional teaching was slightly greater (.59 SD) than for the higher achieving students. Therefore, low mathematics ability students especially profit from the use of computer programs as compared to whole-class teaching. ● Our study indicates that the most frequently utilized ICT in primary education are tutorials and that exploratory environments are utilized far less. ● Teachers should keep in mind that computer programs are effective if they are used regularly (more than 30 minutes a week during a longer period of time). ● Teachers need to choose programs that are in line with the mathematics curriculum the students follow and teachers should integrate the instruction for the programs into their regular classroom instruction

Herodotou (2018)	Young children and tablets: A systematic review of effects on learning and development	19	5 years and younger			Tablets/ Mobile devices	● Improvements after interacting with mobile devices were reported for near (yet not far) transfer learning events relevant to telling the time and measuring with unconventional units, quantity of different sets, growth, and projectile motion for older children only, early number skills for low-income children, ● Math enhancement using digital manipulatives, content knowledge about pets, and an increasing complexity of ways of reasoning about Math. It remains unknown what an effective technology-enhanced early year curriculum looks like.
Higgins, Huscroft-D'Angelo, & Crawford (2019)	Effects of Technology in Mathematics on Achievement, Motivation, and Attitude: A Meta-Analysis.	24	Kindergarten to Grade 8	Achievement = 0.68 Motivation = 0.3 Attitude = 0.59	Impact on achievement, motivation and attitude. Tech-assisted versus tech-based instruction		● Results from 24 articles (4,522 subjects) indicate a significant overall impact of technology on student achievement, motivation, and attitudes; however, results vary based on the different aspects of the intervention examined. ● Facets of this study reveal that while technology greatly enhances student outcomes in some areas (e.g., short interventions and content areas such as numbers and operations), it has the potential to be ineffective as well. ● Interestingly, no differences were found for the type of intervention (either technology-based or technology-assisted)—both types positively influence student achievement and attitude.

							● However, technology-assisted instruction enhanced student motivation whereas technology-based instruction did not.
Hillmayr, Ziernwald, Reinhold, Hofer & Reiss (2020)	The potential of digital tools to enhance mathematics and science learning in secondary schools: A context-specific meta-analysis.	92	Grades 5 - 13	These 92 effect sizes range from g ¼-0.33 to g ¼2.46	Impact on achievement and attitude	Intelligent tutoring systems, simulations, hypermedia systems	● Use of intelligent tutoring systems or simulations was significantly more beneficial than hypermedia systems. ● The effect size was larger when digital tools were used in addition to other instruction methods and not as a substitute. ● The overall effects show that the use of digital tools had a medium, significantly positive effect on student learning outcomes and a small, significantly positive effect on student attitudes. ● Interventions that provided teacher training in the digital tool used in class produced significantly larger effects than studies that did not provide specific training.

Holmes (2013)	Effects of Manipulative Use on PK-12 Mathematics Achievement: A Meta-Analysis	17	PK-12	0.22 and 0.20		Mathematics manipulatives (with some focus on virtual manipulatives)	● Results from this review provide evidence that student achievement in grades PK-12 can be improved through the use of mathematics manipulatives. ● No published meta-analytic reviews about the effects of virtual manipulatives exist. ● Results indicated that students who used virtual manipulatives during mathematics instruction performed one-fifth of a standard deviation higher on mathematics outcome measures of achievement than their peers who used physical manipulatives during mathematics instruction.
Juandi, Kusumah, Tamur, Perbowo, Siagian, Sulastri, & Negara (2021)	The Effectiveness of Dynamic Geometry Software Applications in Learning Mathematics: A Meta-Analysis Study	50		1.07		Dynamic geometry software	● This study found that learning using DGS has a relatively high positive effect on math skills (as effect size is 1.07). ● The results showed a strong relationship between the DGS effectiveness and education level. ● This meta-analysis also showed there was no significant difference in effect size based on the type of DGS used. This means every type of DGS is effective in mathematics learning, with the largest combined effect size of 0.98 was GeoGebra

Juandi, Kusumah, Tamur, Perbowo, & Wijaya (2021)	A meta-analysis of Geogebra software decade of assisted mathematics learning: what to learn and where to go?	29		0.96	Impact on achievement	GeoGebra	● On average, students exposed to GeoGebra-based learning outperformed math abilities, which was initially equivalent to 82% of students in traditional classrooms. ● The GeoGebra software used was more effective in sample conditions less than or equal to 30. ● GeoGebra software is more effective when the treatment duration is set to less than or equal to four weeks
Jung & Won (2018)	Systematic review of research trends in robotics education for young children	47	Pre-K to 5th Grade			Robots	● Our review showed that more than half of the reviewed studies (63.8%) have focused on the benefits of robotics education for young children. ● We suggest developing and enhancing the robotics-intensified knowledge, skill, and attitude domains for robotics education. In particular, considering that robotics is a part of computer science, robotics education is often positioned only in the context of STEM disciplines. ● We suggest shifting the focus of robotics education research from robotics technology and its effects to young children themselves.

Kakavas & Ugolini (2019)	Computational Thinking in Primary Education: A Systematic Literature Review	53	Elementary (K-6)		Computational thinking	Plugged and unplugged activities, robotics, game programming, simulation	● The combination of ‘full-embody activities’ with the ‘practice of computational perspective-taking’ in solving problem in the area of mathematics improves CT-skills, the understanding of mathematics as well as programming skills
Kiru, Doabler, Sorrells, & Cooc (2018)	A Synthesis of Technology-Mediated Mathematics Interventions for Students with or at Risk for Mathematics Learning Disabilities	19	K-12, elementary school, or high school		Technology-mediated mathematics interventions		● TMM interventions that incorporate features of explicit mathematics instruction can potentially enhance mathematics instruction and increase student mathematics achievement.

Kul, Celik & Aksu (2018)	The Impact of Educational Material Use on Mathematics Achievement: A Meta-Analysis	54	Primary, Middle, High Schools and Universities		Manipulatives (largely non-digital focus)	Digital manipulations are computer applications and software copies of web-based applications.	• The results of the meta-analysis showed that using materials in mathematics has a positive and high influence on achievement. • Physical and digital materials are found to be more effective in mathematics achievement compared to other types of materials.
Lakhan & Laxman (2018)	The Situated Role of Technology in Enhancing the Academic Performance of Indigenous Students in Mathematics Learning: Application within a Maori Cultural	15	Secondary school			Tablets, social media such as Facebook, Skype and Twitter	• Web 2.0 tools in the classroom including Facebook have potential for maximizing learning opportunities in education. • Features of these tools allow formation of videos or images for feedback rather than students being passive learners. • Being socially connected means collaborating and sharing of these resources to create learning opportunities and promote informal learning opportunities (Kong et al., 2014). Students are already using these social sites for educational purposes.

	Context in New Zealand						
Lei, Chiu, Li, Wang & Geng (2020)	Computational thinking and academic achievement: A meta-analysis among students	34	1st graders in primary school to 4th year seniors at university	Overall, computational thinking was significantly positively correlated with students' academic achievement r = 0.288;	Computational thinking		● Results from 34 studies showed that computational thinking and academic achievement were positively correlated (0.288). ● Furthermore, culture, grade level, gender, and achievement measure moderated this link.

Lo & Hew (2021)	Student Engagement in Mathematics Flipped Classrooms: Implications of Journal Publications From 2011 to 2020	33	K-12 and higher education		Flipped classroom as a pedagogical practice		● Most studies provided evidence that the use of the flipped classroom approach increased students’ interaction and attention/participation compared to traditional lecturing. ● Students’ levels of effort appeared to be similar in traditional and flipped classrooms across studies. ● Most studies supported the idea that the use of the flipped classroom approach increases students’ course satisfaction compared to traditional lecturing. ● Most studies provided evidence that the use of the flipped classroom approach increased students’ understanding of mathematics and fostered their preference for challenges.
Moyer-Packenham & Westenskow (2013)	Effects of Virtual Manipulatives on Student Achievement and Mathematics Learning	66	Pre-K to University	The comparison for virtual manipulatives (used alone or in combination) vs. all other instructional treatments yielded a moderate effect (0.35). The comparison for virtual manipulatives		Virtual manipulatives	● Virtual manipulatives allow students to explore mathematical ideas in ways that are very different from typical paper and pencil activities, providing opportunities for different kinds of mathematical observations and learning to occur.

				(only) vs. other instructional treatments produced a moderate effect (0.34), virtual manipulatives (only) vs. physical manipulatives produced a small effect (0.15), and virtual manipulatives (only) vs. classroom instruction using textbooks produced a moderate effect (0.75). (A number of others given in text)			

Papadopoulos, Irena; Lazzarino, Miah, Weaver, Thomas, & Koulouglioti (2020)	A systematic review of the literature regarding socially assistive robots in pre-tertiary education.	21	Pre-tertiary education		Artificial Intelligence	Socially Assistive Robots (SARs)	● The authors grouped their findings under four categories: learning gain, user experience, attitude, and usability of SARs within classroom settings. ● Overall, the use of SARs in pre-tertiary education is promising, but studies focussing on mathematics and science are significantly under-represented.
Popat & Starkey (2019)	Learning to code or coding to learn? A systematic review.	10	5-17 years		Coding		● The aim of this review was to find evidence of educational outcomes beyond coding that were influenced by learning to code. ● The results demonstrate that although students are learning to code, a range of other educational outcomes can be learnt or practiced through the teaching of coding. These included mathematical problem-solving, critical thinking, social skills, self-management and academic skills. ● The review also identified the importance of instructional design for developing these educational outcomes through coding.The reviewed literature suggests that mathematical problem solving is an educational outcome when learning to code.

							● Personal skills developed through coding included social skills and self management or active learning
Ran, Kasli, & Secada (2021)	A Meta-Analysis on Computer Technology Intervention Effects on Mathematics Achievement for Low-Performing Students in K-12 Classrooms.	31	K-12	Statistically significant and positive effect of CT (d= 0.56) on low performing students' mathematics achievement. Of four CT types, the largest CTeffect was found with problem-solving system (d=0.86), followed by tutoring (d=0.80), game-based intervention (d=0.58), and	Use of technology in schools; Impact of technology on low-performing students in maths; Technology interventions		● The overall effect of CT on LP students was evaluated by the outcome variable of mathematics achievement. Under the random-effects model, CT was found to be significant in mathematics achievement for LP students (z=5.83, p < .01). ● The significant estimated effect size value indicates that mathematics achievement and CT are significantly and positively related to each other with a large magnitude (d= 0.56, p < .01). ● These results suggest that CT interventions were largely effective for LP students' mathematics achievement. ● Our findings indicated that CT interventions had significant effect for kindergarten and primary school students. However, we found that CT did not significantly influence on high school students. ● We found that CT interventions on problem-solving seem to be more effective than on

				computerized practice (d= 0.23)			arithmetic skills or on multiple skills (contradictory finding, compared to the review by Kroesbergen and Van Luit (2003)) .
Scherer, Saddiq, & Viveros (2019)	The Cognitive Benefits of Learning Computer Programming: A Meta-Analysis of Transfer Effects.	105	Pre-K to 12 and tertiary education	Overall transfer effect size of g = 0.49			● Study focused on the transferability of learning computer programming to cognitive skills. ● Of the cognitive skills examined for far transfer, the transfer effects were large for creative thinking, mathematical skills, and reasoning—other cognitive skills benefited less (e.g., school achievement, literacy). ● The transfer effects on mathematical skills (g = 0.57) were larger than those found in similar meta-analyses that focused on the transfer effects of chess instruction, technology-based instruction, music education, or working memory training. The effect size was comparable to that of direct training studies. Thus, learning computer programming might be an effective approach to developing students’ mathematical skills.

See, Gorard, Lu, Dong, & Siddiqui (2021)	Is technology always helpful?: A critical review of the impact on learning outcomes of education technology in supporting formative assessment in schools	56	5-18		Formative assessment		● Some of the studies suggest that formative feedback delivered digitally can improve children’s maths and reading, but not writing. ● There is some promise that digitally delivered formative assessment can facilitate the learning of maths and reading for young school-age children. There is no evidence that it works for other school subjects or for older children. ● Analysis of PISA data showed that students who used computers very frequently at school do worse in most learning outcomes than those who use them moderately, even after controlling for social background and student demographics. ● No obvious improvements in students’ reading, mathematics or science were seen in countries that had invested heavily in information and communication technology (ICT) for education.
Siregar, Rosli, Maat & Capraro (2020)	The Effect of Science, Technology, Engineering and Mathematics (STEM) Program on Students' Achieveme	17	Elementary, secondary and university	The overall weighted average effect size was 0.242 with a corresponding p-value of 0.023 demonstrating that	STEM		● The overall weighted average effect size of 0.242 indicated that STEM programs are educationally important for student achievement in mathematics. ● When examining individual studies, the analysis shows the majority, 10 of 17 studies yielded statistically significant positive effect sizes between 0.118 and 1.571. These findings illustrate that the STEM program approach utilized in these ten studies might have

	nt in Mathematics: A Meta-Analysis			STEM had an impact on student mathematics achievement			improved students’ achievement in mathematics in some way. ● Policy makers and teachers should utilize this evidence in reforming instructional approaches in a classroom for improving student achievement at all levels.
Slavin (2020)	Effective programmes in reading and mathematics: Lessons from the Best Evidence Encyclopaedia 1	346	Primary and secondary		Impact of technology on mathematics		● There were 130 qualifying studies of the use of various types of technology in reading and mathematics. ● The effect sizes were modest in all categories. ● Technology innovations had their largest effects in primary mathematics (ES = +0.19), but of these, the higher quality randomised studies had much lower effects, averaging +0.10.

Sokolowski, Li, & Willson (2015)	The Effects of Using Exploratory Computerized Environments in Grades 1 to 8 Mathematics: A Meta-Analysis of Research	25	Grades 1 to 8	Exploratory computerized environments produced a moderate effect size (effect size (ES) = 0.60, SE = 0.03) when compared to traditional methods of instruction	Exploratory computerised environments		● While this study found a moderate positive effect size (ES = 0.59) associated with ECE, this finding does not diminish the importance of good teaching. ● Several studies found that using computers purely as a method of instruction does not improve students’ mathematics understanding. ● Hence, although computers have been used in mathematics classrooms for several decades now, the question regarding to what extent they can impact the teaching and learning of mathematics seems to be open for further investigations.
Steenbergen-Hu & Cooper (2013)	A meta-analysis of the effectiveness of intelligent tutoring systems on K-12 students' mathematical learning	26	K-12	Average effect sizes ranging from g = 0.01 to g = 0.09	Intelligent tutoring systems, Computer-assisted learning environments		● Findings of this meta-analysis suggest that, overall, ITS had no negative and perhaps a very small positive effect on K–12 students’ mathematical learning relative to regular classroom instruction. ● The effects appeared to be greater when the ITS intervention lasted for less than a school year than when it lasted for one school year or longer. The effects of ITS appeared to be greater when the study samples were general students than when the samples were low achievers.

Sullivan & Heffernan (2016)	Robotic Construction Kits as Computational Manipulatives for Learning in the STEM Disciplines.	21	P-12 classrooms (pre-kindergarten to grade 12)		Robots, Computational thinking	Robotics construction kits	• The analysis of existing research reported here supports a computational thinking learning progression in the robotics domain that begins with sequencing abilities, advances to reasoning abilities (causal inference and conditional reasoning), and results in improved systems understanding; all of which is aided by problem solving activity. • The research into computational thinking and robotics suggests that younger children are capable of sequencing and making causal inferences about simple programs using two representations, whereas older children of upper elementary and middle school age are capable of causal reasoning related to complex programs using two representations and conditional reasoning using one sensor.
Sun, Hu, & Zhou (2021b)	Which way of design programming activities is more effective to promote K-12 students' computational thinking skills? A	86	K-12	Hedges' g = 0.601 (improvement of programming on K-12 students' CT skills)	Computational thinking	Code.org, Scratch. Robotics, Logo	• Through the analysis of 86 quantitative empirical studies with 114 effect sizes, we concluded that programming had a moderate positive influence on students' CT skills. • Different programming instruments had a significant positive impact on K-12 students' CT skills, among which the effects of Code.org, Logo, Scratch, and Robotic were found to be more prominent. . • As most studies have reported, programming can positively develop students' CT skills through participation in either solo or collaborative programming activities.

	meta-analysis.						
Sun, Else-Quest, Hodges, Frenc & Dowling (2021a)	The Effects of ALEKS on Mathematics Learning in K-12 and Higher Education: A Meta-Analysis		Grades 3-12, Undergraduate and graduate education	The overall effect of ALEKS on learning performance was small and not statistically significant, g = 0.12	Online learning technologies	Assessment and LEarning in Knowledge Spaces (ALEKS)	● Learning performance with ALEKS were comparable to that with traditional instruction (g = .05), but ALEKS was especially effective when used as a supplement to traditional instruction (g = .43). That is, ALEKS can significantly enhance learning when combined with traditional pedagogy.

Svela, Nouri, Viberg, & Zhang (2019)	A systematic review of tablet technology in mathematics education	39	Kindergarten to higher learning		Mobile learning	Tablets	● The results show that there is a clear focus on foundational level mathematics in elementary school settings. ● Thus foundation subjects that tend to reach a wider audience of learners will be subject to application development and deployment on tablet hardware in educational settings in higher volume and frequency than more complex applications dealing with, for example, 3D geometry. ● The most used pedagogical approach, either standalone or combined with others, is game-based learning. Tablet technology opens the door for mathematical games to be designed that are touchscreen based, networked, visually and audibly stimulating and most of all fun.
Talib, Aliyu, Zawadzki & Ali (2019)	Developing student's computational thinking through graphic calculator in STEAM education	21	Secondary schools		Computational thinking, STEAM education	Graphics calculator	● Many studies indicated that students developed a deep understanding of concepts when computational thinking was employed to facilitate instruction that involves STEAM education. ● Computational thinking and STEAM education are interwoven with one another. ● Recommendations for teachers that were given in this study were for chemistry teachers.

Tamur, Juandi & Kusumah (2020)	The Effectiveness of the Application of Mathematical Software in Indonesia; A Meta-Analysis Study	51	Grade 4 to College	1.162	Impact on achievement	Mathematical software	● The effect size of 1.261 shows that learning using mathematical software has a very strong influence on students' mathematical abilities compared to conventional learning. ● The analysis showed a significant difference in the use of software but not significant in the year when the study was conducted. ● An investigation of effectiveness based on study characteristics revealed that the use of mathematical software was more effective in certain conditions. ● This meta-analysis also revealed that the latest study group showed an increasingly large effect size.
Tikva & Tambouris (2021)	Mapping computational thinking through programming in K-12 education: A conceptual model based on a systematic literature Review.	101	K-12		Computational thinking		● The examination of the studies reveals that the most common proposed learning strategies are Game Based Related Strategies and Modelling & Simulations ● Related strategies leveraging scaffolding and collaborative strategies ● Findings not specific to maths

Tingir, S.; Cavlazoglu, B.; Caliskan, O.; Koklu, O.; Intepe-Tingir, S. (2017).	Effects of mobile devices on K–12 students' achievement: a meta-analysis	14 (2010-2014). 3 out of the 14 students investigated students' mathematics achievements.	K-12		Learning mathematics with mobile devices, therefore, is likely to be more challenging because of the additional skills that students need to have.	Mobile devices (tablet, PDA, smartphone, mobile device)	● Most of the mobile device applications were mathematical games . ● Mathematical games may enhance student interest and motivation as well as some skills necessary in learning mathematics,but their effect on academic achievement could be limited. ● Use of active learning strategies in teaching mathematics with mobile devices is still insufficient(Carr, 2012) as the teaching in mathematics frequently occurred via traditional lecturing (Weber, 2004). ● Learning mathematics requires other skills (e.g., compu-tational skills, abstract thinking, problem solving and spatial thinking in addition to basic reading skills) for understanding the phenomena in mathematical prob-lems. This could be another reason for mobile devices having a smaller effect in mathematics achievement as compared to reading.

Tokac, Umit; Novak, Elena; Thompson, Christopher G. (2019).	Effects of game-based learning on students' mathematics achievement: A meta-analysis.	24 (2000-2017)	PreK-12th grade	A small but marginally significant overall effect (dRE0.13; p=.02) with an associated 95% confidence interval of[0.02, 0.24]. The overall effect of video-gaming instruction on mathe-matical achievement was marginally significant and quite variable, as denoted by the rather wide confidence interval and relatively large standard error (SE = 0.06).	Game-based learning/interventions	Video games on mathematics achievement	● The empirical research on comparing mathematics game-based learning with traditional instructional methods remains limited. Mathematics video games contribute to slightly higher learning gains compared to traditional. ● With regard to grade level, results suggest that mathematics video games were similarly beneficial for students from various grade levels. ● The length of game-based interventions did not have significant explanatory power, where some of the length of game-based intervention consisted of a single game session of 33 min as the shortest and multiple game sessions with a total of 10,080 min as the longest. Therefore, intervention duration has only a small impact on students' academic achievement in both primary and secondary schools.

Verbruggen, S.; Depaepe, F.; Torbeyns, J. (2020).	Effectiveness of educational technology in early mathematics education: A systematic literature review	54	Preschool/ kindergarten/early childhood		The effectiveness of educational technology in early childhood mathematics education.Cognitive loading, the necessity of digital skills and competencies to facilitate mathematical learning.	‘electronic tools and applications that help deliver learning content and support the learning process’	● Nearly all these studies found that the ET was at least as effective as or even more effective than the support provided in the non-ET condition for one or more outcomes in the domain of early mathematics. ● This suggests that ET can be an effective tool for supporting preschoolers’ early mathematical development.
Verschaffel, L.; Depaepe, F.; Mevarech, Z. (2019)	Learning Mathematics in Metacognitively Oriented ICT-Based Learning Environments: A Systematic Review of the Literature	22	K-12 mathematics education: kindergarten (3), elementary school (7), and secondary school (12)		ICT-based learning and metacognition in mathematics education	Online learning environment (computer-supported practice, educational e-books, intelligent tutoring systems, serious games, multimedia, and computer-supported collaborative learning environments)	● Embedding metacognitive pedagogy in ICT-based learning environments or the reverse; the use of ICT to promote metacognitively orientated mathematics learning environments. ● More empirical research was conducted in elementary and secondary schools with only 3 studies conducted in kindergarten which focused on intervention with drill or practice or the use of an e-book. ● The results indicate that these metacognitive pedagogies may either be provided by the ICT itself or be supplemented by the teacher. ● Taken as a whole, these studies provide ample evidence for the positive role that a metacognitively oriented training combined with an ICT-based learning environment can

							play in enhancing (upper) elementary school children’s mathematical performance, their metacognitive skills, and—at least in one study—also their motivation.
Wong, S.L.; Wong, S. L., & Mohd Ayub, A.F. (2020).	Application of geometer's sketchpad in Malaysian schools: A literature review	13 (2004-2020)	Primary & post primary Malaysian mathematics classrooms	not systematic	Dynamic geometry software	Geometer's Sketchpad (GSP)	● GSP has been found to be effective in improving students’ geometry and their learning of graph functions in the Malaysian classroom. ● However, it is important to note that as much as technology can help students understand mathematics better, it does not override students’ need to learn and master basic mathematics skills such as addition, subtraction, multiplication, and division. ● It is important to examine the attitudes and perceptions of both teachers and students towards using GSP. ● While studies have indicated the usefulness of GSP, it is important to bear in mind the challenges faced by teachers when using technology in the classroom. ● Teachers’ and students’ attitudes towards the use of GSP have generally been positive.

							● It is proposed that all mathematics teachers be provided with comprehensive training on using and integrating GSP in their mathematics lesson instead of merely training representatives of selected schools.
Xie, Chen. (2021).	What Can China Learn from Evidence-Based Educational Reform? A Comparative Review of Educational Technology Programs' Effects on Mathematics	78 (1960 to 2018)					● Discusses specific educational technology programmes in the US and China. ● A common feature of eMINTS and ASSISTments is the inclusion of professional development and the training of teachers and school staff (Meyers et al., 2016; Roschelle et al., 2016).

	Achievement						
Zhang, Lechen; Nouri, Jalal. (2018).	A Systematic Review of Learning and Teaching with Tablets	39 (8 studies addressed mathematics)	Primary & secondary		Pedagogical practices	tablets mostly interest Math (8 studies)	● Pedagogical teaching and learning practices that are supported by tablets in maths education namely: collaborative learning, game-based learning, and multimodal learning.
Zhang, L., & Nouri, J. (2019).	A systematic review of learning computational thinking through Scratch in K-9."	55	K-9		Computational Thinking	Scratch	● This systematic review of 55 empirical studies has adopted Brennan and Resnick's (2012) framework as the basis for defining and identifying the expected CT skills in K-9. ● This study defines CT as a thought process, through skills that are fundamental in programming (CT skills), to solve problems regardless of discipline. ● The purpose of this review is to obtain a better understanding of “what to teach” and “what

	Computers & Education 141 (2019): 103607.						can be learned” through Scratch by systematically examining the CT skills that can be obtained through Scratch in K-9, asking the research question: what CT skills can be obtained through Scratch for K-9 learners, given the empirical evidence? ● The results demonstrate that all CT skills in Brennan and Resnick's (2012) framework can be delivered through the use of Scratch. Additional CT skills were found in the examined literature: input/output, reading, interpreting and communicating code, using multimodal media, predictive thinking and human–computer interaction.
Zheng, B., Warschauer, M., Lin, C. H., & Chang, C. (2016).	Learning in One-to-One Laptop Environments: A Meta-Analysis and Research Synthesis	10 (2001-2015) 7 studies on mathematics	K-12	d = .16; 93.28 (p < .001)			● Seven studies of mathematics achievement (Clariana, 2009; Grimes & Warschauer, 2008; Gulek & Demirtas, 2005; Hansen et al., 2012; Lowther et al., Zheng et al. 1062 2012; Rosen & Beck-Hill, 2012; Rosen & Manny-Ikan, 2011) with 21 effect sizes were included in the meta-analysis. ● Positive effects in mathematics were found in several studies (i.e., Grimes & Warschauer, 2008; Gulek & Demirtas, 2005; Lowther, Strahl, Inan, & Bates, 2007; Rosen & Manny-Ikan, 2011), with two other studies reporting no impact (i.e., Bernard et al., 2007; Dunleavy & Heinecke, 2008) and one study showing negative impact in two of the three grades examined (Hansen et al., 2012).

							● Clariana (2009) found that laptop students outperformed non-laptop students on a computer-based assessment after the first year of program implementation, but not on a paper-based standardized assessment. ● Some studies more specifically examined the relationship between the amount of students' technology use and their mathematics achievement. Bebell and Kay (2010) found that more frequent computer use in the laptop classrooms tended to result in higher mathematics scores for students. Interestingly, in the control classrooms, more frequent use of technology was negatively correlated with mathematics scores. This supports a finding by Warschauer (2011) that efficient and effective use of technology is much easier when students have regular daily individual access to laptops, which could further lead to academic achievement improvement.
Zhong, B., & Xia, L. (2020). .	A systematic review on exploring the potential of educational robotics in mathematic	20	Elementary / Secondary		how to teach and learn mathematical knowledge through robotics.	Robotics - Lego accounted for more than 50%	● The results indicate that (1) most studies were conducted with a small sample size, the largest research groups were elementary school students and secondary school students, most studies used LEGO robots, robots were primarily applied to teach and/or learn graphics, geometry, and algebra, and almost half of the studies taught mathematics by engaging students in game-like interactions

	s education. International Journal of Science and Mathematics Education, 18(1), 79-101.						with robots; (2) half of the studies adopted a non-experimental research design, and most studies evaluated student performance through observation, test/examination, questionnaires, or verbal interviews; and (3) instructional implications proposed in the 20 papers can be clustered into four themes: human-robot interaction, connections between mathematics and real life, pedagogical suggestions, and facility conditions. ● The 20 papers suggest that robotics generally plays an active role in mathematics education; however, there are indeed situations in which no significant improvement was found in students' mathematical learning.