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Technology Usage in Mathematics Education Research – A Systematic Review of Recent Trends

Title Page

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Abstract

There is a significant body of research relating to technology-enhanced mathematics education and the perceived potential of digital tools to enhance the learning experience. The aim of this research is to take a structured look at the types of empirical interventions ongoing in the field, and to attempt to classify and analyse the ways in which digital tools are being employed in such research. A systematic analysis of 139 recent, published studies of technology interventions in mathematics education, selected from in excess of 2000 potential studies, has been undertaken. A system of classification, developed as a part of this research, is used to categorise the digital tools, the pedagogical foundations and goals of the activities, and the levels of technology integration in the studies. Analysis of the results of this classification highlights a disparity between what is being researched in published empirical studies, and approaches that have been recognised as optimising the potential of technology to enhance mathematics education. Potential reasons for current trends are proposed and explored.

Keywords: Systematic literature review, technology-enhanced learning, mathematics education, secondary education

1 Introduction

It has been suggested that digital tools, combined with appropriate pedagogy, may have the potential to address some of the issues commonly associated with mathematics education, having the capacity to facilitate realistic, problem-solving and collaborative approaches to teaching and learning, thus providing coherency and context for the mathematics (Hoyles, 2016; ter Vrugte et al., 2015). However, many authors propose that although use of technology in the mathematics classroom is increasing, the outcomes of its utilisation do not live up to their perceived potential to enhance the learning experience (Geiger, Faragher, & Goos, 2010; Lameras & Moumoutzis, 2015; Oates, 2011; Reed, Drijvers, & Kirschner, 2010; Selwyn, 2011; Wright, 2010). In order to investigate why this may be the case, this research offers a synthesis of the general characteristics of recent, empirical research studies relating to technology usage in mathematics education. A classification is developed and implemented, providing an overview of the current state of the field. This indicates that the dominant pedagogical approach is constructivist in philosophy, the usage of technology is largely confined to "augmentation" of existing classroom practice (Puentedura, 2006). This goes someway to explaining why the potential benefits of technology in maths education are not being fully realised. Furthermore, the results of the classification provide a lens that can be used to inform the direction of further research, as well as to categorise new developments in the area.

In order to give context to the study, a summary of background literature is provided, which is divided into two sections: a review of mathematics education and its associated problems; and a focused review of technology-enhanced mathematics education. The purpose of the background section is to identify: (a) the problems that digital tools may have the potential to address, and (b) what might we consider as *good practice*, i.e., the characteristics of technology-mediated mathematics learning activities with the greatest perceived potential to address these issues.

The main body of the paper firstly describes the development of the classification system, and then presents a systematic analysis of 152 interventions in 139 research papers that discuss empirical studies in technology-enhanced mathematics education. The total number of interventions in the 139 papers amounts to 152, as some papers were meta-analyses or considered multiple interventions. This is realised by examining the studies through the lens of the classification that categorises the tools, aims, and levels of usage of digital technology in the each of the interventions. In this research, an 'intervention' is taken to represent the trialling of a given technology or its usage to address a specific purpose. This paper highlights a mismatch between what is recommended in more general literature on technology integration in mathematics education (Section 2.3), and what is being implemented in relevant research.

2 Background

This introduction is intended to provide a broad context to the field of research in which this paper is situated. It includes a focused examination of some of the issues associated with mathematics education, followed by an examination of how technology-enhanced mathematics education may have the potential to address some of these matters. The implications section develops these concepts, highlighting the aspects of technology-enhanced mathematics pedagogy that are considered to constitute *good practice*.

2.1 Issues in Mathematics Education

Recent curriculum reforms recognise that a view of mathematical competence as solely related to procedures and concepts, that can be accumulated with practice, is naïve and incomplete (Contreras, 2014). There are equally important aspects of mathematical proficiency that relate to metacognitive skills such as creativity and problem-solving. However, there remains an unfortunately prevalent belief that mathematics is a collection of unrelated facts, rules, and 'tricks' that are is "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 has contributed to a behaviourist approach to teaching and learning, with an emphasis on formal, abstract mathematics remaining dominant in many countries (Albert & Kim, 2013; Ayinde, 2014; Maaß & Artigue, 2013; Ozdamli, Karabey, & Nizamoglu, 2013; Treacy, 2012). In this context, the teacher is frequently viewed as the absolute authority on the subject, their primary purpose being the transmission of information to the students. In conjunction with a strong focus on assessment, this has led to an environment in which mathematics is presented as a disjoint set of rules and procedures rather than a complex and interrelated conceptual discipline (Ayinde, 2014; Garofalo, 1989; Hoyles, 2016; Schoenfeld, 1992). Didactical teaching methods prevail, with an emphasis on procedure rather than understanding. Content is often favoured over mathematical literacy and learners are not encouraged to explore alternative answers or to seek out their own solutions (Conway & Sloane, 2005; Maaß & Artigue, 2013; Schoenfeld, 1992). The resultant fragmented and de-contextualised view of the subject frequently leads to issues with motivation and engagement (Boaler, 1993; Hoyles, 2016; Star et al., 2014).

Efforts to address some of these issues have been undertaken, but results have had limited success. The importance of embedding mathematics within meaningful context has been recognised (Foster, 2013; Hughes & Acedo, 2014), however this often resulted in pseudo-real-world problems – traditional computational problems with a thin veneer of 'real-world' through translation into simple word problems (Boaler, 1993; Foster, 2013; Olive et al., 2010; Schoenfeld, 1992). As a result of this narrow view of context, lack of emphasis on problem-solving, and overt focus on the mastery of routines and algorithms, students tend to lack the ability to apply their mathematical knowledge in anything but the most familiar contexts (Maaß & Artigue, 2013; Treacy, 2012).

2.2 Technology-Enhanced Mathematics Education

The use of digital technologies in mathematics education has the capacity to address many of the issues identified in the previous section, opening up diverse pathways for students to construct and engage with mathematical knowledge, embedding the subject in authentic contexts and returning the agency to create meaning to the students (Drijvers, Mariotti, Olive, & Sacristán, 2010; Olive et al., 2010). In addition to its computational power, modern technologies 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 (Geiger et al., 2010; Noss & Hoyles, 1996; Olive et al., 2010). For these reasons, the use of technology in mathematics education is becoming increasingly prioritised in international policy and curricula (National Council of Teachers of Mathematics, 2008; Trouche, Drijvers, Gueudet, & Sacristan, 2013).

An evolving recognition of the potential, of technology to alter aspects of mathematics education has increased the perception that problem-solving and inquiry, and not just the memorisation of a catalogue of facts and procedures, should be at the heart of the subject in schools (Geiger et al., 2010; Hoyles & Lagrange, 2010). The availability of technology in a classroom environment will not on its own however, ensure the development of a collaborative and explorative classroom (Geiger et al., 2010; Olive et al., 2010). 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, Kynigos, Hollebrands, & Strässer, 2006; Olive et al., 2010; Swan, 2007).

It is necessary to carefully consider the kinds of gains to mathematics learning that can be achieved through the introduction of technology (Sinclair et al., 2010), and to design tasks accordingly. A historical perspective of early technology usage in mathematics education reveals diametrically opposed approaches to learning, which gave rise to widely differing technologies (Sinclair & Jackiw, 2005). On one hand, the multiple-choice tests of computer-assisted instruction technology (CAI) had a very narrow level of expressivity, and embodied a behaviourist approach to learning. Logo (Papert, 1980) on the other hand, was widely expressive in terms of mathematics and encouraged a constructionist approach to learning, supporting the link between students' actions and symbolic representations (Olive et al., 2010). Artigue (2002) similarly distinguishes between the pragmatic and epistemic value that technology can bring to tasks: digital technologies can act as efficiency tools, to increase the speed and accuracy of computations (pragmatic), or they can contribute to students understanding of the mathematics (epistemic), thus becoming a conceptual toolkit and a "source of questions about mathematical knowledge" (Artigue, 2002, p. 248; Oates, 2011; Olive et al., 2010; Ruthven, Hennessy, & Deaney, 2008).

As a starting point for task design, several authors highlight the importance of genuine and engaging contexts for the activities in order to create compelling challenges that the students require mathematics to solve, and in which the technology has an important role (Confrey et al., 2010; Foster, 2013; Geiger et al., 2010; Hughes & Acedo, 2014; Olive et al., 2010). Many argue that it is preferable to use technology in tasks that are significantly transformed through the tool use, rather than in tasks that could have been completed without it (Laborde, 2001, 2002; Noss et al., 2009; Oates, 2011; Oldknow, 2009; Olive et al., 2010). In such an environment, students are given an opportunity to use technical tools as experimental instruments to make practical use of mathematics for genuine and productive purposes, rather than for the application of rote-learned formulae and procedures to contrived scenarios (Olive et al., 2010).

An inquiry based approach has been identified as being particularly appropriate for technology-enhanced mathematical activities (Confrey & Maloney, 2007; Geiger et al., 2010; Psycharis, Chalatzoglidis, & Kalogiannakis, 2013). The potential of technology to facilitate experimentation and testing of ideas, as well as for modelling and the visualisation of abstract mathematical concepts, can change the nature of the mathematics classroom from a transmission-based, teacher-led environment, to a student-centred, investigative and constructivist one (Olive et al., 2010). A fundamental concept of task design in an inquiry-based learning environment relates to the open-ended nature of the activities (Geiger et al., 2010). The use of digital technologies in mathematics education can allow for diverse routes for learners to solve problems and reach their goals (Hoyles & Lagrange, 2010), giving students control over their progress through the material (Buteau & Muller, 2006; Olive et al., 2010; Wright, 2010). Supporting students' autonomy over their learning in this manner has the potential to strengthen their mathematical confidence and increase their enjoyment of the subject (Boaler, 1993; Noss et al., 2009).

In order to achieve an environment that facilitates technology usage in an inquiry-based, constructivist manner, a change in the pedagogical approach and the learning experience of the students is required, and this is fundamentally dependent on the actions and beliefs of teachers (Donnelly, McGarr, & O'Reilly, 2011; Ertmer & Ottenbreit-Leftwich, 2010; McGarr, 2009). However, issues around teachers' beliefs can be very deep-rooted and difficult to change (Donnelly et al., 2011; Ertmer & Ottenbreit-Leftwich, 2010). In the traditional conception of a classroom, the teacher commands a dominant position, is regarded as "knower", and their role is one of transmission of information (Authors, 2013a; Lameras & Moumoutzis, 2015). Often the pedagogic approaches that are complemented by technology do not fit comfortably with this teaching culture (Ertmer & Ottenbreit-Leftwich, 2010; Fullan & Langworthy, 2014; Voogt & Pelgrum, 2005). Attempts to alter the teacher's role from initiator and controller, to facilitator, through the integration of technology and associated "21st Century" pedagogies into the classroom, are sometimes seen as undermining of the teacher's position in the classroom (Euler & Maaß, 2011). As a result teachers may accommodate the technology to conform to their current, "lecture-based" practice rather than alter their approach to make best use of the digital tools (Ertmer & Ottenbreit-Leftwich, 2010; McGarr, 2009; Voogt & Pelgrum, 2005). Furthermore, even when teachers are keen to integrate innovative practices, more systemic issues such as large class sizes and short class periods tend to hamper the meaningful use of technology (Dede, 2010b; Voogt & Pelgrum, 2005).

2.3 Implications, barriers and recommendations

Traditionally, a behaviourist approach to mathematics education has been adopted in many classrooms, manifesting in didactic teaching methods with an emphasis on procedure over understanding, and rote learning of subject content over literacy (Albert & Kim, 2013; Ayinde, 2014). In such an environment, the mathematics is frequently presented without the context and connections that could lend it a level of coherency (Ayinde, 2014; Hoyles, 2016). This has been identified as impacting negatively on students' engagement with, and confidence in, the subject. Although several recent curriculum reforms in the United States and Europe aim to address these shortcomings (National Council of Teachers of Mathematics, 2008; NCCA, 2011; NGA Center & CCSSO, 2010), the traditional approach frequently remains what is actually implemented in classrooms (Contreras, 2014; Maaß & Artigue, 2013).

This review of the literature indicates that the use of digital technologies that align with a more constructivist, epistemic approach may have the capacity to address these issues, facilitating realistic, problem-solving and collaborative approaches to teaching and learning, and providing coherency and context for mathematics. In order to achieve this, it has been identified that technology usage should not be merely assimilated into traditional practice, but should be used in a meaningful, or *transformative*, manner (Laborde, 2001, 2002; Noss et al., 2009; Oates, 2011; Oldknow, 2009; Olive et al., 2010). That is, the use of technology should be emphasised primarily in situations that could not have been completed without it. However, some authors have identified a shortfall in theory relating to the integration of the inquiry-based approach and traditional instruction (Li & Ma, 2010; Maaß & Artigue, 2013; Noss et al., 2009).

Similarly, difficulties are highlighted in altering the role of the teacher from instructor to facilitator, indicating that such a role can be demanding and difficult to implement in a traditional classroom setting, and pointing to a need for a structured approach based on sound research (Donnelly et al., 2011; Fullan & Langworthy, 2014; Means, 2010; Noss et al., 2009; Voogt & Pelgrum, 2005). A number of authors have conducted meta-analyses of the integration of technologies in school environments, with a particular focus on identifying what does and does not work (Li & Ma, 2010; Means, 2010; Voogt & Pelgrum, 2005). Drawing on their work, it appears that the positive effects of technology on learning were strongest when combined with a constructivist, team-based, project-based pedagogic approach, and non-standardised assessment methods (Ertmer & Ottenbreit-Leftwich, 2010; Li & Ma, 2010; Voogt & Pelgrum, 2005). In addition, larger positive effects on learning are identified when the students did not have a one-to-one relationship with the technology (Means, 2010). Voogt and Pelgrum (2005) identify that in successful interventions the teachers act as facilitators to the students, providing structure and advice and keeping track of their progress.

Means (2010) points out that many teachers will only expend the effort required to integrate technology into their teaching practice when they can see that there are significant benefits in terms of learning outcomes. However, current forms of standardised, high-stakes testing and assessment prevalent in many countries, tend to focus on routine skills, and not on the kinds of problem-solving, creativity and decision-making skills that can be facilitated by the interactive, communicative and accessible nature of technology (Conole, 2008; Dede, 2010a; Fullan & Langworthy, 2014; Star et al., 2014). Until evidence is provided that the use of technology will be of benefit, and that the skills that can be developed through its use are valued in assessment, it will remain difficult to convince teachers to change their practice (Donnelly et al., 2011). In addition to the appropriate methods of teaching and learning, Donnelly et al. (2011) and Fullan and Langworthy (2014) suggest that for change to be successfully accomplished, teachers require resources, practical examples and support from colleagues and management.

If it is agreed that *good practice* in technology-enhanced mathematics education incorporates a structured approach to activities that are transformed by the use of digital tools, encouraging more exploration, inquiry and collaboration, in which the teacher acts as a facilitator of learning, then one might expect that this should be reflected in recent empirical research. This analysis aims to investigate the extent to which researchers are designing technology-enhanced learning activities that align with such practice. In order to do this, a system of classification has been developed; this is discussed in the following section.

3 Development of the Classification

This section of the paper will firstly discuss the development of a system of classification of technology interventions in mathematics education, and will then analyse the results of the classification applied to 139 research papers.

The objective of this research was to provide the scholarly community with a current synthesis of research in the area in order to facilitate the emergence of conjectures about the present situation, grounded in research. An initial baseline analysis of 25 papers was conducted in 2012 (Authors, 2013a), and subsequently, relevant papers were collected on an ongoing basis, in order to extend the reach of the analysis. This resulted in a cumulative total of 139 relevant papers. A timeline for the development of the classification system and analysis of the results is provided in Figure 1.

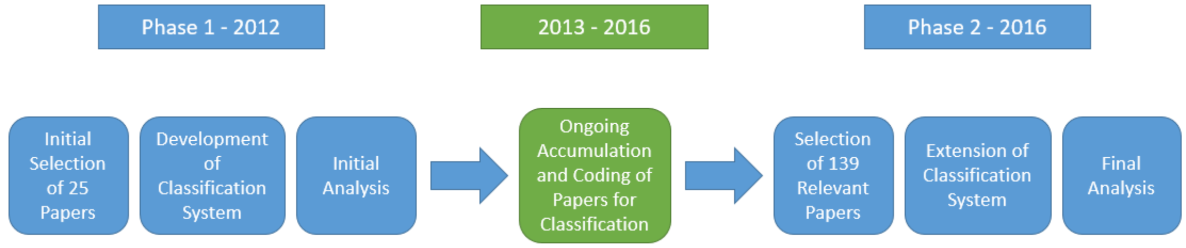

Figure 1: Timeline of the Development and Analysis of the Classification

A classification is an process through which ideas and objects are recognised, differentiated and understood (Cohen & Lefebvre, 2005). A system of classification should be dynamic and be able to keep pace with changes in the status quo; it should also permit generalisation, and provide a basis for the explanation of an emerging argument (Authors, 2013a). In this research, an ongoing, systematic review of recent literature in which technology interventions in mathematics education are described, provides the data for the classification. The electronic databases searched for the initial review of recent literature were chosen for their relevance to education, information technology and mathematics and include ERIC (Education Resources Information Center), Science

Direct, and Academic Search Complete. The results of this process resulted in the Phase 1 classification. Subsequently Google Scholar was also used, returning search results on an ongoing basis. The general search terms for all databases included the Boolean operators ‘AND’ and ‘OR’, and the wildcard (*) function, and were not restricted to abstract or title, in an attempt to retrieve all of the relevant research:

math* AND (technolog* OR tool*) AND education

The results were restricted to articles issued since the beginning of 2009, and full text availability was required.

A preliminary set of 25 papers made up the initial data set (Phase 1) (Authors, 2013a). An automatic Google Scholar alert using the above search terms facilitated an ongoing search process over the subsequent 4 years, with the retrieval of a large number of papers of possible interest (>2000). These were scanned manually on an ongoing basis and selected for classification if the title and abstract were relevant; that is, the papers were required to discuss empirical studies of the use of technology in post-primary or upper-primary mathematics education, papers that did not fit these criteria were disregarded.

In addition to the articles that emerged through the search facility, papers from the technology working groups at the Congress of European Research in Mathematics in 2013 and 2015 (CERME8 and CERME9) were analysed. This biennial, international conference facilitates a working group specifically for researchers with an interest in using technology for teaching and learning mathematics, thus providing a particularly relevant pool of work from which to draw. In addition, five papers published between 1997 and 2008 are also included owing to their particular relevance to the field (Kieran & Drijvers, 2006; Laborde, 2002; Noss, Healy, & Hoyles, 1997; Ruthven et al., 2008; Santos-Trigo & Cristóbal-Escalante, 2008).

In order to inform the development of the classification presented in this report, some existing systems of classification were examined. Although none of these provided a sufficiently comprehensive structure from the point of view of this research, three areas emerged as being of particular interest: technology, levels of adoption, and learning theories. The first phase of the classification was developed from these systems. However the final classification system has been subject to an iterative process of review and refinement throughout the duration of the research, based on emerging areas of interest (Phase 2). These are discussed in detail in the following sections.

3.1 Background to the Classification

This aim of this research is to provide an overview of recent empirical research relating to technology usage in mathematics education. The types of technology, the ways in which it is used in an intervention, and the approach, or learning theory adopted, are all seen as particularly relevant. Other domains, such as teachers’ beliefs and (technology) pedagogy, and content knowledge (TPACK) (Hill, Ball, & Schilling, 2008; Koehler & Mishra, 2009; Koehler, Mishra, & Cain, 2013; Shulman, 1986), while recognised as being important and undeniably having an impact in practice, were frequently not discernible in the reviewed studies.

3.1.1 Existing Classifications of Technology

Two classifications of technology for mathematics education by Hoyles and Noss have been particularly influential in this research. The first (Hoyles & Noss, 2003), differentiates between programming tools and expressive tools. *Programming tools*, such as the microworlds *Mathsticks* and *SimCalc* (Roschelle, Kaput, & Stroup, 2000), are defined as providing novel ways of modelling and representing mathematics. *Expressive tools* on the other hand, provide easy access to the results of algorithms and procedures, without the user being required to understand the intricacies of their calculation. The category of expressive tools is further broken down into *pedagogic tools*, designed specifically for the exploration of a mathematical domain, and *calculational instruments*, which are frequently adapted to, rather than designed for, pedagogic purposes. Dynamic Geometry Environments (DGE) such as GeoGebra, are examples of pedagogic tools, and spreadsheet programs would fall into the category of calculational instruments.

In later research, Hoyles and Noss (2009) classify tools according to how their usage shapes mathematical meanings. They refine and extend their previous framework differentiating between: DGEs; tools that outsource processing power, of which computer algebra systems (CAS) are an example; and tools that increase connectivity, such as knowledge fora.[1]

3.1.2 Classifications of Technology Adoption

There are a number of theories that describe technology adoption at an organisational or societal level, such as the Hype Cycle (Lowendahl, 2010) and Roger's Innovation Adoption Lifecycle (Rogers, 1962). Two perspectives were identified that categorise technology adoption within specific educational interventions: the FUIRE model (Hooper & Rieber, 1995) and the SAMR hierarchy (Puentedura, 2006). While the FUIRE model provides a lens through which to examine an individual's use of technology and their level of adoption of it in the classroom, the SAMR model is particularly suited to describing the level of technology adoption associated with a specific task or activity. As this research is attempting to classify the interventions, the SAMR model is most appropriate. The significant overlap between the SAMR model and the four-level model specific to Dynamic Geometry Environments presented by Laborde (2001, 2002) and described below, make it particularly suited to this work.

The SAMR hierarchy (Figure 2) can be divided into the two broad categories of Enhancement and Transformation, each of which has two further subsections. *Substitution* describes situations in which the technology is used as a direct substitute for the traditional method, without functional or conceptual change, such as measuring and drawing using a graphics program. In the *Augmentation* level, the technology is used as a substitute for an existing tool, but with

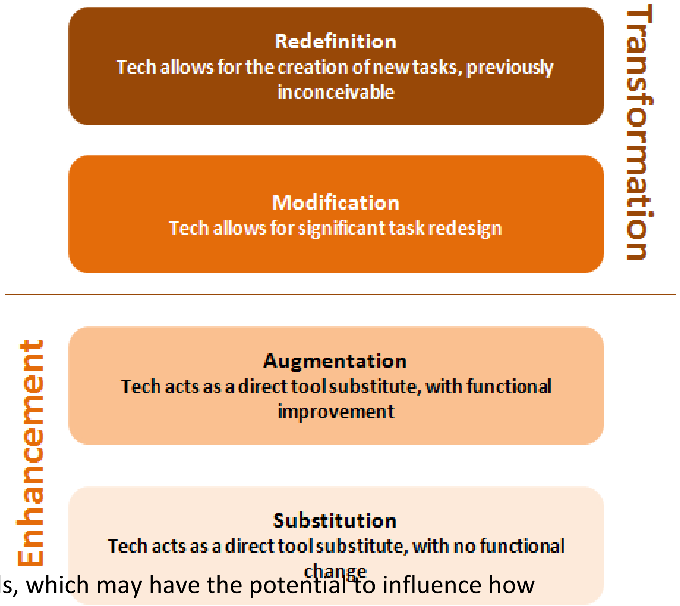

Figure 2: The SAMR Hierarchy

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[1] Hoyles and Noss also refer to new semiotic tools, which may have the potential to influence how mathematics is represented, in their classification. However, there has been no evidence thus far in the papers reviewed, of semiotic tools that change the representa not represented in the system of classification.

some functional improvement regarding facilitation of the task, e.g. accessing content online with links to practice exercises. The augmentation level can also be seen as aligning with the usage of technology for more pragmatic purposes (Artigue, 2002), such as increasing calculational accuracy and efficiency.

The Transformation levels on the SAMR hierarchy describes interventions, activities or tasks that are significantly changed through the use of the technology (modification), or that use the potential of the technology to design new tasks that would previously have been inconceivable (redefinition). In terms of mathematics, descriptions of tasks that can be mapped onto the two *transformative* levels of the SAMR hierarchy have been described by Laborde (2002) as:

1. Tasks in which the technology facilitates significant task redesign, or modifies the solving strategies of the user. For example, Granberg and Olsson (2015) discuss students' use of GeoGebra [2]to construct a system of linear equations according to given specifications (make a square), and then to manipulate the formulae in order to achieve certain conditions. (SAMR level - Modification)
2. Tasks that could not be posed without the use of the technology. These can be tasks in which the technology permits the use of strategies that would not be possible using non-technological tools, or tasks that could only be carried out in a specific environment. This could involve the use of video analysis software, such as Tracker[3], to generate and analyse functions and graphs representing authentic video footage taken by the participants (Authors, 2013b) (SAMR level - Redefinition)

3.1.3 Classification of Learning Theory

The learning theories considered in this classification fall into the two main categories of Behaviourism (Skinner, 1938) and Cognitivism (Bruner, 1977). Some cognitive learning activities can be further classified as Constructivist (Kolb, 1984; Piaget, 1955), and within this, as Constructionist (Papert, 1980), and Social Constructivist (Vygotsky, 1978) (Figure 3). Each of these theories will now be examined in more detail.

Behaviourist theory holds that learning is manifested by a change in behaviour; the environment shapes behaviour; and events must occur in quick succession, and be reinforced in order for a bond to be formed. Thus, learning is the acquisition of new behaviour through (classical or operant) conditioning.

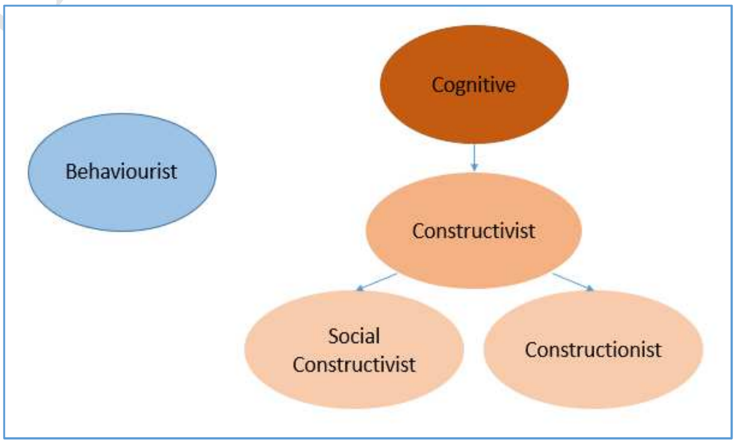

Figure 3: Learning Theories

In *cognitive* learning theories, learning is viewed as a combination of internal mental processes consisting of insight, information processing, memory and perception. From a cognitive perspective

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[2] https://www.geogebra.org/
[3] http://physlets.org/tracker/

therefore, education should focus on building intelligence and on cognitive and metacognitive development in such a way that the learner will develop capacity and skills to improve learning.

Constructivism falls within the cognitive domain, and is founded in the belief that knowledge is constructed rather than transmitted (DiSessa, 1983; Piaget, 1955). In constructivist learning environments “the problem drives the learning, rather than acting as an example of concepts and principles previously taught” (Jonassen, 1999, p. 218). Social constructivism adds another layer to this, and has its foundations in social learning theory (Bandura, 1977; Vygotsky, 1978), which stems from the perspective that people learn within a given context and that the effects of culture and interactions with people play a significant role in how we learn. In particular, Vygotsky believed that the potential to learn is greatly enhanced through interaction with a ‘more able other’, and where learners are challenged close to, but slightly above, their current level of ability.

The theory of *constructionism* has its foundations in the work of Papert (Papert, 1980; Papert & Harel, 1991). His thesis is that learning can happen most “felicitously” when people are actively engaged in the creation of tangible, public objects (Papert & Harel, 1991). Constructionism involves experiential, problem-based learning and builds on the theory of constructivism. Learning is viewed as a construction, as opposed to a transmission, of knowledge, and is most effective when the activity involves the creation of a meaningful product or artefact - "learning by making".

3.2 Process of Classification

The process of classifying the papers was facilitated by the qualitative analysis software NVivo10[4]. Initial coding of the first 25 papers (Phase 1) was directed by the following categories, which were drawn from the classifications described in the previous section:

1. Technology: DGE, Outsourcing, Collaborative by design, Programming tools.
2. SAMR hierarchy: Substitution, Augmentation, Modification, Redefinition.
3. Learning Theory: Behaviourist, Cognitive, Constructivist, Social Constructivist, Constructionist

Throughout the second phase of analysis however, it emerged that the initial classification was insufficient, and a number of changes and extensions were required. The methodology underpinning the development of the classification process thus initially followed a directed coding technique (Phase 1) (Hsieh & Shannon, 2005; Krippendorff, 2004; Namey, Guest, Thairu, & Johnson, 2007), with a subsequent emic approach, not based on a-priori theoretical distinctions (Yin, 2014) used to identify emerging themes (Phase 2). As is demonstrated by this process, the system of classification is emergent and would be expected to be expanded and refined on an ongoing basis, in order to maintain relevance to developments in the field.

3.2.1 Emerging Classification of Technology

In the second phase of this study, the amalgamated classifications by Hoyles and Noss (Hoyles & Noss, 2003, 2009) were further refined and developed to provide the foundation for the technological component of the emerging classification. Through the ongoing review of the papers a number of extensions to the Hoyles and Noss classification were required. The category of *toolkit* has been added as a distinct class. Integral to the definition of the toolkit category is the design of

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[4] http://www.qsrinternational.com/nvivo-product

technologies in accordance with a specific pedagogical approach, along with the provision of support for the student and the teacher through tasks and lesson plans, and feedback for assessment, all founded in the relevant didactic theory. The category of Multiple Linked Representations (MLR) describes tools that integrate diverse representations of single mathematical entities. MLR would be used to describe, for example, a tool that integrates the capacity of a Dynamic Geometry Environment (DGE) and Computer Algebra System (CAS) in a single, dynamically linked system. A number of the interventions originally classified as belonging to the category "Outsourcing", relate to outsourcing the delivery of content to the technology. Therefore, the Outsourcing category was split into 'Outsourcing – Computational' and 'Outsourcing – Content'. The resulting technological aspect of the classification is thus as follows:

- Collaborative by Design
- Dynamic Geometry Environments (DGE)
- Multiple Linked Representations (MLR)
- Outsourcing – Computational
- Outsourcing – Content
- Programming Tools
- Toolkit

3.2.2 Emerging Classifications of Technology Adoption

The papers reviewed for this classification did not discuss the usage of technology at the level of Substitution on the SAMR hierarchy. There are a variety of possible reasons for this, the most likely being that although technology is being widely used in a substitutive manner, this kind of usage is not being researched or reported in the literature. Therefore, only three levels of the SAMR hierarchy appear in the analysis of the results of the classification. Some of the papers compared a number of interventions, and as such were classified at more than one level on the SAMR hierarchy:

- Augmentation
- Modification
- Redefinition

3.2.3 Classification of Purpose

An additional layer to the classification was also identified in the phase 2 analysis, which categorises the primary purpose, or aim, of the interventions. The method of identification of the elements of this category was emergent, and arose throughout the process of classification. The aims identified are as follows:

- Change in Attitude
- Improved Performance
- Development of Conceptual Understanding
- Skills-focused
- Support Teachers
- Collaboration and Discussion

The requirement to occasionally code interventions as having more than one aim may indicate that some of these goals are inextricably linked. Although it was not always explicit, it is likely that many of the interventions had more than one underlying purpose. The majority of the categories in this section of the classification are self-explanatory, however the ‘Change in attitude’ encompasses issues around student motivation, self-efficacy and engagement (Hampton, 2014; Kebritchi, Hirumi, & Bai, 2010; Topcu, 2011), and ‘Skills-focused’ relates to the generation of metacognitive skills such as collaborative, problem-solving, and creative skills amongst others. Improved Performance was generally ascertained through pre/post-tests.

3.2.4 Phase 2 Classification

A systematic review methodology (Kitchenham & Charters, 2007) was employed to classify each intervention in the 139 (phase 1 and phase 2) reviewed papers according to the technology used, the learning theory underpinning the intervention, the level of integration of technology and the overarching aim of the tasks. A number of the classified papers considered more than one intervention, had multiple goals, or used various technologies and have thus been classified at more than one of the elements of a single class. Therefore, although the total number of papers analysed to date in this classification is 139, the number of interventions in the analysis add up to 152. The components that make up the system of classification used for the phase 2 analysis of papers are outlined in Figure 4.

Technology	Learning Theory	SAMR Level	Purpose
Collaborative by Design	Behaviourist	Augmentation	Change in Attitude
Dynamic Geometry Environment	Cognitive	Modification	Improve Performance
Multiple Linked Representations	Constructivist	Redefinition	Improve Conceptual Understanding
Outsourcing – Computation	Social Constructivist		Skills-focused
Outsourcing – Content	Constructionist		Support Teachers
Programming Tools			Collaboration and Discussion
Toolkit			

Figure 4: Components of the Classification

3.3 Examples of Classified Interventions

The results from the analysis of the first phase of the classification of papers is published in Authors (2013a). The scope of that research has been significantly extended and to date interventions in 139 papers have been classified according to the lenses of technology, learning theory, level of technology adoption, and aim.

In order to illustrate the process of coding the papers for the classification, three of the interventions that have been examined and classified are presented in detail in this section. Each sample intervention is representative of one of the three upper levels on the SAMR hierarchy: *Augmentation*, *Modification*, and *Redefinition*. A rationale for the classification of each of the examples, according to each of the categories of technology, learning theory, level of adoption and aim, is provided.

3.3.1 Augmentation

The paper chosen as representative of the category of *augmentation*, by Hampton (2014), examines why some students choose to view online instructional videos, and investigates differences in the levels of motivation and self-efficacy between those who do and do not view such material. One hundred and eighteen high-school students from a small suburban school in Georgia participated in Hampton's study, each of whom completed a 44-item survey primarily made up of Likert-type questions. Table 1 provides a rationale for the designation of this paper at each section of the classification.

Table 1: Augmentation

	Classification	**Rationale**
Technology	Outsourcing – Content	The role traditionally associated with the teacher to deliver content has been outsourced to the technology.
Learning Theory	Cognitive	In general, the use of online tutorial material reflects a view of learning as an internal mental process including insight, information processing, memory and perception.
SAMR Level	Augmentation	The technology acts as a substitute for the teacher, with the added potential for 'anytime, anywhere' learning, and the ability to pause and rewind.
Purpose	Change in Attitude	The primary purpose of this research is to investigate the levels of motivation and self-efficacy associated with the use of the technology in question.

3.3.2 Modification

Granberg and Olsson's (2015) reflection on the impact that using GeoGebra may have on students' collaboration and creative reasoning is selected as representative of the category of *modification*. In this paper, the authors examine how eighteen pairs of 16 and 17 year old students attempt to solve linear functions in a dynamic geometry environment. Recorded conversations and computer activities constitute the data for the study, which were analysed using established frameworks for creative reasoning (Lithner, 2008) and collaboration (Roschelle & Teasley, 1994).

Table 2: Modification

	Classification	**Rationale**
Technology	DGE	The dynamic geometry environment GeoGebra is utilised.
Learning Theory	Social Constructivist	Students work in pairs in order to solve tasks. In this way, their learning is constructed in a social environment, through collaboration with their peers.
SAMR Level	Modification	The technology facilitates new approaches to the solution of the problem, through the dynamic aspects of the software. In addition, the distribution of the process of problem-solving amongst the participants (each student can manipulate and interact with the technology), is beneficial for collaboration.
Purpose	Skills-focused	The main aim of the tasks described is to increase collaboration and mathematical creativity.

3.3.3 Redefinition

Only 18 of the 152 classified interventions from the 139 papers are categorised as using the technology to facilitate activities that would not have been conceivable without the digital tools –

i.e., *redefinition* on the SAMR hierarchy. One example (Table 3) is provided in the research of Kynigos and Moustaki (2013), who discuss how students' meaning-making processes are shaped by online and face-to-face collaboration, as they try to make sense of mathematical problems in a what the authors term a 'half-baked' microworld. This is an environment that is, by design, incomplete. The students must deconstruct the mathematical problems in order to make sense of the behaviour of the environment. Particular emphasis is placed on how the students' mathematical activity is shaped by their need to explicitly articulate their own ideas in order to share them online, and by the ideas that others bring to the discussion. This study explored the experiences of four 15 year old students in a secondary school in Athens, Greece.

Table 3: Redefinition

	Classification	**Rationale**
Technology	Toolkit	A variety of technologies are used together, in accordance with a specific pedagogic approach, along with the provision of support for the student and the teacher. In this case, Exploratory Learning Environments are combined with Computer Supported Collaborative Tools in one web platform.
Learning Theory	Social Constructivist and Constructionist	The students use a computer-supported collaborative learning environment to communicate. They collaboratively construct artefacts using the "3d Math" Authoring Tool, a constructionist environment (http://etl.ppp.uoa.gr/malt).
SAMR Level	Redefinition	Both the online communication and the exploratory, 3-dimensional mathematical tasks presented would not have been possible without the use of the technology.
Purpose	Increased Conceptual Understanding	There is particular focus on the impact that the collaborative technology, in conjunction with the specific tasks, have on the students' meaning making processes.

4 Analysis of the Results of the Classification

A systematic review is a process of identification, selection and synthesis of primary research studies, with the intention of providing a comprehensive and trustworthy picture of the field of interest (Oakley, 2012). The classification described in this paper provides the framework for a systematic review of empirical studies of technology-enhanced mathematics interventions, permitting a relatively unbiased synthesis and interpretation of the findings..

Due to space restrictions, it is not possible to include a full list of the 139 classified papers in this article; however, they are available to be viewed here[5]. Our intention is to develop this list as an open-source resource that can be added to and developed by stakeholders in the field of technology-enhanced mathematics education. Evidently, as this a review of published papers, the research that has been classified is decreasingly contemporary. Our hope in developing this online resource is that the classification and systematic review will be adaptive to modern trends such as technological developments in the fields of Virtual and Augmented Reality, the use of Serious

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[5] https://docs.google.com/spreadsheets/d/17K2vWBzXY6lg3xNRbXEd9_qGcqwlzM5kMon-dtxPOvQ/edit?usp=sharing

Games, and developments in learning theory such as Embodied Cognition. Consequently, this review has the potential to remain current, and is capable of being updated as new studies are done (Oakley, 2012). In this way an evolving picture of the research landscape will be freely available.

An overview of the sources and years of publication is provided in Figure 5. In this chart, the column entitled “Other Journals” refers to 35 journals that were only referenced once, which include ZDM, BJET and Technology, Pedagogy and Education.

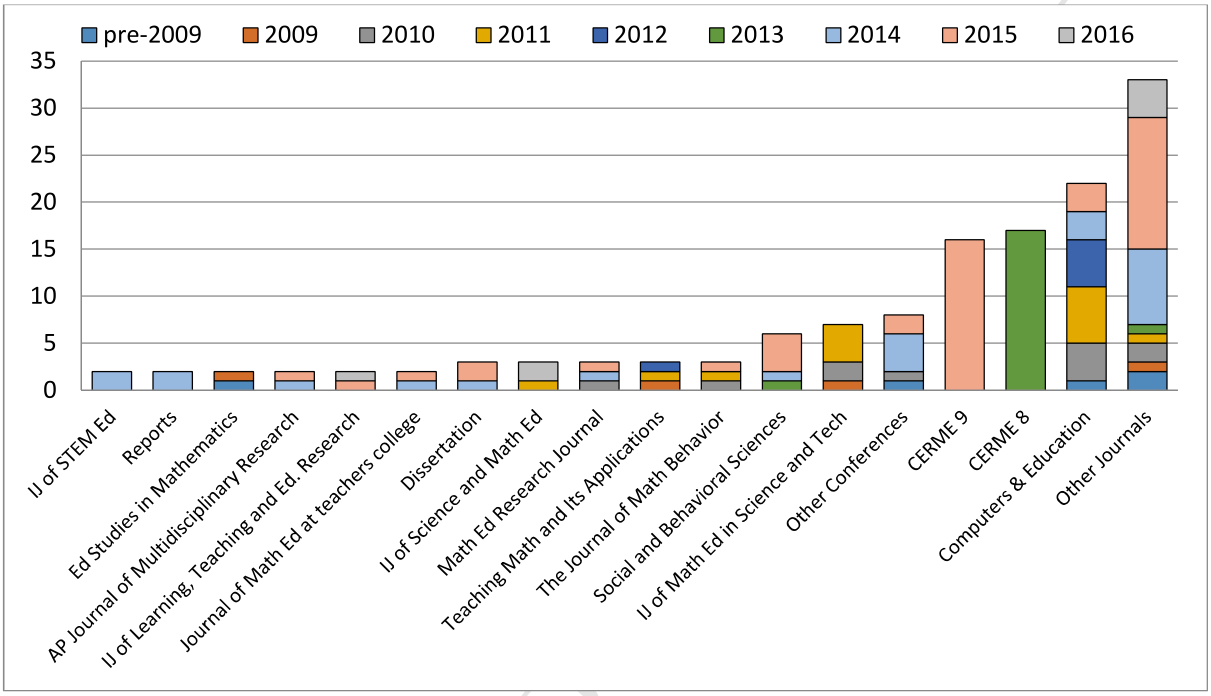

Figure 5: Overview of the sources and years of publication

The process of classification of the 139 papers according to the categories of technology, learning theory, SAMR level and purpose, was expedited by the use of the qualitative analysis software NVivo10. This tool facilitated further analysis and visualisation of the data through a process of matrix coding, which permitted a summative overview of the number of interventions that had been cross-coded at the different elements of the classification. This process allowed exploration and comparison of the interventions through a variety of lenses. The following discussion examines the comparisons of Learning Theory and SAMR (Figure 6), Technology and Learning Theory (Figure 7), Technology and SAMR (Figure 8), Aim and Technology (Figure 9), Aim and Learning Theory (Figure 10), and Aim and SAMR (Figure 11).

4.1 Learning Theory and SAMR

Through this process, a number of interesting patterns have emerged. Figure 6 illustrates the clear constructivist (37%) and social constructivist (34%) trend in the literature, possibly supporting the perception that technology has the potential to realise some of the student-centred, constructivist and collaborative pedagogies proposed by innovative educators since the 1960s (Martin & Grudziecki, 2006; Voogt & Pelgrum, 2005).

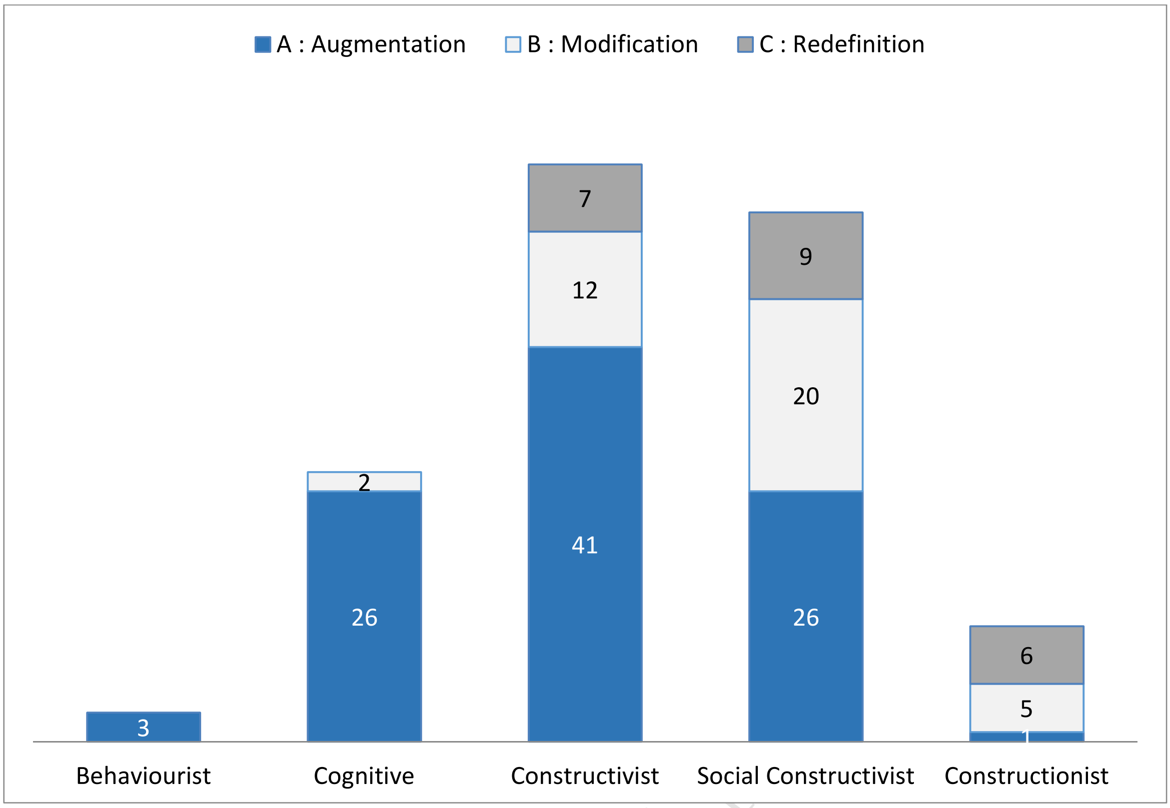

Figure 6: Learning Theory v SAMR

Figure 6 also illustrates the spread of the levels of technology adoption. The majority of interventions (61%) were classified as Augmentation; this means that the technology was used as a direct substitute for traditional approaches, with some functional or conceptual improvement; for example, an increased ability to explore and analyse. Although several researchers have argued that it is preferable to utilise technology in tasks that are transformed by its application – that is, that fit into the two higher levels on the SAMR hierarchy (Noss et al., 2009; Oates, 2011; Olive et al., 2010) – only 39% of the interventions have been classified in this way, with only 14% classified at Redefinition. If these transformative uses of technology are indeed preferable, this analysis serves to bolster claims that although use of technology in the classroom is increasing, its implementation in the mathematics classroom, and indeed in related research, still lags behind its perceived potential to enhance the learning experience (Authors, 2015; Dede, 2010a; Hoyles, 2016; Hoyles & Lagrange, 2010; Psycharis et al., 2013). Despite the small numbers, the high proportion of constructionist tasks classified at Redefinition may highlight a possible synergy, indicating that if technology is being used in a constructionist environment, it is likely to be facilitating tasks that would not be possible without its use.

4.2 Learning Theory and Technology

The predominant classification of interventions in the cognitive domain as being at the level of Augmentation (figure 6) reflects the increasing number of interventions that are using technology to outsource content. This claim is supported by the data in figure 7, which compares technology and learning theories.

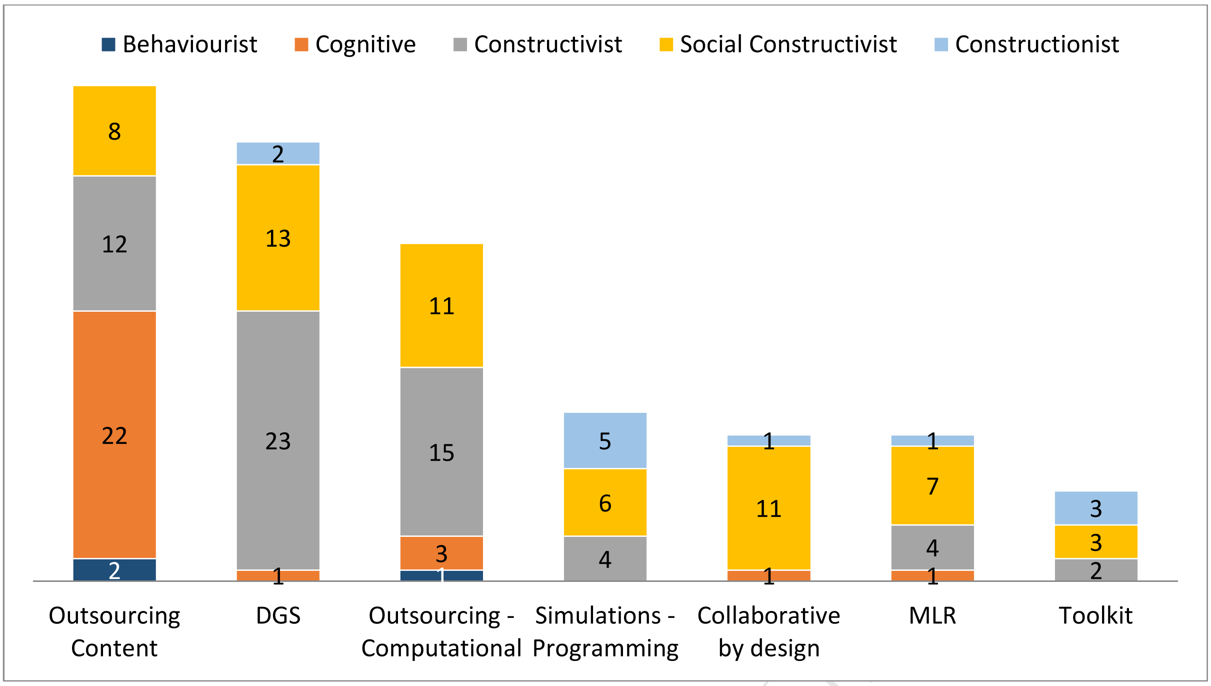

Figure 7: Technology v Learning Theory

In this illustration of the data, it is evident that using technology to outsource the delivery of content is of interest to the research community, making up 27% of the total number of classified interventions. 24% of the total interventions made use of Dynamic Graphical Environments and 19% used technology that outsourced the computation. Unsurprisingly, a social constructivist approach aligns particularly well with technology that is collaborative by design.

Very few of the papers discussed interventions in which the technology had a drill and practice facility, and those that did, primarily couch it within a cognitive approach to learning. However, three papers discuss interventions that have been classified as Behaviourist. These include two that relate specifically to drill and practice techniques, and one that discusses a game-based learning approach to mathematics education, in which students have successful outcomes if they achieve quick fire answers to arithmetic problems (operant conditioning) (Ku, Chen, Wu, Lao, & Chan, 2014).

4.3 Technology and SAMR

The crossover between the technologies and the SAMR hierarchy is shown in Figure 8. This graph illustrates the notably high correlation between the uses of technology to outsource the delivery of content and the SAMR level of Augmentation. This could be interpreted as suggesting that technology used in this way has not, to date, had a major influence on task design. Only one of the interventions classified as outsourcing content discussed the potential for diversifying activities in the classroom owing to the fact that the bulk of the required content had already been covered (Eisenhut & Taylor, 2015).

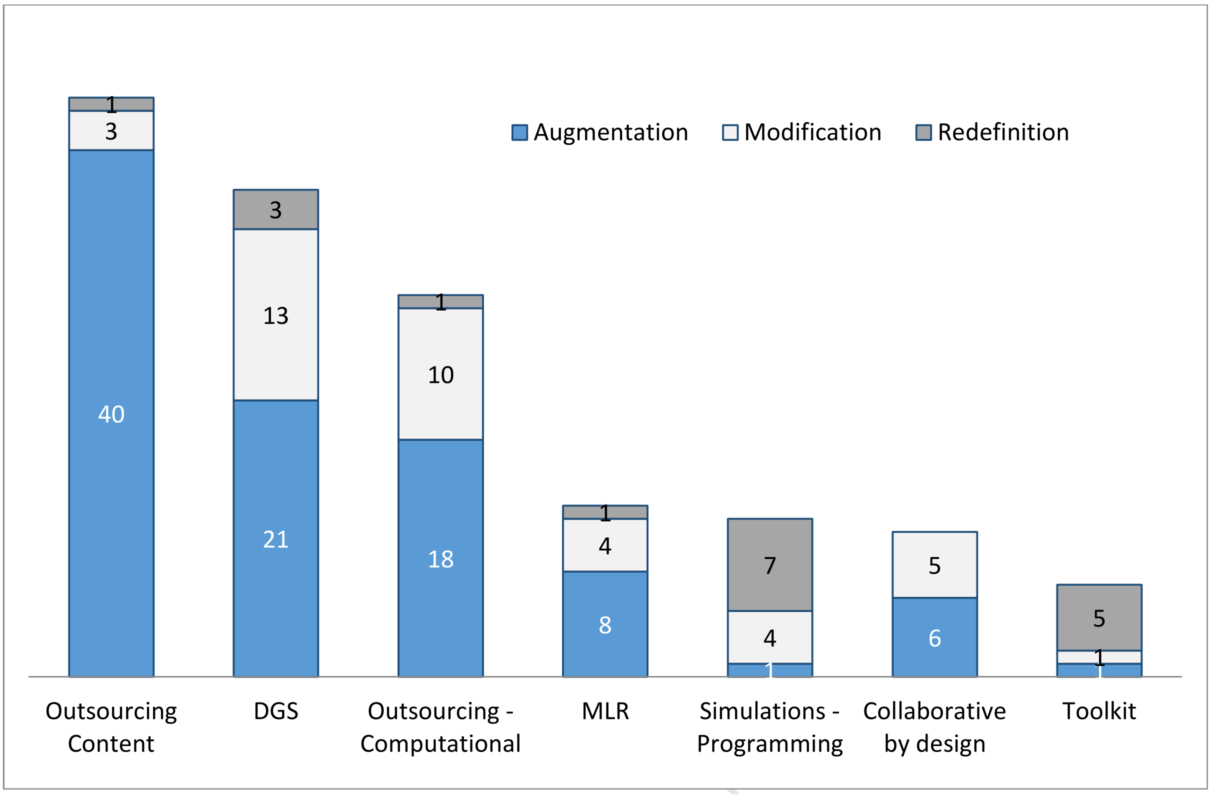

Figure 8: Technology v SAMR

The majority of papers classified as Outsourcing-Computational, were also categorised at the level of Augmentation. This is possibly owing to the fact that a common function of computer algebra systems and graphics calculators are to increase speed and accuracy and, to a lesser extent, to facilitate exploration (Burrill et al., 2002) – that is, it is most commonly used to augment traditional practice . Similarly, it appears that the usage of DGEs and MLRs is still concentrated on the Augmentation space. Moving focus to the Simulations-Programming and Toolkit categories, it is possible to identify a shift in the way the technology is being used into the more transformative arena.

4.4 Aims of Interventions

The aspect of the classification that was added in the second phase of the development and analysis of the classification (Figure 1), relates to the aim, or purpose of the various interventions. Three graphs have been generated to illustrate the crossover between Purpose and Technology (Figure 9), Purpose and Learning Theory (Figure 10), and Purpose and SAMR hierarchy (Figure 11).

The main result of analysis of the first of these comparisons relating Purpose and Technology (Figure 9) is that a diverse assortment of technologies are being employed in an attempt to achieve various aims. The most common goal of the interventions, at 36%, was to improve students' Conceptual Understanding, with Improved Performance constituting the primary aim of 31% of the interventions, and a Change in Attitude, 19%. It is important to recognise however, that a number of these goals can be seen as being linked, and a number of the interventions reported having more than one goal.

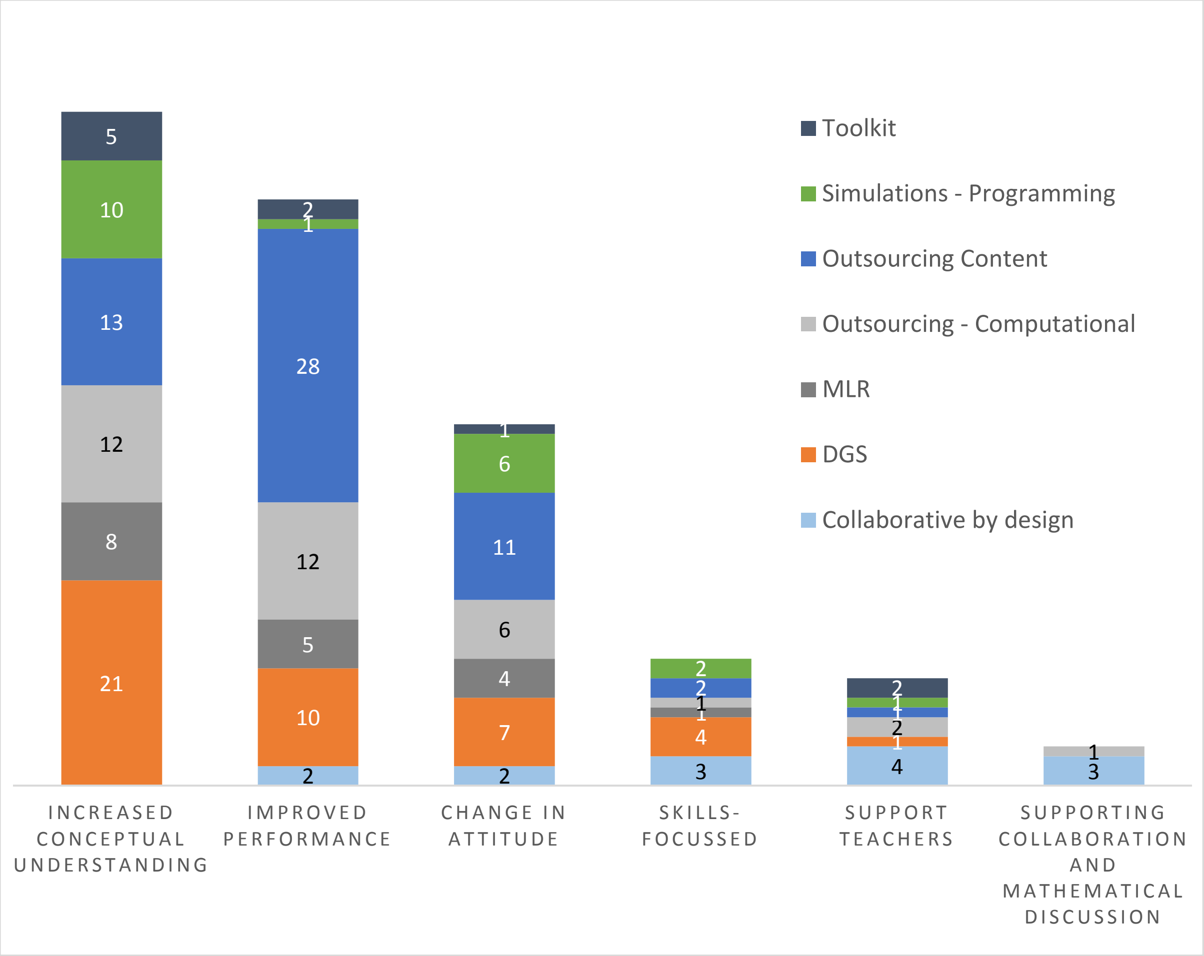

Figure 9: Aim v Technology

The comparison of Aim and Learning Theory in Figure 10 indicates that, with a couple of exceptions, there is a relatively even spread of constructivism and social constructivism amongst the aims. The clustering of interventions that employed a cognitive learning theory among the more common goals could be representative of the fact that a skills-focused intervention, one that supports collaboration, or one that is supportive of teachers, is unlikely to fall within the purely cognitive learning domain. A constructionist learning environment appears to be mostly associated with the goal of increased conceptual understanding, although proportionally, constructionism is more dominant in skills-focused interventions and those that support collaboration and discussion.

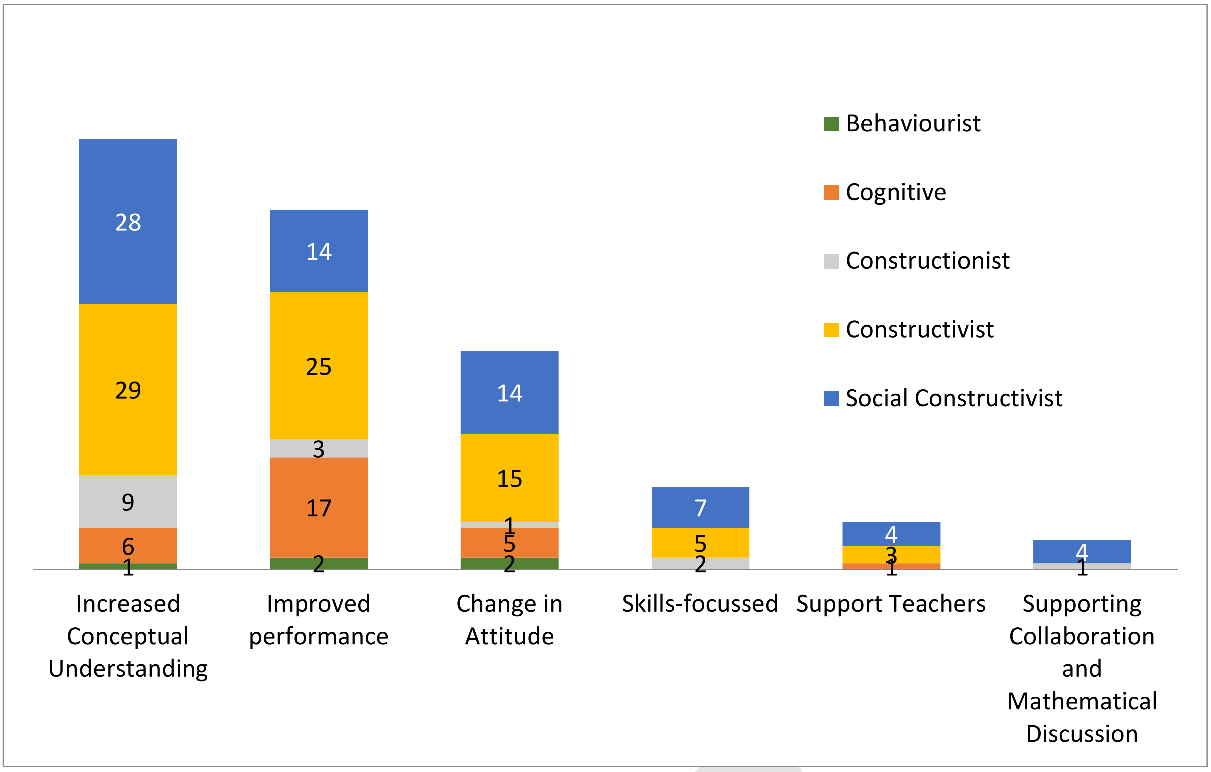

Figure 10: Aim v Learning Theory

An illustration of Aim compared with the SAMR hierarchy is provided in Figure 11. Using technology at the level of augmentation dominates in most of the interventions, but makes up a particularly high proportion of those that aim to improve performance. Interventions that aim to improve conceptual understanding or those that are skills-focused show a higher proportion of technology being utilised in a more transformative manner.

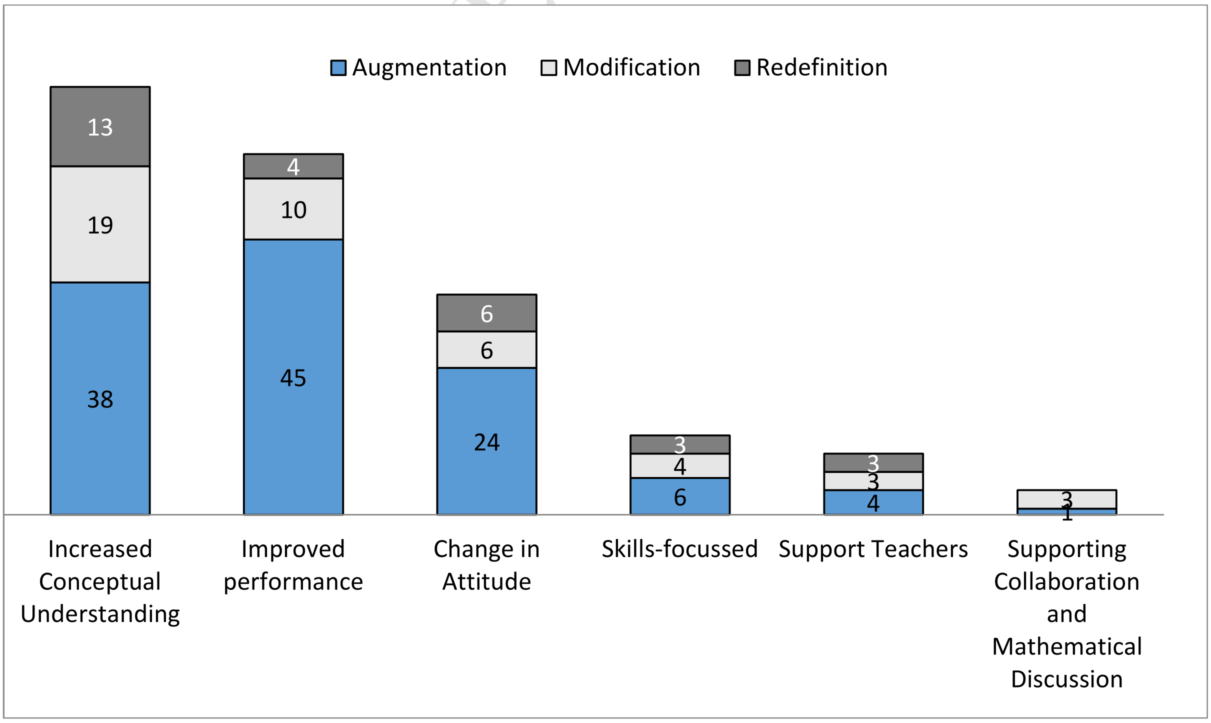

Figure 11: Aim v SAMR

4.5 Limitations of the Classification

"Systems of classification are not hatracks, objectively presented to us by nature" (Gould, 1987). The process of classification is not always clear-cut and it is important to bear in mind a number of points when considering the analysis presented herein. Firstly, this classification is based on the perspective of a single researcher. In certain instances, classification of a given intervention was not straightforward and a level of personal judgement was required. In order to be rigorous, the analysis would benefit from a coding comparison from the perspective of a second researcher – that is however, outside the scope of this research owing to the volume of papers and the time required for analysis.

In addition, the selection process for the papers was based on the results of an electronic search of published research, and was limited to full-text availability. Evidently, a number of suitable papers, as well as funded studies, will have been excluded from the results for this reason. However, it is hoped that the number of full text results is sufficient to provide a reasonable picture of the recent research landscape.

5 Discussion

The initial intention in carrying out a classification of the literature was to develop an empirical understanding of the status quo along with an up-to-date synthesis of the general characteristics of technology-enhanced interventions in mathematics education. Although this classification does not purport to give a definitive picture of what is going on generally in classrooms (which is likely to be quite different to what is going on in the academic research interventions), it does provide quite a clear indication of research trends. It is evident from the classification, that a wide variety of types of technologies are being researched in different environments, with different agendas and from varying theoretical standpoints. The predominance of Constructivist and Social Constructivist tasks may be indicative of a realisation of the potential for technology to support inquiry-based, student-centred and collaborative approaches to mathematics education (Martin & Grudziecki, 2006; Voogt & Pelgrum, 2005).

Although none of the classified research discusses uses of technology at the SAMR level of substitution, there is evidence that digital tools are frequently utilised in this manner in classrooms (Ottenbreit-Leftwich et al., 2012; Thinyane, 2010), for example, in an Irish study, basic technologies, such as the internet and PowerPoint, are reported as being the technologies of choice among teachers (Egan, FitzGibbon, & Oldham, 2013). At the research level, it appears that the majority – over 60% – of technological interventions in mathematics are using digital tools to augment traditional practice. This majority usage of technology at the lower levels of the SAMR hierarchy can be considered as corroboration of claims that although innovative practices undoubtedly exist within and outside the field of research, the perceived potential of technology to improve the learning experience is not generally being promoted in classrooms (Hoyles, 2016; Hoyles & Lagrange, 2010; Pimm & Johnston-Wilder, 2005; Psycharis et al., 2013). In fact, a further conjecture can be made, that even within the relevant field of research, the potential of the technology to "transform" the learning experience of students, is not being harnessed. Predominantly, technology is not being used in tasks that are transformed by its application – that is, tasks that fit into the two higher levels of the SAMR hierarchy – but rather in tasks that could have been completed without its use.

Technology that was used for “Outsourcing - Content” was one of the more commonly researched areas. Once again, the tasks that were most cross-referenced with this class of technology fell within the level of Augmentation. Looking at the technology usage across the years (Figure 12), it is clear that the outsourcing of content delivery in this way is of increasing interest to the research community.

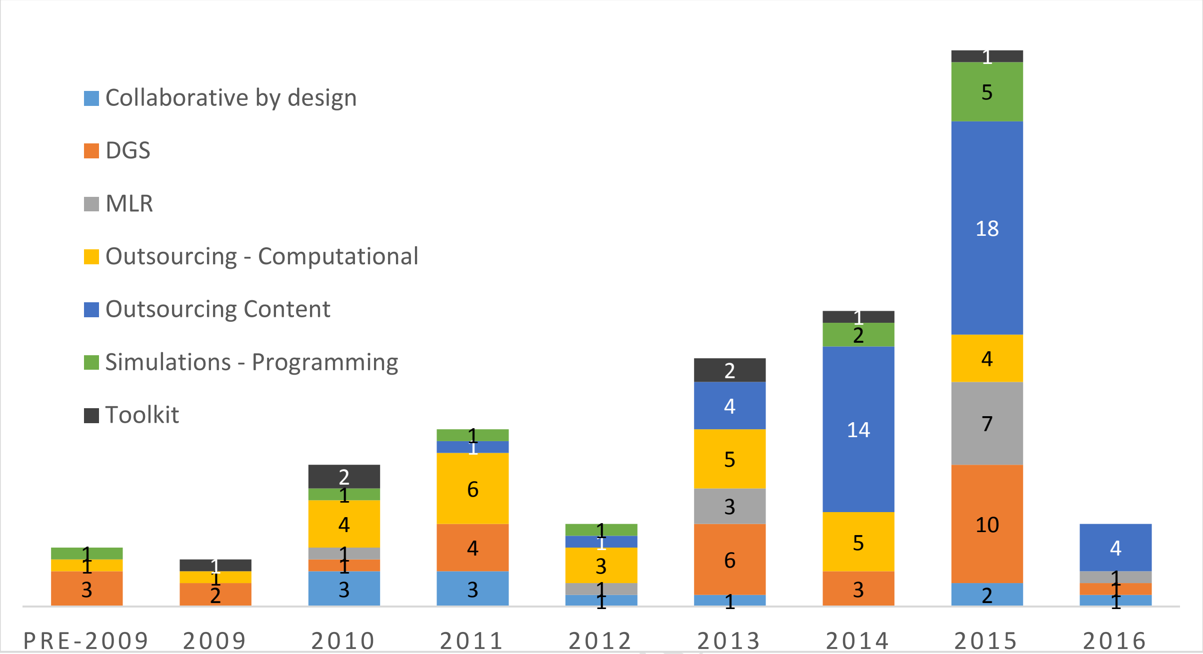

Figure 12: Technologies through the years

Used in conjunction with innovative approaches to task design, it is easy to see how the use of technology in this manner could be very meaningful and positive. However, in these interventions, significant transformation of the in-class tasks, as a result of outsourcing the content, was not generally discussed.

Some of the high level barriers to the integration of ICT and associated 21st Century practices in education relate to systemic issues around curriculum and assessment (Euler & Maaß, 2011; Fullan & Langworthy, 2014; Voogt & Roblin, 2012). In this study, a significant proportion (76%) of interventions classified as having “improved performance” as their primary aim, were also classified at the SAMR level of augmentation. 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. In order to radically change the dominant pattern of augmentative technology usage in classrooms, it is likely that a change in focus away from the prevalent high-stakes assessment and associated curriculum pressures will be required (Dede, 2010a; Fullan & Langworthy, 2014; Schoenfeld, 1992).

The papers classified in this research predominantly report positive outcomes, although a few comparative papers did not achieve a significant difference between control and experimental groups and a number of drawbacks to the use of technology were recorded (Borba, Azevedo, & Barreto, 2015; Kebritchi et al., 2010; Triantagyllou & Timcenko, 2015). However, very few of the papers reported on longitudinal studies (one exception to this is the Migen project reported on by Noss et al. (2009), Noss et al. (2012), and Geraniou and Mavrikis (2015)) or incorporated dissemination plans into the research. Thus, it is possible to conclude that although they were successful in the short-term, they may fall into the practice-research gap identified by Boaler (2008), Maaß and Artigue (2013), and Pimm and Johnston-Wilder (2005). Teachers are most likely to be influenced by other teachers and they look for pragmatic examples of activities and tasks that are possible with their own resources. For this reason, many of the innovative uses of technology that are described in research projects are likely to remain at the periphery of general use and do not transition into mainstream classrooms (Lameras & Moumoutzis, 2015; Authors, 2013c).

6 Conclusion

In order to generate an informed idea of trends in technology-enhanced mathematics education research, a review of recent interventions was carried out. A systematic analysis of relevant studies was conducted through the lens of a classification system developed specifically for this purpose.

Through the background literature review, this research identified aspects of what may be considered *good practice* in technology-enhanced mathematics education. These incorporate a structured approach to activities that are transformed by the use of digital tools, encouraging exploration, inquiry and collaboration, in which the teacher acts as a facilitator of learning.

Some of the classified research does address issues around the role of the teacher, creating a shift in empowerment from the external authority of the teacher, to the students as “generators of mathematical knowledge and practices” (Drijvers et al., 2010). The technology is used to “motivate students to take on, more and more, the responsibility of mediator in their own mathematics learning” (Buteau & Muller, 2006, p. 77). Tools are also being used to give students new ways to visualise concepts and approach problems in a dynamic way; authentic contexts and realistic data can be used without becoming overbearingly complex. The classification also reveals a clear trend towards Constructivist and Social Constructivist tasks, supporting collaborative, problem-solving and inquiry-based approaches.

However, this review also reveals that 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 (Geiger et al., 2010; Hoyles, 2016; Reed et al., 2010; Selwyn, 2011). Although the majority of students and teachers engage in the creative use of digital technologies every day, they do so less frequently in an educational context; here, even within the literature, it is more often used to simply enhance traditional practice (Ainley et al., 2011; Crompton, Burke, & Gregory, 2017; Hyde & Jones, 2013; Oldknow, 2009).

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 in terms of student engagement with learning, which in turn requires support for teachers, and a structured approach based on sustained and reliable research (Donnelly et al., 2011; Drijvers et al., 2010; Fullan & Langworthy, 2014; Lameras & Moumoutzis, 2015; Noss et al., 2009). The development and deployment of innovative interventions may give food for thought but, in many cases, this is also the limit to academic involvement. Pimm and Johnston-Wilder (2005) liken the mismatch between theoretical and technological developments and their impact on pedagogy to “attempting to walk on a shale hillside" (p. 6). Exemplars are developed, often relying on the assistance of the research team to deliver them in practice, but when the researchers move on teachers are left to their own devices. Hence many interesting educational technology innovations remain at the periphery of practice and do not make their way into the mainstream (Boaler, 2008; Maaß & Artigue, 2013; Authors, 2013c).

In his plenary keynote at the ICMI17 conference, Papert challenged participants not to be too bound by current constraints, but instead to spend a portion of their time considering the new kinds of mathematical knowledge and practices that might emerge through the use of technology (Hoyles & Lagrange, 2010). There is the potential for the transformative use of technology integrated in a structured way, and with sustainable support for teachers, to have a significant, positive impact on the domain. However, according to the analysis in this research, this is not yet being achieved on a large scale. This research is beneficial to researchers through its provision of a synthesis of the field of technology-enhanced mathematics education and its identification of shortfalls in the area. Using this information, researchers can design studies to address these issues and continue to add to the research base. Through this work and the projected development of an associated open-source resource with the potential to track trends in the field of technology-enhanced mathematics education, there is an opportunity to highlight research areas that require advancement, and to rise to Papert's challenge.

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Technology Usage in Mathematics Education Research – A Systematic Review of Recent Trends

Highlights

- A classification system for technology interventions in mathematics education was developed
- 139 studies were classified by Technology, Learning Theory, Aim, and level of integration (SAMR)
- Analysis of Results indicate high levels of usage of technology to augment traditional practice
- Lower levels of transformative usage of technology were identified within the empirical research
- Sustained, research-based support is required to achieve the full potential of technology.