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The Royal Society Vision: The impact of technological change on STEM education

Paul Davies, Geoff Kent, Diana Laurillard, Manolis Mavrikis, Richard Noss, Dave Pratt, Sara Price

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Contents

Executive Summary	2
1. Introduction and remit.....	4
2. What it takes to learn STEM subjects.....	4
3. Engaging STEM thinking through technology	5
3.1. Modelling using design and production tools	6
3.2. Exploring and experimenting with simulations.....	11
3.3. Experiential learning through mixed reality technology	14
3.4. Inquiry learning with data gathering and analysis tools	18
3.5. Collaboration through communication and productive technologies	22
3.6. Problem-solving with game-based learning.....	28
3.7. Adaptive support.....	30
3.8. Online resources for self-study	33
3.9. Generic learning technologies.....	34
4. Evaluation of technology in STEM.....	35
4.1. Impact on students	35
4.2. Teacher uptake	35
5. Discussion and conclusions	36
6. Commentary: The Vision for 2030	38
6.1. Using technology to engage more students in STEM subjects.....	39
6.2. Ways of using technology for assessment	39
6.3. Fostering cross-disciplinary work	41
6.4. Supporting active independent learning.....	42
6.5. Linking school work to the home	42
6.6. Drivers and barriers affecting technologies in STEM education	44
6.7. Alternatives for the future	46
7. Recommendations	49
Appendix 1: Method	51
7.1. Searches	51
7.2. Selection.....	51
7.3. Exclusions	52
8. References	53

Executive Summary

The remit for the literature review asked for a focus on use of learning technologies to support teaching and learning in Science, Technology, Engineering and Mathematics (STEM) education, on its uptake, the factors affecting uptake, and the challenge of understanding their effects. We followed a standard methodology for the literature search (Appendix 1), and selected studies that illustrate the potential of a range of digital technologies for STEM (Section 3).

Digital technologies provide symbolic, graphical, and dynamic representations of STEM systems. This makes them accessible to design, exploration and testing, by students of all ages, at varying levels of digital literacy. Their particular value for STEM subjects is to make the abstract world more accessible through experiential learning. In the report we illustrate how students can manipulate complex ideas - represented on screen as computational objects - to gain a deeper connection with the ideas.

The evidence reported here shows a wide range of digital technologies that have the potential to transform STEM education, and make it accessible and exciting for a much wider range of students. Digital technologies provide opportunities for students to

- develop a formal model of some aspect of the world, supported by the feedback from the behaviour of their model;
- explore the behaviour of simulations of STEM systems, and carry out safe and efficient virtual experiments and inquiry projects both in the classroom or at home online;
- experience virtual decision-making scenarios that give them a better appreciation of the power and limitations of science and mathematics;
- use virtual learning interfaces that keep them engaged and on-task, becoming self-motivated, rather than externally driven, and thereby developing the skills of reflective independent learning;
- discover and explain the world around them using digital tools to plan their project, gather and analyse the data, and represent their results in different forms of textual, graphical, statistical, mathematical, and dynamic representation;
- experience collaborative learning through an orchestrated online process of negotiating the representation of a model, or document, or plan, or inquiry, and sharing and discussing their ideas;
- learn from digital games that have the potential to support and guide independent practice in problem solving and high-level conceptual thinking in science and maths;
- benefit from automated formative assessment that teachers can also use to track students' needs and progress;

Open online resources and tools for STEM subjects open up new challenges for teachers: they need time to develop an appreciation of what these resources provide before they can use them to help their students develop more independent learning skills

Generic digital learning technologies are of equal value to all curriculum areas, including the STEM subjects, because they also support, for example, personalised learning, self-efficacy, open online access, communication skills, students with disabilities, learning analytics, and the link between school work and the home.

Most of the studies of viable technology-based innovation in the literature review derive from research-based learning technology products for STEM learning; there are few reports of successful commercially designed STEM-oriented software, which too often falls short of exemplifying good pedagogy.

The grey literature, and online teaching communities show that there are many good examples of viable innovation in schools and colleges but these are the exceptions, rather than the rule in terms of what happens day-to-day.

For the Commentary on the future in section 6, we summarised a successful STEM education system in 2030 as follows:

- the use of technology for practice-based, social, collaborative, and creative forms of learning will be commonplace in all STEM subjects for every school;
- it will foster cross-disciplinary thinking by using students' increasing digital skills to use technology tools for solving complex problems that work across the disciplines;
- the exploitation of learning technologies will be a normal way to carry out high quality summative assessment of complex conceptual understanding and high-level skills in STEM subjects.

To achieve this vision we have to reform the curriculum and its assessment to support and reward interdisciplinary work, enable teachers to blend in technology methods that help to scaffold and develop independent learning in their students; give teachers the means to integrate the range of technologies available to support STEM learning; and overcome the barriers of the out-dated STEM curriculum and assessment methods, rapid technological change, non-adaptive leadership, the diminished knowledge base for policy, the lack of teacher involvement in innovation, and the social challenges of equity of access to technology.

If we are to benefit from the potential of digital technology to transform 21st century STEM teaching and learning, we need a radical shift in the way the teaching profession is conceptualised. Specifically, our recommendations are to:

1. Make the curriculum, assessment and quality systems accountable for supporting teachers in developing technology-based innovations.
2. Address the barriers identified by asking each agency and institution responsible to report on how their practice could help teachers to contribute to technology-based innovation.
3. Develop a common understanding across teachers, leaders and policy-makers of the wide variety of ways in which digital technologies offer a more ambitious curriculum for STEM.
4. Encourage the STEM education community to promote the findings of the Vision study across their extensive networks and act to address the issues identified.
5. Create a culture of teaching innovation across the STEM teaching profession by:
 - enhancing the teachers' role as collaborative innovators in technology,
 - linking existing STEM teacher communities, teacher training organisations, researchers and the digital industry to collaborate on the development of learning technologies for STEM concepts and skills, and
 - building research-teaching collaboration to orchestrate new pedagogic designs and the collection of learning analytics to support further evidence-based teaching and policymaking.

1. Introduction and remit

This report is a response to the Royal Society Vision Committee's assignment to carry out a literature review and future commentary on the impact of technological change on Science, Technology, Engineering and Science (STEM) education. The Vision Committee would like to better understand the extent to which these technologies are having an impact on teaching and learning, as well as their potential.

For the review the team followed the methodology set out in Appendix 1. For the Commentary we used the findings of the review, additional searches for other future technology scenarios, team discussions, and iterative drafting, to arrive at an agreed output.

There is a cautionary note. The learning technology research field is still relatively immature because it attracts a low proportion of the funding for both educational and computer science research and, especially since the abolition of Becta in 2010, has been unable to keep abreast of the continuing technology innovations now in use in schools and colleges. The grey literature is an important supplement to the research literature, therefore, particularly in relation to anticipating future developments.

In considering the role of technology in education it is wise to begin with a clear sense of what the educational system needs from the technology, rather than an analysis of what the technology can do. It can do many things and plays a wide variety of roles in education. However, the critical issue here is how it can transform the learning of some of the most important, and most challenging concepts and skills in the curriculum. The report begins with a brief account of what it takes to learn STEM subjects, as a way of testing the extent to which technology helps to solve the most difficult pedagogical demands that schools and colleges face.

We then review the types of STEM thinking and practicing that innovative digital technologies are most likely to enhance now and in the future. Wherever possible we illustrate these with screencasts that help to give the reader a clearer visual sense of the nature of the student learning activity supported by each type of technology.

The discussion of the findings and recommendations is followed by a Commentary on the future potential of digital technology in the STEM curriculum, with an analysis of the drivers and barriers affecting that potential, and recommendations for future actions that address them.

2. What it takes to learn STEM subjects

Science, technology, engineering, and mathematics (STEM) education is essential to all learners because of its importance to national economies and the need to develop citizens able to make informed decisions in modern society. STEM education has foundational value because it develops the general skills of making sense of communications about science and mathematics, solving problems and interpreting data. It does this by engaging students in understanding complex concepts and developing the high-level skills of abstraction and modelling, investigation and experimenting, data gathering and analysis, testing and problem solving. Skills and knowledge develop in tandem: the practice of the skills requires the development of the concepts, which in turn modify and generate further practice. In this way the student gradually gains better understanding and control over aspects of the physical world and its formal conceptual representations.

Learning this kind of expertise is not easy and to be successful the teacher is confronted with the tough challenges of:

- ensuring that the learner is motivated and convinced of the value and meaning of their learning goal;
- selecting or designing activities to involve the learner and engage them in active learning;
- designing tasks that challenge learners' alternative conceptions, which are often resistant to change (Driver et al., 1985; Cobb et al., 1992);
- supporting learners to take the time to practise and develop, and find the motivation to tolerate the delayed gratification that complex conceptual work requires.

STEM teachers must design appropriate tasks that target the students' needs, motivate them by engendering a sense of ownership and self-efficacy (Keat & Urry, 2011), and provide feedback and support mechanisms that keep students on-task, and help them to reflect on their level of their understanding in order to move forward.

There are many digital technologies, such as word processing and search engines that enhance all learning in generic ways. These are equally valuable for STEM subjects and are discussed at the end of the next section. We focus primarily on those that are particularly exciting for STEM subjects.

Digital technologies have a transformational potential for STEM education because they foster sensori-motor experiences and interaction with the environment, providing opportunities for students to explore and examine invisible phenomena or abstract ideas in concrete ways. Psychologists and philosophers, such as Vygotsky, Luria, Leontiev, have long argued for the important role of sensori-motor interaction with the world for cognitive development (e.g. Clark & Chalmers, 1998), and the role of external tools in shaping activity and mediating cognition.

This review examines this range of digital technologies because they play an important role in supporting STEM learning in particular, adding to the teacher's repertoire precisely the kind of learning activity that aids the concentration and motivation students need if they are to change and develop their conceptions of the theoretical ideas required in STEM subjects (Duit et al, 2003, Laurillard, 2012).

The research on learning technologies indicates their potential for teaching and learning, and yet successive Ofsted reports draw attention to the underdeveloped use of digital technologies in schools (Ofsted, 2008; 2012). The evidence reported in Section 3 shows that there is a wide range of digital technologies that have the potential to transform STEM education, and make it accessible and exciting for a much wider range of students. In later sections we address the barriers to uptake and our broader recommendations for overcoming them.

3. Engaging STEM thinking through technology

In this section we look at the variety of ways in which learning technologies influence students' learning and engagement with STEM subjects. We have organised the material in terms of the different kinds of skills and practice afforded by different technologies, and the extent to which they engage students in thinking through complex concepts to develop deep knowledge and high level skills. In each subsection, we review studies from science and engineering and from

mathematics and computational thinking. All the examples here are appropriate for use in schools including those studies from colleges and universities.

3.1. Modelling using design and production tools

Among the most important 21st century skills are mathematical and computational modelling. Modelling is working out how to represent the constructs and relations in a human or natural system in the form of a model that can be manipulated, tested, and improved in relation to real-world data. A model may take the simple form of a linear equation to describe how different interest rates yield different values, or the very complex form of algorithms to select and process values and probabilities to determine the most likely outcome of a set of decisions. These skills bring value to every level of the economy, every type of job, as well as leisure activities. Digital tools can assist the process of making and testing models, or designs, and they are now being developed for even very young learners, giving them the experience of how a coding language, or symbolic language can express aspects of the world around them.

Digital technologies enhance the repertoire of actions the student can take to define and control a theoretical model. Once we only had the language of mathematics, then we could code and display formulae; now we can have touch-screen manipulation of curves in the graphical representations of formulae. So the relationship between the intuitive and the formal is being constantly redefined.

For the last decade or so there has been an increased recognition that learners from a very young age engage in the informal and untutored use of digital technologies, interpreting animation and visualisation in sophisticated interactive games, and even construction of their own artefact using simple design and production tools. Young learners have frequent access to digital technologies in the form of desktop, internet or mobile applications. This is important for STEM education, because it is mathematics and computational thinking that invisibly drive the tools that pupils grow up with. A promising approach, therefore, mostly initiated by research groups, has been to design interesting and relevant software that taps into youth culture as a means of motivating and sustaining student educational progress (Kafai 1995; Rosasa et al., 2003; Confrey et al. 2010)

Modelling tools support STEM learning by providing opportunities to manipulate both virtual and actual environments. Students are able to develop their conceptual understanding of material science and improve the mathematical skills that are fundamental to the discipline. For even very young children, physical and tangible computing offers constructive kits for building their own models, stimulating their creativity and imagination. For example, *Topobo* (Raffle et al., 2004) is designed to support understanding of the physical principles of kinematics. Children can build creatures out of digitally embedded pieces, which record and play back physical motion. This process of creating models helps develop a greater understanding about the functioning of objects and systems, and is shown to facilitate children's expression of the concepts of movement and co-ordination, and to support their conception of the effects of e.g. balance and torque on motion systems.

Fab Labs (Fabrication Laboratories) was developed by MIT (Mandavilli, 2006; Mikhak et al., 2002; Posch et al., 2010) and is now established as an interactive exhibition space, currently supported

in the UK by the University of Manchester¹, but spreading more widely across the UK. It provides the general public, and also school and university groups, with opportunities to work with product design experts to develop prototypes of innovative ideas. Using both 2D and 3D design, and novel digital technology, such as CNC machining, 3D printing and arduino kits *Fab Labs* are emerging as important sites of development and design for the future².



Figure 1: The Topobo construction kit for building an understanding of kinematics

Computer modelling and simulation is becoming increasingly important in engineering science, especially in relation to design and production. *NetLogo*³ and *Scratch*⁴ are direct descendants of *Logo*⁵, a derivative of *LISP* that emanated from MIT nearly 50 years ago. These are genuine programming languages that allow for design, production, and most importantly, the computational expression of many of the constructs of engineering and mathematics, such as the idea of a variable, recursion, and generalisation. *Logo* is a traditional, but simplified, text-based environment.

MaterialSim, based on *NetLogo*, (Figure 2), has been shown to develop students' ability to design and test the physical properties of different materials (Blikstein & Wilensky, 2008). The focus of *MaterialSim* is on understanding the science that underpins design, specifically, that the behaviour of particles at the microscopic level is related to the behaviour of the material at the macroscopic level. Using the program to develop and test different models for different materials, students are able to apply their scientific understanding, and consider the important scientific principles that explain the behaviour of materials. The simulation allows students to act

¹ <http://www.fablabmanchester.org/>

² See also Neil Gershenfelds TED talk http://www.ted.com/talks/neil_gershenfeld_on_fab_labs.html

³ <http://ccl.northwestern.edu/netlogo/>

⁴ <http://scratch.mit.edu/>

⁵ <http://www.logotron.co.uk/imagine/>

like scientists by carrying out authentically complex manipulations of variables, which they can then test rigorously.

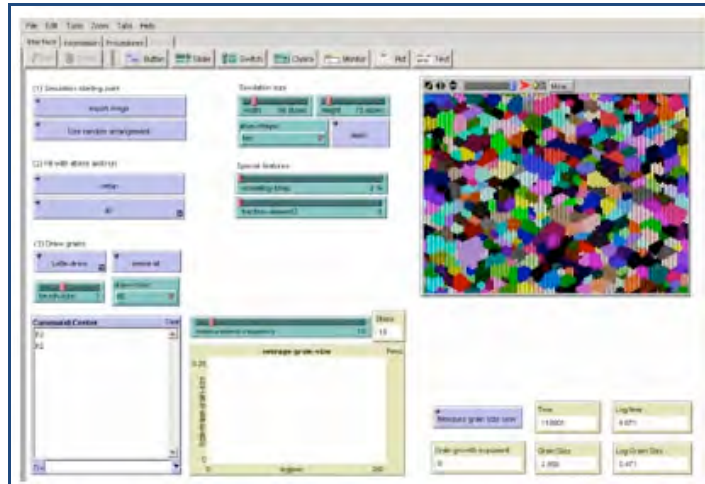


Figure 2: Screenshot of MaterialSim, investigating growing grain size in metallic materials. The buttons on the left allow the user to adjust variables, e.g. size of particle and temperature, and run many cycles to investigate how they affect the properties of the material they have developed. The image on the right shows the ‘material’ as it develops.

More generally, programming a model helps learners to develop computational thinking, an important skill they can develop from a very early age with the right tool. This overlaps and draws together the relationship between scientific and mathematical activity. *Scratch*⁶ is an example of a programming language designed explicitly for young learners to create interactive art, stories, simulations, and games — precisely those areas that motivate learners by relating the skill to their personal interests. *Scratch* taps directly into pupils’ culture because they can use social interaction media to share their creations with other students online. Many of the concepts that students encounter in *Scratch* reflect constructs in mathematics, such as the concept of recursion evident in the examples in Figure 3. Classroom integration, however, is still a challenge particularly due to the fragmentation of computational and mathematical thinking imposed by the curriculum (see 5.3).

While considerably simpler than languages in use by experts, *NetLogo*, *Scratch* and their intellectual neighbours still require the learning of programming, which many regard as an unnecessary overhead in the teaching of what is already a complex and – to some – daunting subject. Efforts are therefore being made to reduce the initial complexity of the programming language and enable non-experts to build serious models without first learning programming. An example of such a project is *Modelling4All* (Kahn & Noble, 2010) that has used and extended *NetLogo* to provide a web-based tool that encourages students to construct, share and investigate agent-based models by composing pre-built modular components called *micro-behaviours* without the need for programming. So far it has been used mostly with university students in life or social sciences to help them learn both about the domain (e.g. the dynamics of epidemics) and about the process of modelling and its role in their discipline.

⁶ <http://scratch.mit.edu/>

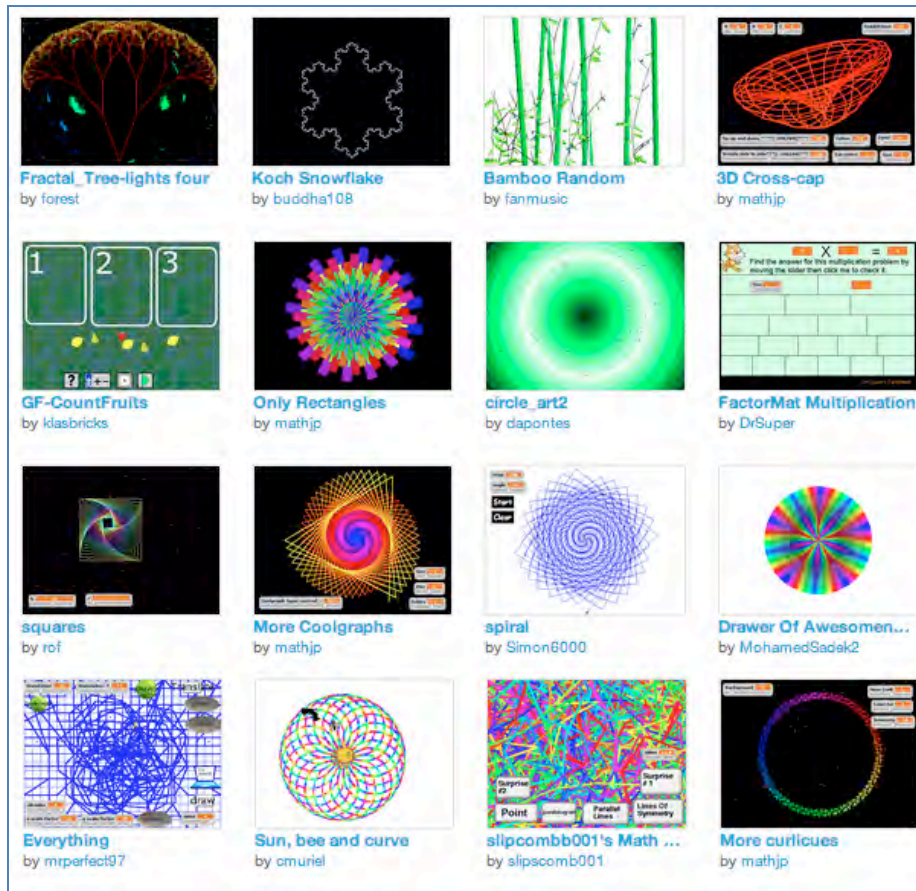


Figure 3: One of the many collections of Scratch projects that demonstrate and require both mathematical and computational thinking. They are made by experienced Scratchers or teachers to inspire students. Of the 3m people in the Scratch community many are schoolchildren.

Dynamic Geometry Environments (DGE) are digital environments that provide tools for constructing geometric objects from a range of ‘primitive’ objects such as points, straight lines and circles to “classical” constructions (e.g. midpoint, parallel lines, perpendicular lines, etc.). They provide tools for “transformational” geometry (e.g. reflection, translation, rotation, similarity, etc.) and a wide range of geometries including hyperbolic, elliptic, and projective geometry. Over the last two decades, dynamic geometry tools have become one of the most widely used digital technologies for mathematics supported by research that has demonstrated their potential for scaffolding students’ geometric thinking (Jones et al., 2010).

Similarly, evidence is starting to emerge that the ‘outsourcing’ of computation to Computer Algebra Systems⁷ (CAS) that allow symbolic manipulation, provides opportunities for mathematical inquiry (Oates, 2011; Geiger et al., 2010), as well as assessment (Sangwin, 2013)⁸. This implies that the introduction of CAS challenges the traditional role of algorithms and

⁷ http://en.wikipedia.org/wiki/Computer_algebra_system

⁸ <http://stack.bham.ac.uk/>

techniques, which were designed for pencil and paper. By using these kinds of production tools for constructing representations of mathematical relationships and obtaining immediate feedback, students can re-align the balance between technical and conceptual knowledge, to the mutual benefit of both (Artigue, 2010).

The design and development of products lies at the heart of engineering education, and digital tools are ideal for developing the STEM knowledge and skills to accomplish real world problem solving through design, troubleshooting, and analysis activities. A comprehensive review of projects to bring this activity to children in early primary education testifies that projects such as the STAR learning cycle, using Software Technology for Action and Reflection, engage learners in an authentic design cycle that continually challenges their thinking, and generates real enthusiasm for the subject (Brophy et al., 2008). The difficulties they identify for wider implementation are (a) teacher readiness and the lack of teacher development provision for subject content knowledge, and (b) inappropriate curricular standards and assessment. Enthusiastic teachers nonetheless pursue this innovative pedagogy by organising long-running competitions for schools such as Robofest in the US⁹, or the Bebras competition for Informatics Education in Europe (Zoltan & Kalas, 2009).

Research projects and curriculum development have explored the educational impact of the interesting idea of engaging children in the design and production of computer games, and in creating models of decision-making scenarios (Kirriemuir & McFarlane, 2004; Egenfeldt-Nielsen, 2005; Mor et al., 2006b; Kafai, 2006)¹⁰. The *MakingGames* project is an example of the former. It gives students a high-level language of game objects and rules for their behaviour, which the students use to construct the player's interactions with a game environment. At one primary school, for example, MissionMaker¹¹ is used to develop logical thinking. Students have to understand the sequencing involved in solving a problem, learn problem-solving skills, think through why something happens, then go back to try again (trial and improvement is a level 6 maths skill) and find another way, modifying their program all the time, until it works. This kind of thinking is crucial for maths and science – the logic of investigations, and the process of investigating, and making a fair test in an experiment. This type of tool is potentially a way of motivating learners to understand, for example, the physics of movement, in order to design their game for other learners to test.

Two examples of modelling decision-making scenarios are: (i) Deborah's Dilemma where science and mathematics teachers created models of what might happen should a fictitious young woman decide to have an operation to cure her spinal condition to compare with their model of what might happen should she not have the operation; (ii) Highway Link, part of the Bowland Mathematics set of case studies¹², where students have to plan a highway link through or around a village. In Deborah's Dilemma, the teachers had to confront their own understanding of risk, contemplating the tensions between the degree of harm, the probability of side-effects, and the personal circumstances such as Deborah's family situation or her desire to conduct various

⁹ www.robofest.net

¹⁰ http://people.ioe.ac.uk/dave%5Fpratt/Dave_Pratt/Software.html

¹¹ www.immersiveeducation.eu/index.php/missionmakerm

¹² <http://www.bowlandmaths.org.uk/>

sporting activity. In Highway Link, the students needed to consider the cost of building a longer road alongside laws about the maximum curvature of bends allowed for safety reasons and the ethical dimensions of destroying key buildings or forested areas. In both examples, mathematical or statistical ideas had to be considered simultaneously with aspects of life that are rather less conducive to measurement. In so doing, the modelling process sensitises learners to both the power and the scope of science and mathematics to inform such decision making.

The act of developing a formal model of some aspect of the world provides a rich and intensive learning experience requiring the learner to use and develop STEM knowledge and skills, supported by the feedback from the behaviour of their model.

3.2. Exploring and experimenting with simulations

Modelling tools provide the coding language to build a model to simulate the behaviour of a system. In this section we look at how the simulation model itself plays a significant role in STEM education. Students control some of the parameters in the simulation which then produces and displays the resulting behaviour of the system being modelled. It could be something as simple as finding out at which angle of projection a ball travels furthest, or as complex as finding out which combinations of parameter values in a climate model produce the lowest mean global temperature. In the process of exploring and experimenting in this digital version of a real-world system, students have to decide on a goal, generate hypotheses, generate actions to test it, record results, interpret them, generate new actions, and reflect on results until they judge the goal is reached. The process is motivating and requires intensive concentration, which is why it is potentially important for learning, as the studies in this section show.

Graphical and virtual simulations have been shown to promote cognitive gain in STEM learning (Vogel et al., 2006) because they allow learners to work on tasks in a simulated environment that embody the kinds of knowledge and skills they will need in the real world. Students can explore risky behaviours, manipulate data in interesting ways and speed up processes so that results can be analysed quickly. Importantly, simulations encourage essential STEM thinking by students through the testing of their own hypotheses, asking “What if?” questions, exploring different outcomes, and reflecting on feedback to improve those outcomes in relation to a goal.

The *River City* multi-user virtual environment is an excellent example of how a simulation allows learners to explore virtual worlds, in this case, through guiding an avatar on a quest to discover why people are becoming ill (Ketelhut, 2007) (Figure 4).

In *River City*, students adopt the role of an avatar and investigate a virtual world where a water-borne disease is causing the town’s population to become ill. Students are able to use the simulation model to collect and examine water samples and test them for a range of different factors, for example disease-causing bacteria, as in the screenshot. Through running tests and examining predictive models, students problem-solve the source of the disease. This simulation has been shown to promote inquiry-based learning skills and self-efficacy in students from a wider age range (Ketelhut, 2007).

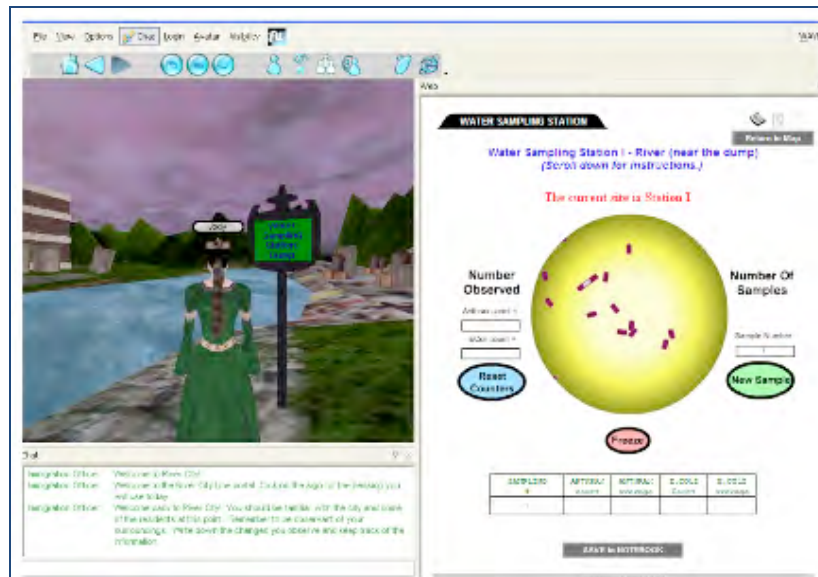


Figure 4: Screenshot from River City showing, on the left, the avatar exploring the virtual world with user instructions and avatar 'chat' interactions shown in the green text in the box below and, on the right, the results from a water sample being investigated for bacterial load. In this section the user can adjust the number of samples to be investigated and run a series of bacterial load counts.

Yenka simulations (published by Crocodile Clips) originated with the idea that the electronic engineering simulations used in industry could be very helpful in schools, provided they were usable by children. For education, the industry-based tools are over-engineered, and sometimes do more for the user than is suitable for learning contexts. However the underlying computational model is very similar. With Yenka, simulations can be created by the teacher to give students a model they can manipulate to achieve a specific goal, and thereby test and develop their understanding of the system, e.g. to carry out experiments on the properties of substances; to build an electrical circuit that lights a bulb when a switch is closed. The simulations give students the informational feedback that supports their learning of the basic scientific concepts (Herga & Dinevski, 2012). These simulations are available for all the STEM subjects.¹³

Simulations have been found to be useful in supporting conceptual change, and particularly in areas of science, which are known to be either challenging or particularly resistant to change (Chinn & Buckland, 2012). Taking a constructivist approach, many simulations take a problem-solving approach, which involves skills of reasoning and analysis. For example the *Biologica* web labs (http://biologica.concord.org/webtest1/web_labs.htm) provide students with background information they then use to solve genetics problems, as they navigate their way through the website (Buckley et al., 2004).

An example of simulation software designed particularly for mathematics is *SimCalc* MathWorlds, which comes with curriculum activities designed to introduce the Mathematics of Change and Variation (MVC) to middle school students.

¹³ <http://www.yenka.com>

SimCalc was motivated by the idea of ‘the democratization of calculus’ – that the 21st century is permeated by economic, social, and technological change so that *all* children need to participate in this change, and learn to make informed decisions in their personal and political lives, using mathematics (Roschelle, Kaput, & Stroup, 2000). From around 2007, implementations of the *SimCalc* tools and the MathWorlds curriculum have been tested thoroughly in various experimental settings in the US including treatment-control experimental designs, revealing repeatedly the potential of the *SimCalc* approach for robust learning.

Since 2007, the ‘*Cornerstone project*’ has sought to exploit and extend this approach for teaching mathematics, both in the US and in the UK, by integrating the technology into existing curricula, designing ‘replacement modules’ that offer teachers low-risk but potentially transformative means to teach complex ideas like linear functions. In Figure 5 below we see how multiple representations are used to help students grasp mathematical concepts. They already know the ‘Little Red Ridinghood’ storyline, and here the characters’ journeys are plotted in a table, a graph and an animation to help students see the relationships between these multiple representations.

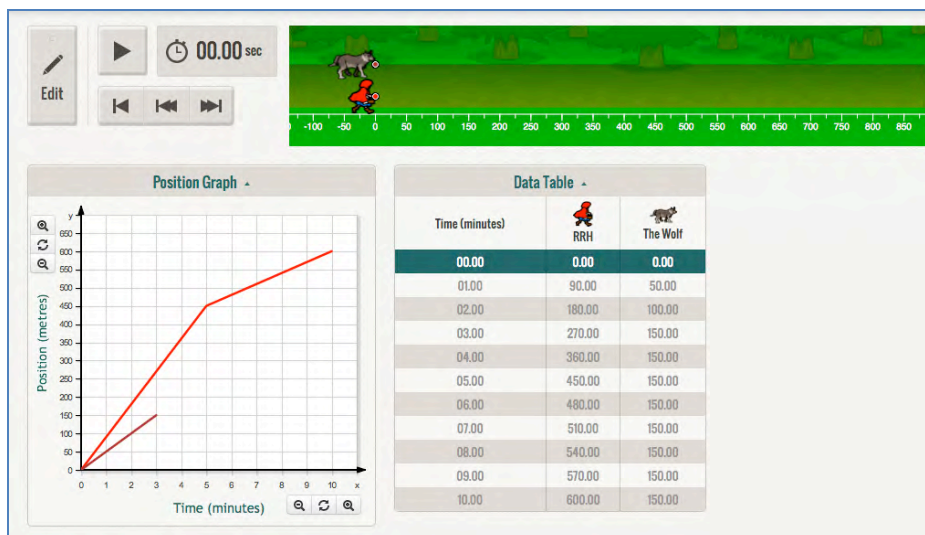


Figure 5: *SimCalc* enables students to control the characters’ journeys by changing numbers in the table, and seeing the resulting representation on the graph and in the animation

This type of simulation demonstrates to young learners the way in which mathematics and computational modelling help them describe and make decisions about aspects of the world.

Allowing students the ability to manipulate data, test predictions, and explore the abstract world, simulations have much to offer STEM education. Although not without criticism in terms of their authenticity (Winsberg, 2010), research shows that models of this kind help students to explore complex relationships. For example BGuLE software has been designed to allow the exploration of predator-prey relationships and complex ecological patterns in an argumentation framework (Basu et al., 2011), and natural selection (Sickel & Friedrichsen, 2012).

Simulations also allow students to work with professional scientists. A good example is the use of the website *Bioinformatics: decipher the secrets of the genome* to support students’ understanding of genetic (Gelbart et al., 2009). The website (<http://stwww.weizmann.ac.il/bioinformatics>) allows students to explore how an understanding

of genomics can be used to predict genetic crosses through a series of tasks that support a guided inquiry pedagogy. Students act out the role of genetic researchers: manipulating genetic material and examining the outcomes of breeding experiments, for example with mice. The simulation supports learning by providing information, both within the platform but also via links, with data that real geneticists use in their everyday work. The simulations allow many genetic crosses to be carried out, and complex genetic crosses to be manipulated. Taking a research approach, with in-built 'assignment' goals, the website has been shown to support learners in genetic literacy and provide teachers with access to authentic science settings, an important feature in the development of scientific inquiry.

More generally, simulations enable students to carry out many safe and efficient virtual experiments and inquiry projects in the classroom and at home online that would otherwise be impossible. Digital tools must always be used alongside the real-world practical work that helps students develop the skills of manipulation and measurement, planning and time management, negotiation and organisation of resources, etc., as well as the understanding of why experiments do not always work.

3.3. Experiential learning through mixed reality technology

Science concepts can also be explored and 'experienced' with more recent technologies, such as mobile, augmented reality, tangible, and sensor technologies, where the physical world is digitally augmented in different ways. One example using augmented reality is *Environmental Detectives*, a game on a handheld device, which encourages students to explore their environment by taking on the role of environmental engineers investigating a simulated chemical spill. The handheld device records real environmental data and then augments disasters, such as chemical spills and establishes a set of problem-solving tasks, which, if completed, lead to a solution. Playing the game in "real" situations has been shown to support learners' inquiry skills and promote their drawing on preexisting knowledge and abilities to link theoretical and practical elements of learning together (Squire & Klopfer, 2007).

A very different type of science concept can be experienced through the use of augmented reality in the 'Embedded Phenomena' projects¹⁴. Digital augmentation is used to simulate a physical experience to engage learners with various scientific phenomena in the classroom. For example RoomQuake (Moher et al., 2005) is a classroom embedded with a combination of sensor technologies and physical artefacts used to simulate scientific earthquakes. Across a six-week period, during the normal school day, seismic events are programmed to occur randomly via Pocket PCs, which are strategically placed throughout the classroom. Students can monitor the seismic events, investigate them and experience seismological practice. Studies show how large groups of students can be collectively engaged in an authentic and active learning process that fosters role-play as a scientist (Figure 6), and improves students' performance in seismological practice and the understanding of temporal, spatial, and intensity distributions of earthquakes (Moher et al., 2005).

¹⁴ <http://www.evl.uic.edu/core.php?mod=4&type=1&indi=292>

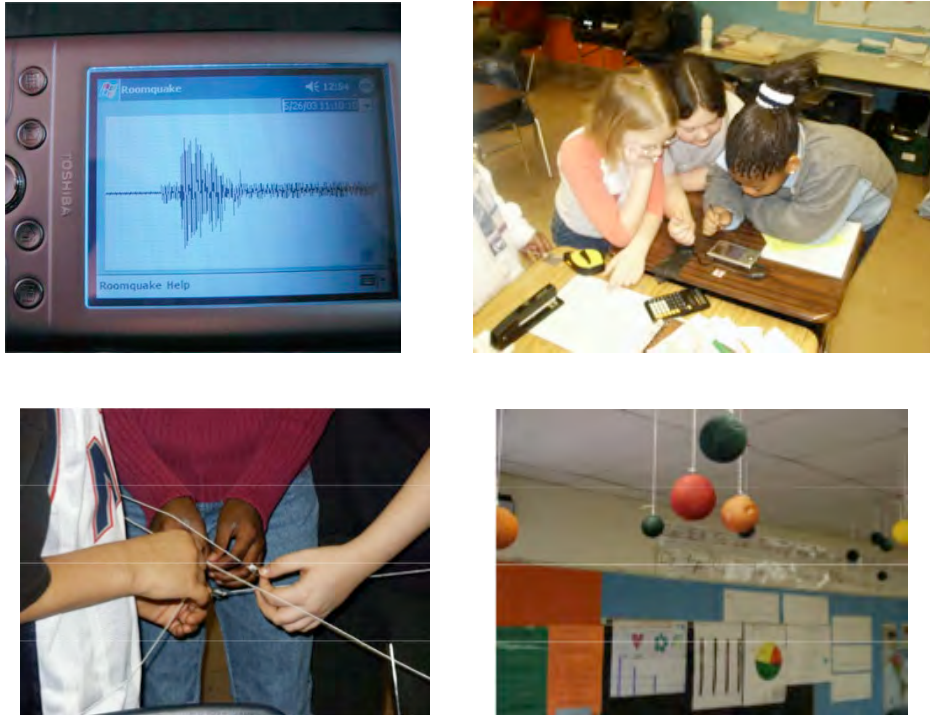


Figure 6: The Pocket PCs provide dynamic readings of the simulated earthquakes, which students then use to create a physical model of the earthquake size and epicentre through trilateration using string, and Styrofoam balls hung from the classroom ceiling.

SMALLab uses transportable off the shelf technology to create experiences where students actively engage with scientific phenomena. A case study example illustrates how students use the processes of Geologic Evolution as a time-based generative process in order to understand the ‘products’ or cross sections of the earth’s surface, as the result of a complex dynamic process (Birchfield et al., 2008). Their findings highlight the impact of this kind of experience on student motivation to engage. They also show how the nature of reflective discussion changes from teacher-led moving to teacher-moderated then to student-led discussion. *SMALLab* learning was developed in 2010 and they now provide interactive game-based learning experiences. There are a number of ready-made scenarios for science based learning topics, but users can configure new scenarios, and developers can write new software code modules.¹⁵

The *SMALLab* Geologic Evolution environment consists of a visual projection onto the floor where students can deposit sediment layers and fossils (Figure 7). Each selection is visually depicted; a geologic clock shows time advancing to show each period of time; a graph shows fault tension; and exceeded fault tension results in an uplift in the layers. Audio feedback is given to support the selection of layers and fossils, helping to highlight actions taking place. Studies show that student driven interaction is higher than traditional class-based instruction (Birchfield et al, 2008). Other studies on learning outcomes suggest significantly higher test scores than normal classroom instruction (Tolentino et al, 2010).

¹⁵ <http://smalllearning.com/>

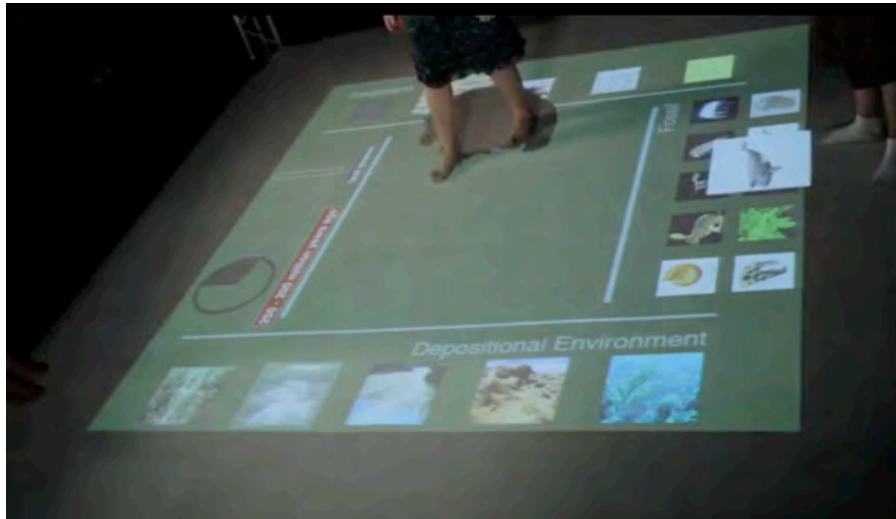


Figure 7: the SMALLab Geologic Evolution environment

Tangible technologies can also engage students in thinking about scientific concepts through the physical manipulation of objects that offer hands-on engagement with invisible or complex scientific processes. ‘Tangibles’ are computer interfaces where computational power is embedded in everyday artefacts or customised objects, which can be wirelessly and dynamically linked to various forms of digital representations. Commonly these are visual in nature, but can equally well be linked to audio or haptic representations. They can augment the physical handling or placing of objects, and the relationships between them, by depicting them in terms of the relevant scientific phenomena and thereby support the learners in their interpretation of the physical world in terms of those scientific phenomena. Studies in neuroscience suggest that, whether by touch or by vision, object recognition activates similar brain regions, which is why haptic technologies might provide a valuable extension of physical activities (Kim & James, 2010)¹⁶.

For example, FlowBlocks generate visual representations of behaviour; in this case ‘flow of light’ according to the way the objects are combined (Zuckerman et al., 2005). Flow Blocks are designed to support young children’s exploration of concepts such as counting, probability, looping and bending. Initial studies showed how learners moved from structural focus to a behavioural focus, i.e., focusing on the behaviour of the lights rather than the structure of the blocks (Figure 8).

¹⁶ See also the review *What are the Implications of Psychology and Neuroscience Research for STEM Teaching and Learning?*

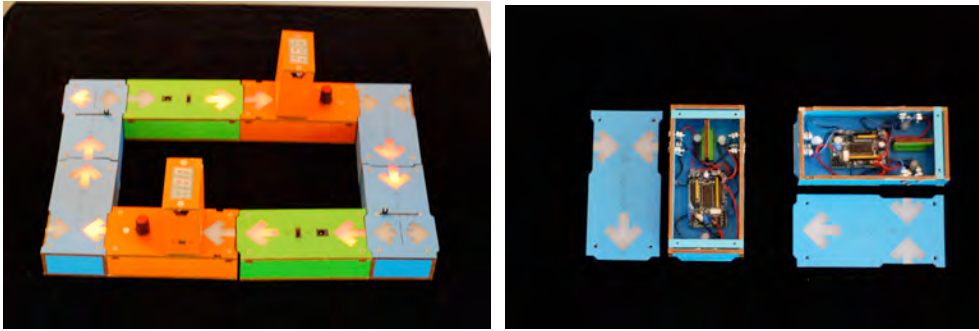


Figure 8: FlowBlocks (designed and developed by Oren Zuckerman, MIT Media Lab).

The LightTable is a tangible environment designed to support learning about the behaviour of light, particularly basic concepts of reflection, transmission, absorption and refraction of light, and derived concepts of colour (e.g. Price et al., 2009; Pontual Falcao & Price 2010). Of particular interest here is the role of the physical properties of objects that are central to the scientific idea, and their linking to digital representations in fostering learners' interpretations (e.g. green reflects green, while red reflects red; rough objects reflect in a diffuse manner, while smooth do not). Environments such as these enable hands-on engagement with scientific ideas that are motivating for students, and that support pattern seeking and recognition, problem solving, reflection, reasoning and analysis.

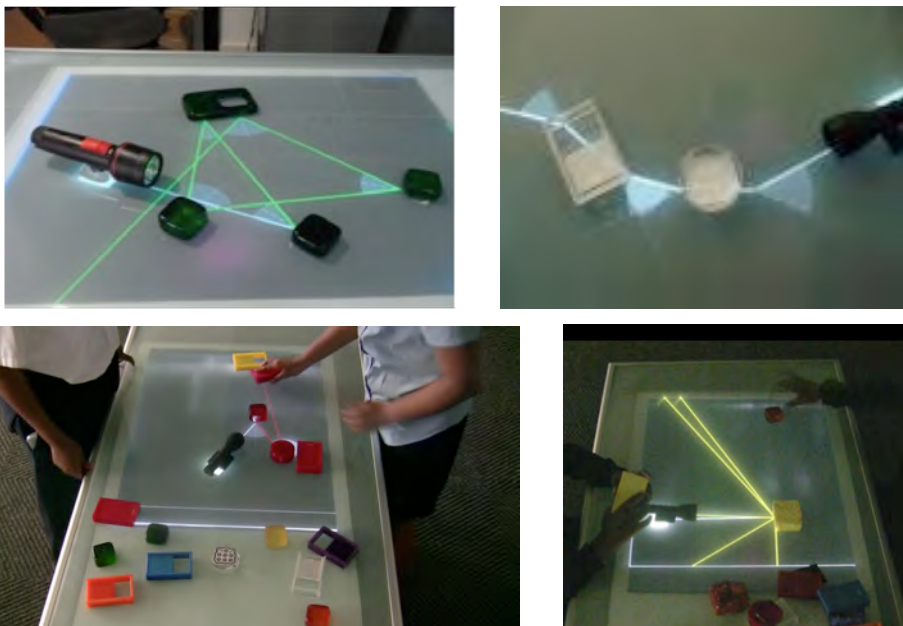


Figure 9: The LightTable consists of a torch and several different coloured, shaped and textured objects.

In the *LightTable*, each object is tagged with a marker called a 'fiducial'. When tagged objects are placed on the surface they are tracked by an infrared camera, recognized by the computer system and programmed digital effects are projected onto the table surface (Figure 9). The torch emits a digital white light beam when placed on the surface. Children interact with the LightTable by manipulating the different physical objects in the digital beam, causing it to dynamically reflect, and refract and/or absorb the digital light beam, according to their physical properties (shape, material and colour).

Tangible simulations have also been developed for further education contexts; for example, the 'Tinker environment' uses physical models linked to digital visualizations for training logistics assistants through practical exercises (Jermann et al. 2008; Zufferey et al. 2008); *URP* software is designed for experts in Urban Planning.¹⁷

While research shows that tangible simulations and tangible interfaces are effective in increasing motivation, and fostering collaboration in different and effective ways (e.g. Dillenbourg & Evans 2011; Harris et al., 2009; Piper & Hollan 2009; Price et al, 2009, Pontual Falcao & Price, 2010; Shaer et al., 2010; Higgins et al., 2011; Horn et al., 2012; Schneider et al., 2012), the degree to which they support learning is still very much a focus of research today. In particular, research shows that the design of these interfaces is crucial to their value for learning. For example, learners' interpretation of scientific phenomena is influenced by the design of physical artefacts, visual representations and mappings between them, and how and when feedback is provided is also important (Cuendet, et al., 2012). Recent research with a Tinker environment shows how complex this can be, suggesting that "participants who did not receive feedback manipulated less, reflected more, and in the end learned more than those who received feedback" (Cuendet et al., 2012).

Learning through immersion in these virtual learning interfaces has been explored through Flow Theory, which draws on both cognitive and affective responses to learning experiences and promotes deep engagement with learning. The immersive experience is similar to the experience of electronic games. Research shows that the experience of 'flow' is a common element of many games and is "so gratifying that people are willing to do it for its own sake" (Csikszentmihalyi & Csikszentmihalyi, 1990). It is of great value for the individual learning experience, because it keeps the learner engaged and on-task, becoming self-motivated, rather than externally driven. This is the kind of experience that develops the reflective independent learner.

3.4. Inquiry learning with data gathering and analysis tools

Practical work in school science has a long history of using data-logging technology but mobile and hand-held devices now afford much more extensive learning opportunities. In particular they offer new ways of supporting data gathering and manipulation, and scientific inquiry activities in the field. Within science education, research to date has primarily focused on the value of mobile and handheld technologies for supporting field trips, and particularly those that are environmentally or ecologically orientated.

A project using *Science Scope data loggers* and *Garmin GPS* technology, with students aged 11-13 years, showed advancement in the students' conceptual knowledge of the impact that environmental factors can have on health. The students also developed a deepened understanding of the role of collaboration in science (Woodgate et al., 2011).

The combination of the *Science Scope data loggers* and *Garmin GPS* technology allowed students to collect environmental data, including pH, noise level, carbon dioxide concentration and light intensity and tag it to place data in Google Earth™ (Figure 10a and b). The subsequent sharing of the tagged data allowed the students to map changes over space and time and begin to search for correlation and causal patterns and so provides an authentic learning experience.

¹⁷ Underkoffler and Ishii, 1999 (http://www.organicui.org/?page_id=38)

Mobile technologies, being accessible and online everywhere, offer new ways of supporting data gathering and analysis for scientific inquiry activities in the field. Within science education, research to date has focused primarily on the value of mobile technologies for supporting field trips, and particularly those that are environmentally or ecologically orientated. For example, the Ambient Wood project (Rogers et al., 2005) used various mobile and sensor technologies to support children learning about habitat distributions and interdependencies in outdoor woodland. The technologies provided access to contextually relevant information, represented in a variety of media, at opportune times during the field trip (Figure 11). Information was represented in a variety of media, including images and sound, and was designed to draw attention to invisible data, to complement the visible information readily available in the physical world.



Figure 10a: The Science Scope data logger and Garmin GPS kit



Figure 10b: Screenshot of Google Earth™ showing carbon dioxide data superimposed on the lower left hand side over the Google Earth™ image.

A sound horn provided sounds to prompt and foster reflection about invisible processes such as plant respiration and photosynthesis (Randell et al., 2004), which are important for understanding habitat distribution. PDAs were used to both receive and store information; and GPS tracking was used to record and log all of the data captured by the students. Studies showed that students' exploration of relevant aspects of the physical environment was enriched through the digital information, as well as fostering collaborative learning and the practice of inquiry

processes (e.g. Rogers & Price, 2004; Price & Rogers, 2004). Similar examples of mobile support beyond the classroom for students' fieldwork include: nQuire¹⁸ and LillyPad (Rogers et al., 2007).

Virtual labs that use wireless networks, mobile devices, and cloud-based software¹⁹ make scientific experiences more accessible for schools that lack fully equipped labs, where an experiment can be conducted numerous times with greater efficiency and precision, and provide students with authentic scientific experiences without the associated costs of building and maintaining physical lab spaces. Digital tools such as the Open University's virtual microscope (Wellington, 2004) and the Bradford Robotics Telescope (Baruch et al, 2007)²⁰ have been used in schools to extend the opportunities for a wider range of data gathering and analysis that despite being digital (and increasingly, *because* it is digital) is an authentic scientific experience.



Figure 11: The Ambient Wood project, where the probe tool was used to take environmental readings, such as light and moisture, which were instantly displayed and recorded on the PDA.

More recently, the nQuire software was developed to support inquiry-based learning both within and beyond the classroom. It enables students and teachers to design and run science inquiries at school, at home, or outdoors on mobile devices. Students are guided through the inquiry process, from creating their research question and planning how they will carry out their inquiry, to collecting data, then sharing and presenting results (Mulholland et al, 2012). Teachers can

¹⁸ <http://www.nquire.org.uk/node/1>

¹⁹ The 'cloud' refers to a real-time communication network that by using a large number of connected computers can extend the capacity of a local network. For other special terms in learning technology please see the Technology Enhanced Learning Dictionary at http://www.tel-thesaurus.net/wiki/index.php/TEL_Dictionary_entries

²⁰ <http://schools.telescope.org>

choose from a set of ready-made inquiries for their students, modifying them as they need, or creating their own new inquiries using the *nQuire* authoring tools. Teachers can monitor their students' progress through inquiries, and give them access to new parts of inquiries as they complete each stage. Developers can create new inquiries for students and teachers to use, and extend and develop the open source *nQuire* system to achieve their own goals.

The recent rise of geospatial technologies, such as Geographic Information Systems (GIS) and Global Positioning Systems (GPS), has made the ability to collect and manipulate scientific and spatially related data much more readily accessible (Hagevik, 2011). Together with the increase use of mobile smartphones and tablets, and innovative Internet based resources like GoogleEarth™, more people are using spatial skills in their everyday lives, which provides further important opportunities for teaching and learning in schools (Charlesworth, 2009). Research exploring the role of mobile geospatial technologies in education is beginning to show how they can enhance scientific thinking in new ways (e.g. GeoSciTeach; Epicollect²¹). Indeed a recent book focuses on the emerging use of geospatial technology to teach science and environmental education (MaKinster et al, 2013) and organisations like the ESRI²² are developing GIS systems for use in schools.

While research has shown ways in which mobile and handheld technologies can be used for education and learning (e.g. collecting, organizing, and exchanging data quickly) there is to date little widespread adoption of mobile technologies in the classroom. Such use is more prevalent in further and higher education than in primary and high school contexts. Nevertheless research indicates their potential and need for integrating into school-based education is becoming increasingly important, not least because of their ubiquity and everyday use across most age groups, and thus are becoming (or have become) an essential tool in everyday life.

In mathematics, evidence is beginning to emerge about the potential of supporting students' statistical thinking with specialised tools like *TinkerPlots* (Watson & Donne, 2009). Recent research explores the use of *TinkerPlots* in an after-school programme of lessons and reports on the benefits of encouraging and structuring students' peer-to-peer dialogic interaction in order to support conceptual understanding (Kazak et al., 2013). *Tinkerplots* is having a huge influence amongst statistics educators by allowing students to conduct exploratory data analysis and learn in an informal way about statistical inference (Figure 12). Recent developments now enable students to create stochastic models of phenomena as well as manipulating data graphically and numerically. Encouraging students to develop such skills is important under the current climate that demands maths literate students e.g. for accounting, finance and data-mining.

²¹ <http://geosciteach.wordpress.com/> ; <http://www.epicollect.net/>

²² <http://www.esriuk.com/schools/gis-for-schools>

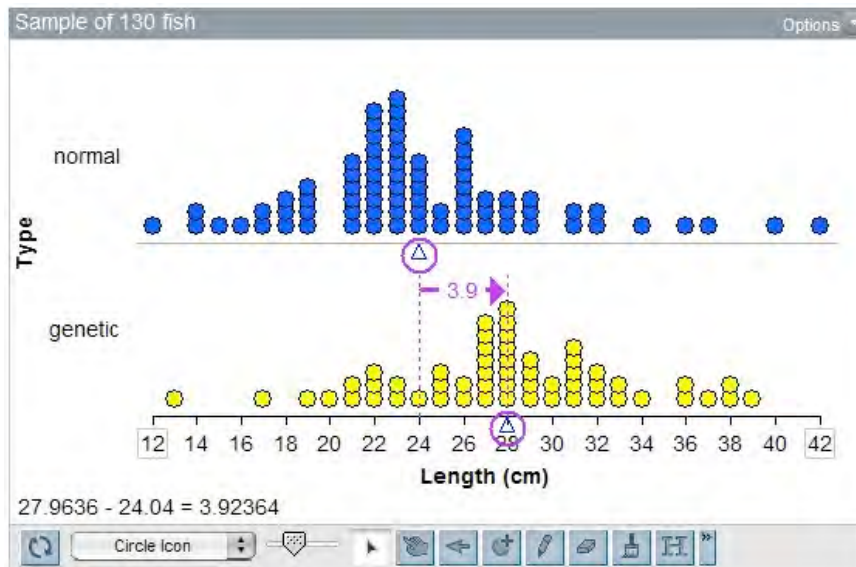


Figure 12: TinkerPlots²³ is data exploration software designed to help young learners develop data analytics and visualisation skills. TinkerPlots and other similar environments can play a significant role in helping students to construct links between local data and the global pattern.

The mobile data gathering and analysis technologies bring students close to authentic scientific inquiry, enabling them to see that they can discover and explain the world around them, by planning their project, gathering the data and using the tools of analysis. They can relate the scientific concepts they encounter in the classroom to their immediate relevance in their own local contexts.

3.5. Collaboration through communication and productive technologies

The use of collaborative learning is becoming more widespread in schools and post-16 educational settings partly through the use of tutor-guided group work, tutor guidance and peer feedback in Virtual Learning Environments, or VLEs (Kemp et al., 2009). Collaborative learning is motivated through students sharing in the production of some output, or artefact. It is this joint endeavour that promotes discussion, debate, repeated practice, and the requirement to produce something. If the product is technology-enabled and public, the students focus more on the rigour and quality of their output, which helps to motivate attention to what they are learning.

An emerging use of this kind of technology brings together teachers, experts and student peers in the collaborative learning process. A good example is the *Solar6voyages* website which is designed to support students' understanding of the solar system (Figure 13).

*Solar6voyages*²⁴ is a website developed by Duke University Libraries where students work through a series of directed tasks to learn about features of the solar systems. They then build a website, which is shared as a Wiki with peers and astronomy experts providing feedback and

²³ <http://www.keycurriculum.com/products/tinkerplots>

²⁴ <http://solar6voyages.wikispaces.com/Home>

evaluative commentary. In this way, students develop their knowledge and engage with the material in more authentic ways. The use of Wiki tools in providing accessible collaborative learning is becoming a more common feature of STEM education (de Castro et al., 2011).



Figure 13: Screenshot from Solar6voyages showing part of a Wikipage about the planet Jupiter, developed by a student, where images and text explain the history of Jupiter and its conditions.

Cloud computing will allow more opportunities for collaborative learning and sharing of large-scale data because it provides increased computational power, and this will be important for STEM learning. For example, the MIT Cloud-Computing Infrastructure and Technology for Education (CITE) centres have developed a Climate Modelling Initiative which has harnessed this technology to support student understanding of climate modelling (Johnson et al., 2010).

Understanding climatic change is challenging, but predictive modelling simulations make accessing this information more straightforward. Using shared computational power in the 'cloud', MIT²⁵ has developed a climate modelling resource that allows school and undergraduate students to work collaboratively and increase the computational power and speed of the modelling software, through shared computer resources. These students are co-constructing knowledge in a collaborative environment (Figure 14).

²⁵ <http://paoc2001.mit.edu/cmi/default.htm>

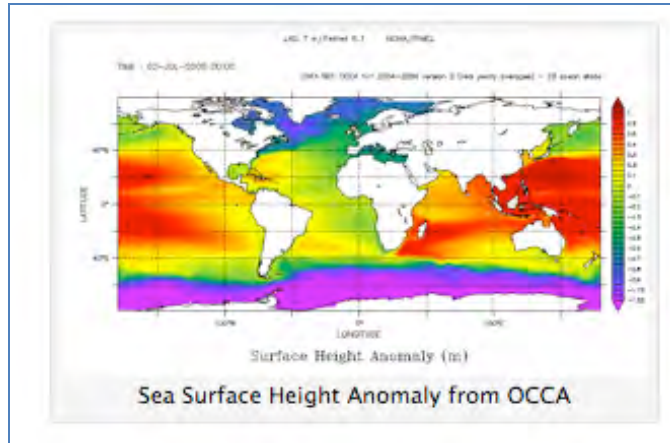


Figure 14: Screenshot of CITE Climate Modelling Initiative showing a student-sourced map of predicted sea surface temperatures (red is the hottest), using their data shared in the cloud.

Interactive tabletops are currently particularly interesting in the context of computer-supported collaboration, because the nature of the interface facilitates small group simultaneous interaction that supports collaboration in a number of ways (Figure 15). They support co-location, multiple users, hands-on activities and multiple forms of communication (Dillenbourg & Evans, 2011), awareness, and sharing, highlighting the importance of face-to-face interaction, and physical forms of interaction.

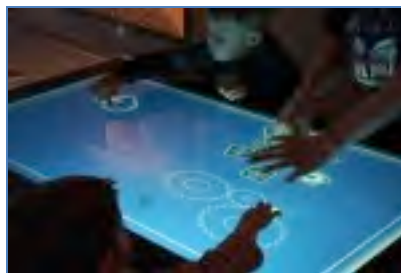


Figure 15: Example multi-touch surface (interactive tabletop) from Ideum

Research with multitouch tabletop technologies is being explored in a number of areas in schools. *Phylo-genie* is a tabletop interface for fostering collaborative learning of phylogenetics for novice biologists. A recent study showed that engagement was higher than with paper materials, with evidence of enhanced collaboration through a “more balanced division of labor between users, participants took more turns and spent more time pooling information, coordinating activities rather than working independently” (Schneider et al., 2012: 3078). *G-NomeSurfer* (Shaer et al., 2011) is a multitouch game to support learning about biological engineering in primary school, showed educational benefits for tabletop interaction over mouse interaction through increasing physical participation, encouraging reflection, and fostering effective collaboration.

The *SynergyNet* project²⁶, developed a classroom environment of networked interactive tabletops (Figure 16) to explore how they could be used for collaborative problem-solving.



Figure 16: Synergynet classroom with multiple interactive tabletops

Interactive tabletops are useful in STEM teaching because they afford greater use of the body and gesture in the context of collaborative scientific discourse, which eases communication and encourages “deeper understandings of new concepts” (Piper et al., 2012: 18).

These kinds of physical interfaces offer new ways for younger students to study new concepts in STEM subjects, using hands-on activities that fit well with the focus on active and collaborative learning in education (Laurillard, 2012).

It is also possible to facilitate collaborative learning by using movie-making programs, such as *iMovie* and *Movie Maker*, or a simple productive technology like *Slowmations*²⁷, to author stop-motion films (Figure 17). These are currently being used to investigate children’s ideas about science to encourage them in sharing their knowledge and understanding (Hoban et al, 2011; Vratulis et al., 2011).

Slowmation production involves students in communicating their ideas by storyboarding a sequence of images to explain a specific science concept. Text and audio can be added to enhance the quality of the explanation. Drawing on socio-constructivist theory, this type of productive technology has been shown to support learners in the development of greater sophistication as they move to better explanations of ‘how and why’ (Braaten & Windschitl, 2010), which is an important skill in STEM learning.

²⁶ <http://tel.dur.ac.uk/synergynet/>

²⁷ <http://slowmation.com/>



Figure 17: Primary school students engaged in the production stage of a Slowmation.

Computer Supported Collaborative Learning (CSCL) has made substantial progress in the last few years in understanding how to use technology to orchestrate collaboration between students in a way that enhances their learning (Stahl, 2006; Hoyles et al., 2010). There is a range of platforms designed to support discussion and debate for student-student and teacher-student dialogue. When designed with care, they can be very effective at challenging students' alternative conceptions and supporting co-construction of meaning, in line with constructivist approaches to learning.

A good example in science is the development of the *Web-based Scientific Enquiry* environment (*WISE*). Established in 1997, *WISE* has developed into an online platform for designing, developing, and implementing science inquiry activities. Current data shows it to have been used by more than 15,000 teachers and over 100,000 students around the world²⁸ (Figure 18), which is a remarkable figure for a single educational product of this kind.

WISE provides a simple interface, cognitive hints, a place to record notes, an online discussion forum, and software tools for activities such as drawing, concept mapping, diagramming, and graphing. The discussion forum allows for peer-peer chat and evaluation in real time, as well as teacher-student interaction. The integration of these features provides an explicitly structured process for conducting the collaboration, to build and scaffold students' inquiry skills in science (Slotta & Linn, 2009).

²⁸ <http://wise.berkeley.edu/webapp/pages/features.html>

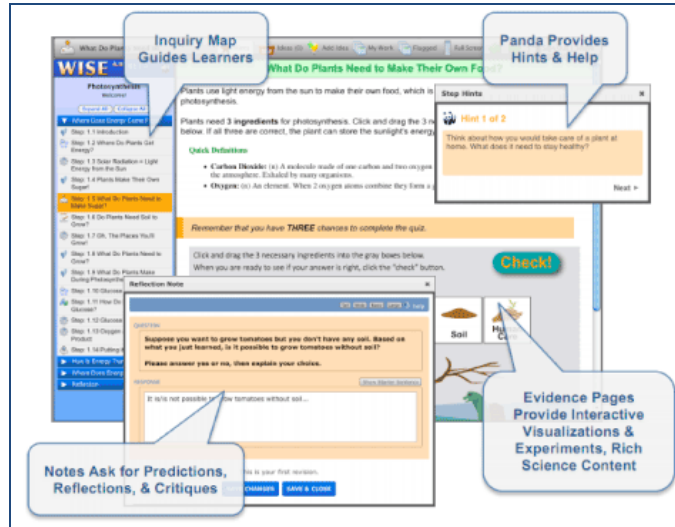


Figure 18: Screenshot of a typical WISE interface where labels show how students are guided and supported through the inquiry process.

In the UK a series of EU-funded projects²⁹ have investigated the potential of collaborative technologies for mathematics, in both synchronous and asynchronous communication. For example, the *Playground* project in 1998, when online communication and social media were far from developed, reported that stripped of even the semantics of gestures our extremely young students found it increasingly natural to try to communicate via the various formalisms that the system provided (Hoyles et al, 2010). Research since has shown that carefully designed systems can provide affordances for students to embed the artefacts they have constructed into their reports and discussions thus enabling students to build, share, discuss, and compare their work and their emerging mathematical knowledge (Mor et al, 2006a; Dragon et al, 2013).

By offering a space to compare and discuss their artefacts, and by allowing the outcome to persist publicly over time, students have the opportunity to reflect not only about what they are learning but also about their interaction with technology and their collaboration process itself (Hegedus & Penuel, 2008). The indications are that there exists the potential for significant transformation of practice in classrooms due to online connectivity. Yet communication is not a sufficient condition for learning, as the maths example demonstrated: the challenge is how the technology, activities, and teacher strategies together can motivate students to engage in and take responsibility for mathematical discussion of the process by which they construct their own knowledge and the justifications they propose for solutions to mathematical conjectures (Hoyles et al., 2010).

Collaborative learning combines practice and communication, in which students work together to produce a joint output, and in the process find themselves challenged by what it takes to produce an effective output, and by each other, as they debate and explore the best way to do it (Laurillard, 2009). Digital technologies support the students' practical production of a model, or document, or plan, or inquiry, and the means to share and discuss their ideas.

²⁹

<http://playground.ioe.ac.uk>, <http://www.lkl.ac.uk/kscope/weblabs/>, <http://www.metafora-project.org>

3.6. Problem-solving with game-based learning

The use of digital games is becoming important in STEM learning (Hailey et al., 2011; Li & Tsai, 2013), because games can offer students the opportunity to explore virtual worlds and solve problems. From a mathematical point of view, they are a significant source of the power of thinking about formal systems in the process of playing, and even more so, constructing games. They can support the learning of complex scientific and mathematical ideas by challenging students' alternative conceptions and by engaging students' attention through the level of interactivity they offer (Squire et al., 2004). An important feature of games is the sense that students have of "being here", a type of immersion which engages deeper learning experiences associated with Flow Theory (Liu, et al., 2009), as we discussed in Section 3.3.

Some games are simulations that engage students in the exploration of new worlds, or in novel roles. Others scaffold learning through a series of tasks specifically linked to subject content (Li, 2010). In the game *Supercharged!*, for example, students explore a virtual world in outer space (Figure 19)³⁰. To complete each 'mission', they must complete activities on electromagnetism. These tasks challenge students' own understanding and then encourage problem solving through the manipulation of variables and hypothesis testing (Squire et al., 2004).

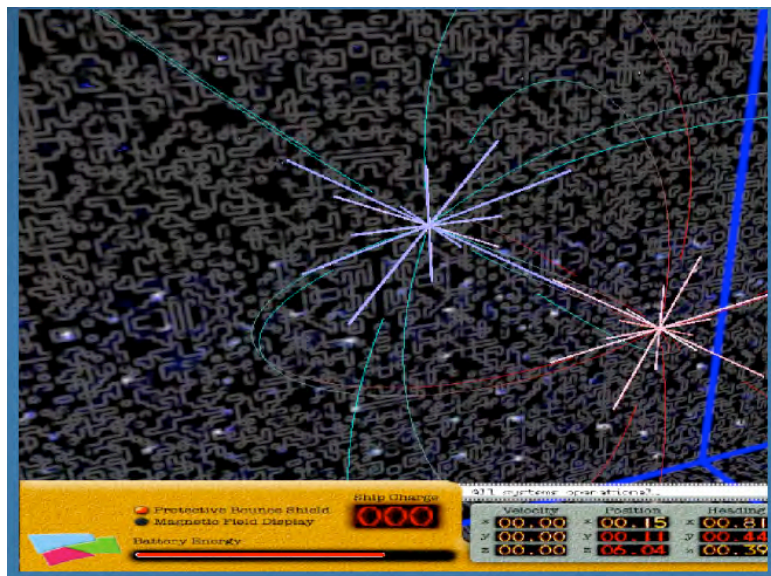


Figure 19: Screenshot of *Supercharged!*, showing the flightpage during the mission. The user's spacecraft starts each mission with a limited number of charges which cause attraction or repulsion to charged zones within the virtual environment. The user must guide their craft through these obstacles (which are features of electromagnetism, including point charges and magnetic planes) by obeying the laws of electromagnetism.

Games support both higher cognitive gains and positive attitudes towards learning (Vogel et al., 2006; Baltra, 1990; Prensky, 2002). However, the literature is mixed in terms of how these gains and attitudinal changes are made and correlated with the nature of the simulation, be it, for example interactive or game-based (Decortis & Rizzo, 2002; Parker et al., 2002). As technology has become cheaper and ubiquitous, people, and especially children, are playing more games

³⁰ <http://educationarcade.org/node/175>

(Lenhart et al., 2008). Surveys show that almost all children with access to digital technology use it to play games for enormous amounts of time (Holbert et al., 2010), with the PEW Internet and American Life Project showing that 97% of all teenagers play video games in some way (Lenhart et al., 2008).

Games support learning in a number of ways that are important to STEM education:

- epistemic literacy (Gee, 2003)
- mimic effective learning environments (Stevens et al., 2008)
- increase learning motivation (Orvis et al., 2008)
- support quantitative reasoning (Satwicz & Stevens, 2008)

There is emerging evidence that the designing and playing of video games also supports constructionist learning approaches (Galarneau, 2005; Harel & Papert, 1991; Kafai, 1995; Papert, 1993). In particular, action-based games, where the player takes on a specific role, through a digital avatar, encourage player-character construction, problem solving and opportunities for game-sharing with other players. The personally meaningful construction of in-game characters allows players to incorporate their own ideas and identities into those of the avatar (Gee, 2003; Harel & Papert, 1991). Designing scenarios, which involve the player using components, rather than complete objects in problem-solving has been shown to allow the player to develop new relationships with both their constructions and the problems they are trying to solve (Cavallo et al., 2004; Wilensky, 1991).

Providing opportunities for sharing of game-play, action games can nurture communities of learners as players interact with one another's methods and problem-solving approaches and construct new solutions (Kafai, 1995; Papert 1993).

For example, in exploring *Geniverse*³¹, students take on the role of a geneticist. By navigating their way through a virtual world, they solve genetic-based problems to understand how simple model organisms are used to investigate the genomes of more complex organisms. In addition, the game encourages the important skill of argumentation, such as evaluation of evidence and justification of claims (Kafai, 1995; Papert 1993) and, in doing so strengthens students' understanding of the complex genetics of inheritance. This collaborative game has been designed to closely match the school syllabus in the U.S. and encourages communication and sharing of good practice between schools.

In mathematics, games are perceived as a response to the need for "interesting, stimulating and challenging applications of mathematics, which are relevant to their world" (Clark-Wilson et al., 2011). While there are some very appealing games that can support learning of mathematics, most of them are designed to provide extrinsic reward for effectively doing drill and practice arithmetic in well-designed contexts replete with graphics, avatars, and sound effects. These games use only extrinsic motivation as a "sugar-coating for completing the educational content" (Habgood et al., 2011: 5), or to practice the concepts and skills already learned, or allow simplified assessment of existing knowledge. They do not assist the learner who is struggling.

³¹ <http://concord.org/projects/geniverse#about>; http://www.youtube.com/watch?v=EKN_Su30lQA

A better design is to integrate the learning content with the core mechanics of the game play. One example is to structure attacks on the enemy in terms of mathematical relationships in the way that the player's weapons combine, so that they learn how to manipulate mathematical representations in order to construct more effective actions (Hapgood et al, 2011).

An alternative approach to this type of integration is to construct the game play in a way that embodies the concept to be learned, so that intrinsic feedback on an action helps the learner work out how to improve their action to achieve the goal. One example is: given one rod length or number, to select the one that makes it up to 10, where the second rod shows a gap or overlap if it is wrong, enabling the learner to work out which one might work better (Butterworth et al., 2011)³². In both types of game record, success represents learner achievement of the outcomes, whereas in games that test students' knowledge using multiple choice questions success only represents the eventual guessing of the answers, so is not an assessment of learning.

Other examples are starting to appear that make authentic use of mathematics within the digital environment and demonstrate that developing procedural skills in mathematics is a means to an end and not just the end itself³³. Such approaches of course require considerably more investment in design and evaluation. Examples are: *Let's Play: Ancient Greek Geometry*³⁴, a series of geometry challenges; Zondle³⁵, a website and mobile app for practising basic procedural skills and to develop further number and fraction sense, with some 65,000 UK users; *Lure of the Labyrinth*³⁶ provides math-based puzzles pre-algebra students; *Dragonbox*³⁷ is an appealing example of a well-thought out game that turns solving algebraic expressions into an absorbing, well-designed puzzle game for young learners; *KickBox*³⁸ is a game developed by the MIND Research Institute³⁹ to promote and support mathematical thinking through puzzle solving.

There are literally thousands of games and other apps for mobile devices for mathematics. A useful resource for indexing them is under development from the Maths4Us initiative⁴⁰.

Interactive digital games have the potential to support independent practice in problem solving that require high-level conceptual thinking in science and maths, but although there is a lot of innovative development, there is very little research evidence of their effectiveness as yet.

3.7. Adaptive support

There is no doubt that teaching is more effective when it adapts to students' abilities, knowledge and skills. Interactive digital technologies are able, potentially, to adapt to what the student is

³² See also the review *What are the Implications of Psychology and Neuroscience Research for STEM Teaching and Learning?*

³³ <http://profkeithdevlin.org/2013/06/19/faulty-logic-in-the-new-math-wars-skirmish/>

³⁴ <http://sciencevmagic.net/geo/>

³⁵ <http://www.zondle.com>

³⁶ <http://labyrinth.thinkport.org>

³⁷ <http://dragonboxapp.com/>

³⁸ <https://itunes.apple.com/us/app/kickbox/>

³⁹ <http://www.mindresearch.net/>

⁴⁰ <http://maths4us.alt.ac.uk>

doing because all their actions in a digital environment can be monitored and interpreted. The decision-making that follows the interpretation requires a pedagogic model that selects the next best task or level for the student to work on, but this is another area that requires much more research than it has achieved so far.

One relatively new mechanism for adaptive support is 'learning analytics'. The term refers to use of the data that students leave behind when interacting with both structured and more open-ended environments, which can be analysed to provide useful evidence for assessment and support. Although research is only beginning to look at this, interaction based on students' interaction on modelling and simulation tools can be assessed on how well it matches real-world practice. In the US innovative means of assessment are beginning to emerge as researchers are realising that "digitized versions of paper-and-pencil item-based tests are insufficient to assess vital STEM skills like science inquiry" (Clarke-Midura & Dede, 2011) As a response, the detailed traces that learners leave behind when interacting with simulations or games are being used for assessment purposes (Dede, 2011; Shute & Kim, 2013).

Learning analytics has been defined as "the measurement, collection, analysis and reporting of data about learners and their contexts, for purposes of understanding and optimising learning and the environments in which it occurs"⁴¹. Seen in that perspective, 'learning analytics' has always been part of teaching and learning. However, the rapid growth of data is opening new possibilities as it brings with it the potential to analyse data patterns to assist in determining possible factors that may improve the learner's success (Chartlon et al., 2013). The field of 'Educational Data Mining' is concerned with "developing methods for exploring the unique types of data that come from educational settings, and using those methods to better understand students, and the settings which they learn in."⁴² Such methods are starting to be employed to test specific hypotheses on student performance, predicting students at risk, or for innovative means of assessment.⁴³ This technology could potentially influence teachers' practice if they are able to make use of detailed information about individual students or classes, which could range from simple analysis of resource usage and common procedural or conceptual errors, to more complex patterns of students' interactions. The technology could enable evidence-based teaching and policy-making, a shared objective amongst several educators.

Electronic voting systems (EVS) are a simple digital technology now frequently used for formative assessment. They are used in schools and colleges to gather feedback from students via handheld 'clickers' (Caldwell, 2007; Fies & Marshall, 2006; Judson & Sawada, 2002; Kay & LeSage, 2009; MacArthur & Jones, 2008) and have been shown to have a positive impact on engagement in the classroom (Caldwell et al, 2009; Amos 2010) and, when paired with appropriate pedagogic approaches, on learning (Fies & Marshall, 2006). Studies with undergraduate students demonstrate the effectiveness of EVS in promoting student interaction and engagement with mathematical problem solving (e.g. Robinson & King, 2009) and the benefits of EVS in probing understanding through diagnostic testing (Perišić, 2012), and learner self-motivation (Nicol, 2007). In addition, in an engineering context, EVSs have been shown to be effective in helping

⁴¹ The Society for Learning Analytics Research <http://www.solaresearch.org/mission/about/>

⁴² The International Educational Data Mining Society <http://www.educationaldatamining.org/>

⁴³ See the Journal of Educational Data Mining and Journal of Learning Analytics for examples of this type of work.

students to group ideas and concepts into themes (Russell, 2008). As handheld 1-1 devices become more common they will take over from the specialized clickers.

A very different form of technology-enabled adaptive support is 'Adaptive Tutoring'. For STEM, and mathematics in particular, it is one of the most well-researched and developed areas in the field of Artificial Intelligence in Education perhaps due to the assumption that these domains are well-structured and easy to model. Such systems have been mostly developed and used in the US⁴⁴, the best-known being the Cognitive Tutors developed at Carnegie Mellon University following a long line of development based on over 20 years of research e.g. Anderson et al., 2000).

UK research and industry is now beginning to make an impact in this area nationally and internationally⁴⁵. These so-called *Intelligent Tutoring Systems* provide a degree of intelligent support, interactivity and personalisation, which have demonstrable potential, usually with respect to structured problem-solving and procedural tasks. For example, in the US, a large-scale, random controlled field survey by the RAND Corporation, revealed recently a statistically significant impact of eight percentile points for students who used Carnegie Learning's Cognitive Tutor Algebra I material (Pane et al., 2013). Interpreting these effect sizes should take into account the narrowness of what is being measured, as this raises questions about long-term efficacy and impact. Many mathematics educators, for example, would not locate the essence of mathematical thinking in the procedural tasks that are currently typically presented in these systems.

Recent research in the field is looking to expand the range of intelligent support for students working in exploratory learning environments by tracking, analysing and responding to their actions and choices. For example, a prototype intelligent system that supports students' interaction in a microworld, *the eXpresser* (Figure 20), helps students develop algebraic ways of thinking (Noss et al, 2012, Mavrikis et al, 2013). The system analyses students' constructions and actions, monitoring whether at any given time they meet the high-level goals of the task and satisfy or violate certain constraints or rules (Gutierrez-Santos et al, 2012). It is also capable of feeding information about students' activities to the teacher, providing, for example, suitable strategies for pairing students for collaborative discussion (Noss et al, 2012).

The challenge is to provide feedback that has inferred what the student understands, and also, what the student is trying to do. This work is in its infancy, but will clearly become more important as computer scientists and STEM educators learn from each other.

Another approach is to embed teaching algorithms within an educational game, such as those being explored for teaching basic numeracy. Learner reaction times and accuracy are used to decide on the optimal next item, or whether to move to a different task or level, as a teacher

⁴⁴ Successful examples in mathematics include the research-based efforts of AnimalWatch (<http://www.animalwatch.arizona.edu/>), Assistments (<http://www.assistments.org/>) and companies like Carnegie Learning (<http://www.carnegielearning.com>) with the cognitive tutors that are backed up by research from the Carnegie Mellon University (e.g. Anderson, Corbett, Koedinger, 1995).

⁴⁵ See, for example, Whizz-Education <http://www.whizz.com> a UK company that has developed an online tutoring system for primary mathematics that is able to assess individual students' levels continuously in different topics in mathematics and empowers teachers to adapt their own teaching based on the classroom level.

would do in 1-1 tutoring (Butterworth et al, 2010; Butterworth et al, 2011). Again, these technologies are research prototypes rather than widely used products.

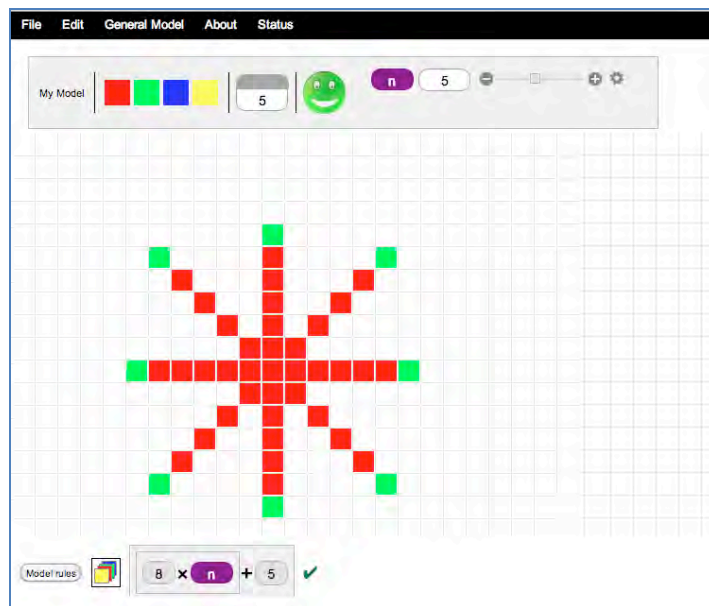


Figure 20: In the eXpresser microworld students construct repeating figural patterns and identify a general rule for the number of tiles in the pattern (in this case $8n+5$), while the system supports their interaction, helping them to develop algebraic ways of thinking <http://www.lkl.ac.uk/projects/migen/>.

There are several examples in the literature that show how the adaptive properties of digital technologies can be exploited to support students' independent learning in STEM subjects. This is an important development because it is another way of helping students to stay concentrated on a concept or problem, and put in the effort they need to understand complex ideas, and develop their high-level skills.

3.8. Online resources for self-study

In the last few years, new types of digital solutions for STEM learning are appearing in the form of a series of open resource online video clips⁴⁶, some of which include interactive question-and-answer activities. The rationale, motivation and potential behind such efforts is that the information and tutoring available is independent of time and place and (assuming it is of the highest quality) allows precious face-to-face time between teachers and students to be invested in more meaningful activities in the classroom, sometimes referred to as 'flipped learning'. Examples of these resources are provided by Bowland Maths⁴⁷ (a project from NCETM), and the NRICH website⁴⁸ (part of the Millennium Mathematics Project), both of which are illustrative of

⁴⁶ Notable examples include LearnZillion (<http://learnzillion.com>) and Khan academy (<http://khanacademy.org>)

⁴⁷ <http://www.bowlandmaths.org.uk/>

⁴⁸ <http://nrich.maths.org/>

the wide range of engaging content, interactive tools, discussion forums, and other resources that can be brought to bear in STEM education through the use of such technologies.

Another emerging resource for self-study is electronic books (e-books), digital publications that are readable on computers and mobile devices. These publications go beyond a normal book product because they embed sometimes highly interactive tools such as those exemplified in the rest of this review. As early as 2004 the e-book “Visual Math: Functions”⁴⁹ demonstrated the great potential of this technology by using interactive linked representations that can scaffold students’ understanding of function concepts. Similar approaches include the Freudenthal Institute interactive e-books⁵⁰ and Wolfram’s Computable Document Format⁵¹, which opens up the computational potential of such e-books.

There are several notable examples of searchable tools and resources for mathematics education, providing content for classroom activities, interactive mathematical tools, and forums for discussion for students and educators⁵². In the UK, the NRICH⁵³ website has become hugely popular with students and educators for providing rich tasks that are designed to engage learners throughout their primary and secondary educations. Learners can share their solutions and get feedback, and access monthly articles on different aspects of mathematics and mathematics teaching and learning.

The impact of these resources and tools, of course, remains to be investigated. It is worth bearing in mind that such resources open up new challenges to teachers who have to develop an appreciation of the content of the resource before they can support students. Then they can begin the transition towards enabling their students to develop more independent learning skills (Pratt, 2005).

3.9. Generic learning technologies

There are many uses of learning technologies that are of value to learners in all subjects. We have focused on studies that show why different kinds of technology have particular value for STEM education. The long list of additional advantages of using generic learning technologies for STEM as in all other subjects includes support for (i) *personalised learning*, because the learner can go at their own pace, receiving feedback on their own work; (ii) *self-efficacy*, because actions and feedback are private to the individual; (iii) *online access* to a wide range of multimedia resources; (iv) *communication skills*, because the asynchronous nature of communications enables learners to take their time to reflect and compose their contributions, assisted by language tools, (v) *students with disabilities*, because there are many assistive technologies help with different kinds of physical, social and cognitive disabilities; (vi) *learning analytics*, because students’ use of digital environments and electronic voting systems can track and analyse aspects of how students are learning; and (vii) *linking school work to the home* via the learning management system (LMS), which also provides the learning analytics on student progress for

⁴⁹ <http://www.cet.ac.il/math/function/english>

⁵⁰ www.fisme.uu.nl/dme

⁵¹ <http://www.pearsonhighered.com/interactivefigures/detail/precalc/index.html>

⁵² www.mathforum.org

⁵³ <http://nrich.maths.org/>

the teacher. For the STEM curriculum, these features add to the value of the particular types of technology covered above.

4. Evaluation of technology in STEM

4.1. Impact on students

There is evidence to show that the use of IT in schools has positive effects on students' attainment and (Becta, 2001; Cox & Abbott, 2004), particularly in science, makes the subject more accessible and stimulating, as well as helping teachers differentiate learning (Rogers & Finlayson, 2004).

Extensive studies into students' attitudes towards science (Barmby, Kind, & Jones, 2008; Osborne, Simon, & Collins, 2003) reveal students to be generally positive about school science when in primary school but this diminishes as they move into and through secondary school (Osborne & Collins, 2001). While technology may not be transformative in itself (Somekh & Davies, 1991), research evidence suggests that technology has a positive effect on learning outcomes (Becta, 2001, 2002; Cox & Abbott, 2004), a major part of this being the role it plays in engaging students (McFarlane & Sakellariou, 2002).

Engagement is an important factor in promoting positive learning outcomes for students. Not only is positive engagement seen as a means of enhancing science learning in school, but as fundamental to securing future career scientists and preparing all students for engaging in scientific issues in adult life (Bennett, Hampden-Thompson, & Lubben, 2011). How students perceive the value of science learning in relation to their own lives has been found to be a critical feature of engagement (Aikenhead, 1996; Osborne & Collins, 2001). It is closely linked to factors that motivate that engagement (Vedder-Weiss & Fortus, 2011), and in how students identify with the science culture embedded within the science teaching and learning they experience (Archer et al., 2010).

4.2. Teacher uptake

Evaluation studies typically focus on the effectiveness of specific instantiations of a digital technology. Evaluation studies of implementation programmes, of a new method of teaching, for example, do report on teacher uptake. However there have been no large scale development and implementation programmes of digital learning technologies. Local uptake of specific technologies tends to happen without formal evaluative evidence, primarily because, inevitably, there is very little that is reliable or validated for local context.

Digital technologies have been shown to allow students to learn in new ways and promote engagement in science (Hammond, 2013; Logan & Skamp, 2012) and the range of digital technologies available to both teachers and students in schools is great (Cox & Abbott, 2004; Hammond, 2013). However, even recently, there is evidence to show that use of this equipment is not widespread and that it is often used in limited ways (Webb, 2005; Yeung, Taylor, Hui, Lam-Chiang, & Low, 2012). However, to be used effectively requires teachers to have expert knowledge of appropriate pedagogical approaches (Mishra & Koehler, 2006), something where teacher preparation and support must play an important role (Muijs & Lindsay, 2008).

We know from older studies of technology use in the wider curriculum that teachers are often enthusiastic and motivated by the potential learning experiences offered by digital technologies

and are keen to integrate them into their practice (Russell, Bebell, O'Dwyer, & O'Connor, 2003). However, the use of digital technology tended to be for fairly 'low-level tasks', such as word processing or presentations, with teachers most commonly using them with students for internet-based research (Eritrea, 2005; Ertmer, 2005). Unsurprisingly, teacher confidence with using digital technology plays a key role in how technology is used by the teacher and students, and the frequency of use (Hennessy, Ruthven, & Brindley, 2005), and there was a lack of emphasis within teacher training programmes on using digital technology in the classroom and this is something that appears to be changing only slowly. The typical reasons for lack of uptake found in a range of studies were reiterated in the Becta report of 2004 as lack of confidence, access, training, time, and technical reliability. These measures were becoming more positive in the later reports up to 2006 (Becta, 2006). More recent updates are lacking due to the abolition of Becta in 2010.

5. Discussion and conclusions

What does evaluation tell us about the uses of new digital technologies in learning in STEM subjects, and the factors that influence their use and uptake?

From the review in the previous section of the research literature, the grey literature, and from online repositories and communities of teachers and developers, it is clear that digital technologies play a wide variety of different roles in supporting learning in all the STEM subjects. Digital technologies provide symbolic, graphical, and dynamic representations of STEM systems that make them accessible to design, exploration and testing, by students of all ages, at varying levels of digital literacy. For all STEM subjects they make the abstract world more accessible through experiential learning, because complex ideas can be represented on screen as computational objects, which students can manipulate as they would material phenomena, facilitating a deeper connection with the ideas.

In summary:

- The act of developing a formal model of some aspect of the world provides a rich and intensive learning experience requiring the learner to use and develop STEM knowledge and skills, supported by the feedback from the behaviour of their model.
- The appropriate use of simulation technologies enables students to explore the behaviour of STEM systems, and carry out safe and efficient virtual experiments and inquiry projects both in the classroom or at home online.
- The examples in Section 3 are from uses of technology across the age range from early primary through to post school. There is no educational reason at this stage to link particular technologies with either age or STEM subject. Safety and security are particular considerations for any use of the internet, and this applies to all age groups.
- Digital tools must always be used alongside the real-world practical work, so that students develop the skills of manipulation and measurement, planning and time management, negotiation and organisation of resources, etc., as well as the understanding of why experiments do not always work.
- The technologies of simulation and modelling facilitate experiences that would not easily be engineered in everyday life or conventional classrooms so that learners are able to act within imagined decision-making scenarios that not only promise a better appreciation of

the power of science and mathematics but also recognise the limitations of those disciplines.

- Learning through immersion in virtual learning interfaces is valuable for the individual learner, because it keeps them engaged and on-task, becoming self-motivated, rather than externally driven. This is the kind of experience that develops the reflective independent learner.
- Mobile data gathering and analysis technologies bring students close to authentic scientific inquiry, enabling them to see that they can discover and explain the world around them using digital tools to plan their project, gather and analyse the data, and represent their results in different forms of textual, graphical, statistical, mathematical, and dynamic representation.
- Digital technologies support collaborative learning in terms of both the students' negotiated representation of a model, or document, or plan, or inquiry, and the means to share and discuss their ideas.
- Digital technologies make it possible for students to experience authentic ways of collaborating on STEM-specific issues and problems, working with experts beyond the school, and sharing ideas with peers, by using the computational power of the cloud.
- Interactive digital games have the potential to support and guide independent practice in problem solving that requires high-level conceptual thinking in science and maths.
- The adaptive properties of digital technologies support students' independent learning by helping them to stay concentrated on a concept or problem, and put in the effort they need to understand complex ideas, and develop their high-level skills.
- Because digital representations make students' conceptions and skills explicit, they can be assessed to some extent by the technology itself, and teachers are able to use this student data for both formative and summative assessment.
- Open online resources and tools for STEM subjects open up new challenges for teachers who have to develop an appreciation of the content of the resources before they can use them to help their students develop more independent learning skills.
- Generic digital learning technologies are of equal value to all curriculum areas, including the STEM subjects, because they also support, for example, personalised learning, self-efficacy, open online access, communication skills, students with disabilities, learning analytics, and the link between school work to the home.
- Most of the studies of viable technology-based innovation in the literature review derive from research-based learning technology products for STEM learning; there are few reports of successful commercially designed STEM-oriented software, which too often falls short of exemplifying good pedagogy.
- What is the teaching community's response to digital learning technologies in both their uptake and perceptions of use in STEM subjects?
- The grey literature, and online teaching communities show that there are many good examples of viable innovation in schools and colleges but these are the exceptions, rather than the rule in terms of what happens day-to-day.

6. Commentary: The Vision for 2030

What will a successful education system look like in 2030 and how will we know it is successful?

In this section we use the findings of the literature review, and an analysis of the current and potential use of technology in schools and colleges, to propose the characteristics of a future education system that uses technology to achieve (a) wider scientific, mathematical and technological literacy among the population in general, and (b) assessment systems that both enable and measure this aspiration for STEM education. We then go on to establish the means by which we might achieve this over the next seventeen years, given the findings in the review.

As in previous sections, we do not explicitly differentiate between primary, secondary and further education in our discussions of technologies of the future. In all cases the teacher must take responsibility for ensuring that their use of technology is appropriate for their students, but we do not focus on the age-related issues of safety and security, only on the pedagogic issues of how to improve the learning of STEM subjects for all students. Very young students can be more self-motivated, and confident in their digital skills and independent learning abilities than much older students, and there is little reason to differentiate by age. It is the teacher's well-rehearsed role to ensure that they take each learner's individual needs into account as far as they can. The new opportunities for technology-enabled learner tracking and feedback should assist them in this.

The annual US Horizon Report is a good source of ideas for emerging technologies in education because it sources these from education and learning technology experts internationally, using a Delphi approach. Of the six technologies highlighted this year, three are of generic importance (cloud computing, learning analytics, and open content), and three are of particular interest to STEM teaching. The 2013 report for K-12 (NMC, 2012) proposed the following:

Time-to-Adoption Horizon: One Year or Less

- Cloud Computing - already in use in some institutions to improve quality of remote access
- Mobile Learning - already widely used to improve flexibility of access for learners

Time-to-Adoption Horizon: Two to Three Years

- Learning Analytics - used in some institutions for teachers to track students' progress
- Open Content – used in many institutions to improve the quality of teaching resources

Time-to-Adoption Horizon: Four to Five Years

- 3D Printing – used in a few schools and colleges for physical outputs from digital designs
- Virtual and Remote Laboratories – used in a few schools and colleges for authentic skills.

The more interesting technologies in terms of their pedagogical affordances for STEM thinking are those covered in Section 3, and their future innovative forms.

One word of caution: we cannot predict the technologies that will be available in 2030. This analysis assumes they will include all the benefits and capabilities of current technologies, and will be sufficiently ubiquitous, low cost, high quality and robust that they can be used throughout the education system. The future technologies that will be transformational and viable in education are hard to predict.

However, David Wood's 1993 version of a future scenario for technology-based learning in 2015 was impressively accurate, predicting fieldwork projects supported by mobile wireless devices, learning with pen tablet computers, collaboration through computer networks, and tools for teachers to analyse the progress and outcomes of learning, all of which are now feasible, though not always widely used (Wood, 1993). In 1993 the barriers were (i) *access to the technology*, (ii) *usability*, (iii) *an outdated curriculum and assessment system*, and (iv) *the lack of involvement of teachers in educational innovation and curriculum development*. The first two have been addressed and account for the impressive explosion of technology use in schools and colleges. The latter two remain (Sharples et al., 2012).

Our future analysis therefore focuses on the means by which an education system stays abreast of, and makes the most of, whatever useful technology innovations may come our way. Above all, the education system must be adaptive, particularly to the economic, social and political changes that will occur over the next seventeen years. It has adapted well to technology changes in the past decade or so, given the pace of technology innovation and the lack of investment in teacher involvement in the mechanisms of systemic change. Our concern here is how to ensure education becomes more adaptive to the changes in technology. We begin with the vision of what the STEM education system needs, and for sections 5.3 onwards we propose the critical conditions for realising this vision.

6.1. Using technology to engage more students in STEM subjects

The review shows that technology is able to engage all learners in STEM subjects because it affords such opportunities as active learning, authentic practice with feedback, collaboration, creativity, ubiquitous opportunities for linking STEM concepts to their environment, links to students' interest, engagement in game-like learning, home-school links, supported independent learning, and many more.

As the review shows, the study of science, technology, engineering and mathematics can be as practice-based, social, collaborative and creative as that of music, drama and art, all of which have the kind of extensive social and practical after-school activities and competitions that are not mirrored in the STEM subjects for many schools. The review demonstrates the wide range of technologies that can support the whole STEM curriculum in all these activities.

In 2030 the use of technology for practice-based, social, collaborative, and creative forms of learning should be commonplace in all STEM subjects for every school.

By this means, we should be able to achieve much wider scientific, mathematical and technological literacy among all graduates from the UK school and college systems.

6.2. Ways of using technology for assessment

The most popular use of technology for assessment has been for summative assessment i.e. employing technology to ease the delivery and marking of tests given at the end of a module, mostly for certification purposes. International assessment tests drive the way we now assess the effectiveness of our education systems, so we must take care not simply to assess what is easy to measure in this way, but to look also for ways in which technology can help with more challenging forms of assessment.

It is important that the Vision for 2030 embraces the true value of STEM education. The UK system is recognised as being successful in educating people to be inventive, innovative, and

critical of the status quo. The regimentation of teaching that creates success in exams yields at the same time a relative failure to foster the critical thinking and capacity to challenge that the Royal Society Vision statement envisages. Chinese Premier Wen Jiao Bao at his speech at the Royal Society in 2011 said: “In my recent conversation with some Chinese scientists, I called for creating an environment which encourages innovation, criticism and risk-taking and tolerates failure, an environment that encourages free exploration of new things and stimulates academic debate.” Asian countries are extremely successful in international tests, and yet they still look to our education system and its ability to encourage these forms of thinking, the essence of a STEM education.

As we consider how best to assess the success of our future education system, we must therefore consider the more interesting function of technology-based assessment, namely its potential to enable both formative and summative assessment of STEM ways of thinking.

Several of the technologies described in Section 3 provide formative feedback in the sense that the learner receives feedback on how effective their actions were in relation to the goal, which helps them to improve their action and so develop their concepts and skills. Because they are using the technology to produce a specific output, the same software can be used in summative assessment as way of representing what they have learned. For example:

- In Section 3.1 the task for the student is to create a model or design that works, and the success of the model is an objective representation of the learning achievement.
- Simulations, in Section 3.2, can be manipulated to deliver a target output, which thereby represents the student’s understanding of how the system works.
- The technology tools discussed in Sections 3.3, 3.4 and 3.5 could all be used by students to produce and submit outputs for the teacher to mark, as representations of the learning they have achieved by using the tools.
- In Section 3.6, the user-constructed outputs required by the games that offer formative feedback enable students to progress through the game to higher levels and higher scores and this achievement represents what they have learned.
- Section 3.7 discusses intelligent tutoring systems (ITS), which can also double as assessment systems because they assess the student’s performance on each task.

Of course the teacher can also use all these forms of summative assessment as feedback on their teaching. The particular value of these different types of technology-based assessment is that they demand high-level performance on a complex mix of theory and practice from students, and yet they can be carried out very frequently, at low cost to teacher time. Moreover, if student performance is collected and tracked by the LMS, it provides the teacher with an ongoing and detailed analysis of the progress, or not, of all their students. Recent studies, for example, provided evidence of the value of this as an early-warning system for failing students (Macfadyen and Dawson, 2010), and on the effectiveness of an ITS for homework assessment, because it enables the teacher to use detailed feedback on individuals and the class, and tailor their teaching accordingly (Singh et al., 2011).

In 2030 the exploitation of learning technologies should be a normal way to carry out high quality summative assessment of complex conceptual understanding and high-level skills in STEM subjects.

By this means we should be able to achieve assessment systems that both enable and measure our highest aspirations for STEM education.

6.3. Fostering cross-disciplinary work

The value of interdisciplinary work in STEM education is now recognised (Romance & Vitale 2012). In both academic and vocational areas of STEM teaching it is possible to use technology to foster more cross-disciplinary ways of teaching these subjects, and show how, for example, the work in the maths lesson and the physics lesson combine to solve the problem in the computing lesson.

We can assume that all students will have the opportunity to develop their digital skills because of the ubiquitous use of technologies that foster them. Even very young children are already capable of thinking computationally, which relates closely to maths skills. However, teachers notice that even if a child is not very good at maths they can still be outstanding at computing. Technologies such as the *MissionMaker* tool (Section 3.1) can engage these children in many aspects of mathematical thinking, thereby creating a bridge across the disciplines.

An example of a crossover between science and computing would be the use of accelerometers in iPod Touches. Remote control of objects such as quadcopters from an iPod Touch invites learners to explore the question ‘how does it work?’ There are apps for landing a shuttle, and controlling models in a gravitational world in which they have to think about how gravity works. Such the tools bridge the disciplines, and afford cross-disciplinary thinking that gives meaning to both the maths and the science. Because of their game-like qualities, there will be many such devices that can be deployed in STEM education.

This is just one example of how we could foster more cross-disciplinary ways of teaching STEM subjects, enabled by technology and by students’ increasing digital skills.

The degree of interdisciplinary work carried out in schools and colleges will be highly dependent on the nature of the curriculum and assessment. Learning technologies do not drive a focus on interdisciplinary thinking but they do enable it. They can contextualise a fundamental concept in one STEM subject by demonstrating its relevance for another within a simulation or modelling task, for example. Schools and colleges could mirror university departments that collaborate across the disciplines by finding the core projects that work across the disciplines, and thereby encourage even very young learners to ask compelling but tractable interdisciplinary questions (Alexander, 2004).

The role of technology in fostering online collaborative work can also be used to foster this contextualised way of thinking about a discipline. STEMNET have been involved in promoting this for a long time⁵⁴ by making it possible for professionals to talk to children about the work they do, such as how technology supports their work as a scientist.

To work towards the Vision for 2030: Foster cross-disciplinary thinking by using students’ increasing digital skills to use technology tools for solving complex problems that work across the disciplines.

Reform the curriculum and its assessment to support and reward interdisciplinary work.

⁵⁴ <http://www.stemnet.org.uk/regions/1601>

6.4. Supporting active independent learning

In the last few years, mostly as a response to technological advances, we have seen a widespread surge of interest in what is referred to as the ‘flipped classroom model’ which started from trying to answer the question: “*What is the best use of teachers’ time in the classroom?*”⁵⁵. The idea is based on two assumptions: (i) that a significant element of traditional classroom activity is a teacher uniformly lecturing a diverse group of around 25-30 students and assessing responses to exercises, and (ii) that this teaching could be made available online, leaving the face-to-face classroom time for teacher-guided group learning and activities. The teaching is instantiated in various forms, such as using screencasting of teacher-created content, or is delegated to websites such as Khan academy videos⁵⁶, or takes the form of general preparation through textbook material and assignments before a topic is introduced. The intended benefit is that students have more individual time to work with their teacher in constructionist inquiry or exploratory activity aimed at deepening understanding and developing skills.

To be successful, the home-based study imagined by the flipped classroom will require further development of all the technology-based pedagogies of practice-based, social, collaborative, and creative learning, as well as the forms of independent learning, discussed in Section 3. Videos are not enough. The teacher must be able to design and orchestrate the work the learner does outside the classroom with the same care they use for lessons on site. It is feasible to do this, given the motivational properties of the different technologies, but the quality of pedagogic design needed to keep students on track while online at home is extremely challenging.

A new approach to supporting independent learning uses ‘agent’ technology to enable students to learn through ‘teaching’ an avatar about the science of river systems. Research linked to neuroscience suggests that even virtual social interactions of this kind activate the brain’s reward circuitry, which helps to embed new learning (Chase, Chin, Oppezzo, & Schwartz, 2009; Chen J, Shohamy D, Ross V, Reeves B, & AD, 2009; Schwartz, Blair, Biswas, Leelawong, & Davis, 2007).

The future school is unlikely to have a larger proportion of home-based study (not least because of the need for the safety and care of children), but it is highly likely to offer a more flexible environment that affords and supports a mix of supervised / independent, online / location-specific, and class / group / individual learning.

To work towards the Vision for 2030: Develop flexible learning spaces in schools and colleges that enable teachers to blend in technology methods that help to scaffold and develop independent learning in their students.

6.5. Linking school work to the home

Students will from now on always be using digital technologies in their home, community, leisure and workplace environments, as well as in schools and colleges.

A recent survey of over 1000 young people aged 8 to 17 in the UK showed that 82% of learners have home access to the internet, and 87% have home access to at least one computer (Davis & Good, 2009). It is therefore already possible for teachers to expect learners to use technology as

⁵⁵ Bergmann & Sams invited lecture in BETT 2013 (<http://www.bettshow.com/>) see also <http://flipped-learning.com/>

⁵⁶ <http://www.khanacademy.org>

part of their homework and preparation, while making provision at school for personal use of computers for all learners⁵⁷. The nQuire project (Section 3.4) is one example of technology supporting learners at home and at school in carrying out their own scientific inquiry.

The technology-enabled link between home and school is one area that will become ever more significant, even if the curriculum and assessment methods remain stagnant. As cloud computing allows students to have more or less continuous access to the digital resources used in the classroom, studying will extend relatively seamlessly across home and school, college or workplace (Sharples et al., 2012). The nature of homework will change accordingly. Whether the classroom is completely flipped or not, it should certainly engage students in more active, online social and collaborative learning.

Using technology to bridge the gap between home and school is also an opportunity to engage parents in their children's learning. The technologies now broadly available are: cloud computing, GPS, mobile learning, open content, curriculum content and home learning orchestrated by the LMS, and technologies for inquiry, simulation, augmented reality, modelling and design. They make a powerful combination.

In the context of science and engineering, geospatial technologies have the potential to change how we view the world, and how we solve problems, and can support practical work in a variety of ways across different subjects. Geospatial technologies comprise a broad range of tools for capturing, managing, analysing and displaying data that is related to a particular location, and which include Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, aerial photography and field sensors. Developments in networking, wireless access and freely available software (e.g. GoogleEarth) have made geospatial tools readily available for everyday interaction, and offer new opportunities to exploit their potential for teaching and learning.

What is particularly interesting about mobile geospatial technologies is their capacity to enable real-time physical location to be experienced in new ways in relation to spatial ideas. Physical experience that begins from one's own location (viewpoint) can be augmented with spatially related information, and can foster local to global ways of thinking, not only in geography and environmental science, but also in science, maths and other subjects like history. This means that they have the potential to play a very important role in transforming the way that teachers might think about their subject, how they might teach that subject, and ultimately have a significant impact on that part of the curriculum (Baker, Kerski, Huynh, Viehrig, & Bednarz, 2012).

It becomes possible to imagine the student being able to call on the formal curriculum to help them interpret and enhance their everyday experiences – looking around their home or community environment, they could use an augmented reality app linked to their LMS to see the mathematics in the shape of a car, or the molecular structure of their cereal, or the algorithm behind the traffic-control system, or to capture and improve the design of a backpack, and share these findings with their peers, and use them in the next class... making real the aspirations of a curriculum that engages all students in the wonder of the natural and social world and how we

⁵⁷ The E-Learning Foundation helps schools achieve the universal access that equalises learners' opportunities by assisting with the cost of 1-1 access (<http://www.e-learningfoundation.com/>).

come to understand it. Giving parents and carers access to the same learning environment gives them a window on their children's education, and the opportunity to take part in the same activities.

To work towards the Vision for 2030: Give teachers the means to integrate the range of technologies available to their students in ways that will support their independent exploration of the STEM curriculum in their everyday lives.

6.6. Drivers and barriers affecting technologies in STEM education

Why has technology not made more impact in STEM education, after more than a decade of infrastructure development in schools? In this section we consider the main drivers and barriers present in the system that affect innovation and implementation.

Drivers of the education system

One of the reasons put forward for the lack of impact in education generally (Laurillard, 2008) is that the drivers of education do not adapt to changes in technology. This affects STEM subjects as well:

- The education system is a complex system of powerful drivers—assessment, curriculum, inspection/quality requirements, funding flows, promotion criteria—none of which have changed significantly in recognition of what technology offers (Laurillard, 2008).

All these drivers determine the ways in which teachers and learners orient their energies and are judged by others. Unless the drivers of the education system change, i.e. the STEM assessment and curriculum in particular, the behaviour of its members will not change.

Barrier - STEM curriculum and assessment

The mathematics curriculum is not fit for purpose. It reflects through its emphasis on 'fluency' and 'calculation', objectives that were essential when society needed thousands of clerks who could conduct accountancy and administrative tasks efficiently. Despite fundamental changes in society in the last 35 years, driven by the development of technology, schools and schooling remain essentially the same. This is primarily because the curriculum and assessment methods in mathematics remain almost unchanged. Without a radical re-think, the opportunities for reform that technology offers will have only superficial impact on the teaching and learning of STEM. In that scenario, the prediction for 2030 would be that the teaching and learning of mathematics will be pretty much as it is now! In the context of geospatial technologies in education, the need to understand how to map these new approaches to the curriculum is highlighted, together with the role that technologies also have on developing curricula. Hagevik (2011) highlights this issue of integration into the curriculum, developing a 5-step programme of teacher professional development to support this process.

The 21st Century skills needed must emphasise areas such as collaborative problem solving, computational thinking, and modelling. Technology offers communication systems, programming and a variety of expressive media ideally suited to support the development of these skills.

Assessment practice also needs to change in order to recognise the more complex and nuanced kinds of understanding that the use of technology affords, for example: the relationship between the knowledge and practices associated with using particular tools and the associated formal knowledge and practices of the STEM disciplines (Goos et al., 2010).

Barrier – rapid change, leadership and politics

The drivers are difficult to change, however, because:

- Technological change is very rapid. We have seen the digital equivalent of many key technologies for education in less than half a century, and have not yet had time to make the radical changes afforded by digital technologies.
- Leaders at all levels of the education system are not comfortable with either the detail or the implications of the technology potential, and those professionals who are knowledgeable are not powerful enough within the system.
- Education is essentially a political activity and a national enterprise, embodying the moral values of a country, so it does not easily become commercialized or globalised, and therefore avoids being subject to the innovation that market forces encourage (Laurillard, 2008).

These characteristics have become barriers to change, and they will not disappear in the near future. Rapid technological change is highly likely to continue, and as communications improve even further, innovation will happen even faster. Leaders in the system will be today's digital natives, but change will always be too rapid for those at the top to be able to manage it well. Leadership in the future will mean learning how to use the professionals who are close to innovations and understand how to use them. Policies will probably remain subject to short-term opinions rather than the evidence that accumulates over time. There is no longer any development of the knowledge base for learning technology available to the political system in England and Wales, and very little investment in research in the field, so there will be little evidence-based policy.

Barrier – lack of involvement of teachers

Neither can the system learn from the professionals:

- Education systems change slowly because they tend to be hierarchical command-control systems, rather than devolved-power adaptive systems. Teachers have neither the power nor the means to improve the nature and quality of the teaching-learning process through technology (Laurillard, 2008).

Similar findings come from research on how to support students and teachers in the development of new practices around teaching mathematics with technology (Joubert, 2013; (Mumtaz, 2000)), and the recent overview of pedagogy innovations (Sharples et al, 2012). These findings suggest that:

- the STEM curricula and assessment systems need to be rethought in the light of changes related to digital technologies;
- providing hardware and software alone is not sufficient;
- teacher support is needed in the form of e.g. teacher assistants for supervising students when using computers;
- large scale change requires commitment and leadership at the policy level;
- we need to foster continuing teacher professional development that enables the profession to respond adaptively to changes in requirements and in technology.

Barrier – teacher attitudes?

Research has established that the beliefs and attitudes of teachers with regard to adoption and use of technology in STEM education are important for success (Goos et al., 2010; (Mumtaz, 2000)). However, it is difficult to gauge the change in attitudes of teachers over the past 20 years, especially since the abolition of Becta in 2010, since when there has been substantial innovation on the ground. The mathematics education community, for example, is clearly focused on the rapidly changing technology landscape, but having predicted massive changes and high rates of integration and adoption, now seems to be grappling with a reality in which adoption and impact are challenged by the complex arrays of obstacles in the curriculum, assessment and quality drivers in the system (Cuban et al., 2001; Ruthven & Hennessey, 2002).

Teachers' perceptions of the tension between what should be covered and the way to 'teach' it explain why very often teachers will use methods and tools they know and feel comfortable with (Mumtaz, 2000). Other factors are the impact of teacher's 'perceived fit' of technology within their goals for students, their own teaching strategies, and the expectations for student learning (Penuel, Roschelle, & Schechtman, 2007). In general, teacher attitudes reflect a growing awareness of the potential power of technology alongside need for more professional background knowledge of the various challenges associated with adoption. This is an area of investigation that remains under-represented in the research.

Barrier – social challenges

There are social challenges that affect the adoption of technology (Healy & Kynigos, 2010; Ursini & Sanchez, 2008) in STEM education, including gender, class, and ethnicity. The indications are that while technology has great potential to enhance teaching and learning in STEM subjects, there is always a danger of inequitable access. We have to ensure inclusive practice that benefits all students and avoid recreating unnecessary patterns of privilege.

Given the drivers and barriers considered here, our recommendations are directed towards not just the pedagogical possibilities of new technologies and the improvement of learning experience and students' learning outcomes, but also towards how best to meet these challenges through changes in teaching as a profession.

To work towards the Vision for 2030: Consider how to overcome the barriers of an out-dated STEM curriculum and assessment, rapid technological change, non-adaptive leadership, the diminished knowledge base for policy, the lack of teacher involvement in innovation, and the social challenges of equity of access to technology.

6.7. Alternatives for the future

Rapid innovation means that there is rarely sufficient research, evaluation, and development to build the knowledge needed to optimise the use of each new technology innovation, and to ensure large-scale implementation. We have to change the way we do technology innovation in schools, as the pace of innovation is unlikely to slow down. At present there is little sign of the system being ready to take a different approach to dealing with the problem. One possibility is to adopt existing models from other professions with a similar challenge. Another is to upgrade current professional development provision. Both have their problems. Our preferred option is the third: to establish the teaching community as a professional development network for innovation, design and action research.

Adopt the health community model

There is increasing recognition that the teaching community could potentially adopt approaches used in the health community, which builds online communities for knowledge exchange among professionals. There is a similar need for continual updating of knowledge in the light of rapid innovation, alongside practitioner knowledge developed from practical implementation in a wide range of contexts (Morris & Hiebert, 2011). Two current examples of this approach are the Educational Futures Collaboration⁵⁸ and an HEA project to use a Department of Health model to build and support a community of 40 simulation development officers across the country, working on a very part-time basis to provide the resources, guidelines and working practices that will make this form of learning work as effectively as possible⁵⁹ (Laurillard, 2013). Funding for such networks within the health sector, however, outstrips that available for schools and colleges. The Teaching Schools network and regional clusters of FE colleges could be using technology enhanced collaboration tools to enable partnerships, chains, and networks to collaborate on innovation in a similar way, to update each other continually. It remains to be seen how well these models work in practice.

Provide continuing professional development in learning technologies

How should teachers know which of the plethora of learning technologies to use, and how to make best use of them? This question is a key reason for providing high quality continuing professional development (CPD) on this for all teachers. Teachers should be able to draw on the range of technologies reviewed in Section 3 and be supported in developing a better understanding of how to make them fit with their learning goals (Mishra & Koehler, 2006). This could be delivered in part through formal CPD, but the size of the task of keeping up with technology innovation, and testing and exchanging ideas on how best to use each new innovation, goes well beyond what can be delivered through occasional training days. The task is also too great for the research community, given its current level of funding. And the commercial sector is unable to derive enough profit from the education sector to be able to fund high quality R&D needed to develop the best technology-based solutions. CPD sessions are important, but mere delivery of the current ideas, is not sufficient, any more than it is for learners. Teachers also need to learn collaboratively (Laurillard, 2008).

Teachers' communities of innovation

The teachers' community of practice, spread across all three sectors of primary, secondary and further education, is in a strong position to discover and test each innovation as it emerges, because they see every day how their students respond to and use technology within and beyond the institution. This is how most of the current innovation has developed. However, the drivers and barriers discussed above distort the process of teacher-driven innovation, and the lack of orchestration of the process diminishes the potential impact of the good ideas that do emerge.

⁵⁸ <http://www.educationcommunities.org>

⁵⁹ Association for Simulated Practice in Healthcare, Higher Education Academy

The shared community knowledge that allows teachers to make good judgments in the choice and use of technology in STEM education is essentially a constellation of the knowledge and practices of the professional community of educators and researchers. The guidance on how best to use digital technologies will need continual updating, and online communities of practice will play a critical role, in updating the current evidence of what works. Training Schools are now doing more action research in schools, which will provide more evidence based research, as well as doing external CPD. They have to show how their practice evolves, so in the near future they could play an important in supporting teachers' online collaborative learning about technology (Laurillard and Masterman, 2009). This is where the use of learning analytics to collect and share evidence needs the guidance and support of the research community to ensure that it is replicable and valid.

Teachers can also draw on the students as contributors, enabling the student voice to influence the way the curriculum is interpreted and taught. The Digital Leaders programme⁶⁰, for example, which encourages students to take the lead in helping a school and other students to use technology well, shows that if we challenge them they will respond.

More links between school and the STEM industry would extend community development process. Current examples are 'Inspiring the Future', which offers a very low cost web-based link between schools and the workplace volunteers who can support them⁶¹; 'Speakers for Schools' provides links to high profile speakers from STEM backgrounds⁶² to broaden the horizons and raise interest of young people in issues of public interest. (Mann & Oldknow, 2013).

Teachers are beginning to organise themselves as communities of practice to share their pedagogic ideas, especially through the subject associations and national centres. However the open resources on offer are mainly presentational, and the pedagogies mainly classroom-based, rather than oriented towards independent interactive learning activities. So we look also at what it takes to create a culture of innovation among teachers, to enable them to keep learning how to make the best use of technology for STEM subjects.

Develop a culture of innovation in teaching

There have always been individual teachers who are interested in innovation and creativity and enjoy thinking about what technologies can be exploited to enhance learning and teaching. For most teachers, who are willing to use technology but cannot take the lead, the culture within the school is critical. Innovative teachers stress the importance of having confidence in the children and giving them the means to experiment, create, and even go beyond what they themselves know.

Digital technology has created the extraordinary cultural shift of making students more expert than their teachers in some key 21st century capabilities. Their ability to learn about technology for themselves means that the culture of teachers should be to learn from the students as well as teaching them. Teachers have to be open to their students having better ideas about using the

⁶⁰ <http://www.digitalleadernetwork.co.uk>

⁶¹ www.inspiringthefuture.org

⁶² www.speakers4schools.org

technology. However being able to use technology is importantly different from being able to learn through technology, just as being able to read is different from being able to learn through reading. Learners of all ages still need expert teacher guidance in how to learn through technology.

Specify the technology requirements for STEM education

The changes to come in the potential for STEM education are only just at their inception. Many of the most compelling technologies reviewed in Section 3 have been developed in research labs, on short term funding, with no rollout to widespread implementation. Many of the technology innovations in the classroom have developed despite the drivers and barriers in the education system. The technologies that are most widespread are those developed for business, commerce and leisure industries, adopted and adapted by education. For technology to have a real impact in education it should be driven more by the requirements of education, rather than dictating what the system should use.

What education probably needs most is the tools that will enable a teacher to give the high quality personalised support and guidance that every student needs if they are to reach their learning potential. The current phenomenon of MOOCs (massive open online courses) has not needed to address this issue as yet, because the great majority of participants are mature professionals with degree qualifications who are good independent learners. Similarly the ‘flipped classroom’ has been used successfully for adults in open universities, but has yet to be properly tested in schools and colleges (Staker and Horn, 2012). If this model is to succeed for younger learners, then teachers will need an ecology of learning design tools and resources for orchestrating independent and collaborative learning, and for monitoring and guiding student progress. We can see the constituent capabilities in the technologies reviewed in Section 3, but teachers are poorly served in the technology tools currently available to them.

Primarily, we should see a continuing trajectory of ways in which students will have access to the deep mathematical and scientific ideas that can be supported through technology. But this will only happen if scientists and educators make common cause to do so. In the absence of this, quite the reverse could occur, in which the visibility of these ideas becomes more opaque. If teachers do not lead the development of new pedagogies through collaborating with software designers, then they will be hijacked by innovators who do not have the teachers’ expertise and experience of what it takes to learn for all the learners in their care.

7. Recommendations

We derive our recommendations from the findings of the literature review, and from our consideration of the ways in which STEM teaching could be using technology to enhance the curriculum and students’ learning and achievement. To formulate the recommendations we have considered the conditions that might most effectively move forward the current work that is good but patchy.

For a 21st century curriculum and for high quality teaching and learning that will meet the demands on STEM provision, we need a radical shift in the way STEM teaching and the STEM teaching profession is conceptualised. Specifically, to:

1. Use the main drivers in the system to enable technology-based innovation by making the curriculum, assessment and quality systems accountable for this change.

2. Address the barriers identified by asking each agency and institution responsible to report on how their practice could help teachers to contribute to technology-based innovation in STEM subjects more efficiently.
 3. Build on this review to develop a common understanding across teachers, leaders and policy-makers of the wide variety of ways in which digital technologies offer a more ambitious curriculum for STEM subjects, and can support and enhance STEM teaching and learning.
 4. Encourage the STEM Education Community (e.g. the NCETM, the National Science Learning Centre, the new network of Science Learning Partnerships, the National STEM Centre and the Professional Bodies) to promote the findings of the Vision study across their extensive networks and plan their own actions to address the issues identified.
 5. Create a culture of teaching innovation across the STEM teaching profession by taking action to:
 - enhance the teachers' role as collaborative innovators in technology,
 - extend and enhance existing cross-institutional collaborative models to do this,
 - link existing STEM teacher communities, teacher training organisations, researchers and the digital industry to collaborate on the development of learning technologies for STEM concepts and skills,
 - build a research-teaching collaboration to orchestrate new pedagogic designs and the collection of learning analytics to support further evidence-based teaching and policymaking.
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Appendix 1: Method

Each member of the team was involved in all stages of the literature review and the Commentary. For the review we followed the methodology below. For the Commentary we used the findings of the review, additional searches for previous future technology scenarios, team discussions, and iterative drafting, to arrive at an agreed output.

7.1. Searches

For the literature review the project team used the following databases: the Applied Social Sciences Index and Abstracts (ASSIA), British Education Index (BEI), Education Resources Information Centre (ERIC) and the International Bibliography of the Social Sciences (IBSS). This was complemented by search in highly regarded journals, such as International Journal of Science Education, Journal of Research into Science Education, British Journal of Educational Technology, School Science Review, and conferences in the field such as the European Conference on Technology-Enhanced Learning, Constructionism, the International Conference on Computer Supported Collaborative Learning and the International Conference of the Learning Sciences.

The search terms used combinations of keywords such as learning, teaching, school, digital, computer, technology and STEM, science, engineering, maths, and special terms such as ubiquitous computing, embodied learning, tangible learning, digital fabrication, computer human interaction, tangible embedded interaction, embodied Interaction, interaction design and children; science, teaching, learning, digital, technology, games, simulation, communication, animation, mobile, GPS, concept, knowledge, pedagogy.

We searched for reports, reviews and evaluation studies in the Department for Education site for government documentation, the Becta archive for reports, the National STEM Centre site and Library, the NCETM, and from education-related organisations such as the subject associations, as well as technology futures reports from the US (NMC) and from BIS.

The team also used internet searches to identify 'grey literature' i.e. material that is not published or necessarily peer reviewed. The learning technology research field is still relatively immature because it attracts a low proportion of the funding for both educational and computer science research and, especially since the abolition of Becta in 2010, has been unable to keep abreast of the continuing technology innovations now in use. The grey literature is an important supplement to the research literature, therefore, particularly in relation to anticipating future developments.

7.2. Selection

Using initially abstract and summary sections, we selected studies that focus on uses of technology that have proved effective in satisfying the aims of STEM education, particularly as defined by the needs of higher education, workplaces, and the requirements of 21st century citizens. Studies that were identified as being important to meeting the aims of the Vision project were then distilled and summarised.

We looked for evidence of the use of technology for STEM subjects in primary, secondary and post-16 educational settings, in informal learning environments, such as science and technology-focused museums, zoological and botanical gardens, and in online social communities for teachers and students in STEM-related areas.

There are many generic digital technologies that are of value to all areas of the curriculum, such as search engines, electronic voting, and discussion forums, but this report focuses on those that afford the type of learning that is specific to STEM. Many of these are highly specialised forms of technology, not always in general use, and therefore studies rarely involve randomised controlled trials, as they tend to be small-scale, formative evaluations designed to improve the technology itself.

The team used their background knowledge, experience and contact with recent educational technology research and development projects to inform their selection. Using grey literature and more informal knowledge, in addition to peer reviewed literature, is important when reviewing this field because of the time it takes for peer reviewed literature to appear, the visionary objective of the review and the commercial or non-profit nature of some of the educational technology that is relevant to it.

Wherever possible we also followed links to pictures or screencasts that help to give the reader a clearer visual sense of the nature of the technology, or its context of use.

7.3.Exclusions

We did not include studies with out of date generalisations about the value of "technology", because (a) these findings are often no longer valid, given the dramatic changes in attitudes and skills relating to digital technology among both teachers and students in recent years, and the equally dramatic changes in the technologies and access to them, and (b) the term covers such an extensive range of tools, resources, and applications that conclusions about the value of "technology" in education are worthless.

There are some general reviews of evaluation studies in education (Haas, 2005; Hattie, 2008), but if they mention technology at all, which is rare, they refer only to evaluation studies of a particular software program, many of them dating from the 1990s and early 2000s, or of long-gone technologies such as television and interactive video, from which it is not possible to draw general conclusions about technology-based methods today. Similarly, studies of the effects of technologies (Campuzano, Dynarski, Agodini, Rall, & Pendleton, 2009; Cavanaugh, 2001; Howard-Jones & Demetriou, 2009) draw conclusions about the effects of very specific instances of types of technology. As Campuzano et al conclude, for example, their work

"... did not study many forms of educational technology and it did not include many types of software products. How much information the findings provide about the effectiveness of products that are not in the study is an open question" (Campuzano et al, 2009, p xx1v).

For these reasons we excluded some of the evaluation studies of learning in general that refer to technology, as they do not provide valid conclusions relevant to this review.

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