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PPRIMARY PUPILS: WORKING SCIENTIFICALLY OR WORKING MATHEMATICALLY?

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Abstract

This paper examines the contribution of an integrated approach to the teaching and learning of two important primary STEM subjects mathematics and science. The paper begins by considering recent developments in the United Kingdom. The two subjects are presented and links between the two established. The skills of science and mathematics are compared and areas of overlap identified. These skills are then considered in more detail and the ways that investigations can be approached from both a mathematical and scientific perspective. The paper explores what it is to work scientifically and to work mathematically and concludes that the two subjects are valuable in their own rights but that they both benefit from their integration. The importance of working mathematically to mathematics education and of working scientifically to science education are emphasised and the value of curricula which lack these elements are considered. The paper suggests that perhaps these sets of skills are best considered as one set of skills, that our artificial subject distinctions cause a blurring which for some individuals is a strength but for others especially young learners may cause confusion. The paper concludes that there is considerable scope for the integration of STEM subjects, mathematics and science in particular but that the success of this integration is down to skilful teaching by thoughtful practitioners.

Keywords: Mathematics, science, integration.

INTRODUCTION

The development of scientifically and mathematically informed citizens is of such importance that it needs to begin in earnest during primary education in order to help ensure children have the best possible start in life and continued throughout secondary education (Royal Society, 2014). With the growing prominence of Primary STEM this paper considers the relationship between two STEM subjects and how the learning of these subjects might benefit from integration. It considers the nature of the subjects, the skills taught and potential benefits of integrated teaching for learning.

Background

Mathematics is regarded by many people 'to be a body of established knowledge and procedures – facts and rules' (Ahmed, 1987). While there are elements of this within learning mathematics, using science reveals how mathematics contributes to real life situations enhancing and enriching the learning of both subjects. In what we might call our scientific world, there are no areas where mathematics is not present! To some making links between these subjects feels intuitive. However, learners might understandably view these two subjects as separate and discrete, perhaps as a result of the way that school systems organise the curricula. This paper in no way advocates the dilution of either subject. Science and mathematics remain pillars of human thought and creativity. Each offers a powerful set of knowledge, understanding and skills but together form a formidable corpus of human achievement with no doubt advances to come, which we cannot imagine. Will the learners in our classes make discoveries? Contribute to the advancement of humanity? Will they be motivated to use mathematics and science in their lives?

Science and mathematics are important STEM subjects (http://www.stemnet.org.uk) and will be pivotally important in the lives of your learners and the society in which they live. Both subjects are essential in helping all of us to understand the world. A report published by The Royal Society (2014) outlined its vision for the next twenty years to unite science and mathematics education. With The Royal Society's fundamental purpose to recognise, promote and support excellence in mathematics and science, this paper is timely with its vision to promote the integration of both subjects through education. The Royal Society report is very clear, however, that nurturing scientific and mathematical thinking needs to begin at the primary school. Forging these links early on is likely to have a long lasting impact on learner attitudes towards these two subjects. The Royal Society (2014) usefully summarise what it is to be a scientifically informed individual and a mathematically informed individual. The qualities listed in Table 1.1 are remarkable in the way the subjects complement one another.

Table 1 What it Means to be Scientifically and Mathematically Informed (The Royal Society, 2014)

A scientifically informed individual:	A mathematically informed individual:
understands scientific theories and concepts and that these are subject to challenge and changes as new evidence arises; can think and act scientifically (e.g. using hypotheses to test and solve problems while also using scientific knowledge) and uses essential reading, writing, mathematical and communication skills to analyse scientific information accurately; makes informed interpretations and judgements (e.g. risk assessment) about scientific information and the world at large as well as engaging in debate on scientific issues; is able to apply scientific knowledge and understanding in everyday life; maintains curiosity about the natural and made worlds.	understands mathematical concepts and recognises when they are present; can think and act mathematically (e.g. applying knowledge and transforming methods to solve problems), uses mathematical skills and forms of communication to analyse situations within mathematics and elsewhere; can make informed interpretations of information presented in a mathematical form and use it to engage constructively in debate on scientific and other issues; is able to apply mathematical knowledge and understanding in everyday life; and maintains curiosity in mathematical concepts, and in other phenomema understood from a mathematical perspective.

Like The Royal Society (2014) Haylock (2010) insisted that links between subjects like mathematics and science are essential. "The skills of handling data and pictorial representation are best taught through purposeful enquiries related to topics focusing on other areas of the curriculum, such as science" (Haylock, 2010). The contribution of mathematics to science education has always been important but never more so than now. Feasey and Gallear (2000) recognised the necessity of this but also the power of numerate individuals engaging in both subjects. English National Curricula (DfE, 2013) recognise the importance of connecting the two subjects through applying 'mathematical knowledge' (DfE, 2013) in science whilst recognising that mathematics is 'critical to science' (DfE, 2013). Connecting mathematics and science can enhance opportunities within a curriculum to be explored and learner's mathematics and science knowledge enhanced.

Researchers and writers talk about the importance of making connections between mathematics and science, often surmising that it is effective teachers who recognise and exploit this connectionist approach to learning (Askew et al, 1997). According to Haylock and Cockburn (2008) learning without making connections is what they would call 'rote learning'. Other reports (Ofsted, 2008; Williams, 2008) observe that the use and application of mathematics is not always embedded in classroom practice. Science provides the perfect medium through which to offer these opportunities. Indeed Treffers and Beishuizen (in Thompson, 1999) encourage children to be purposefully engaged in problem solving situations. Investigations enable science and mathematics learning as they both require real life enquiry, reasoning and problem solving. In her article about teaching mathematics creatively, Naik (2013) included a case study, where a teacher was 'very keen that mathematics work should be linked closely with that of science, noting that there are many natural connections which should be capitalised on' for example, extrapolating from a set of data'.

Mathematics and science share an interest in numeric and other relationships. It is worth emphasising that in science we aim for a number of things. Science enquiry is greatly enhanced through the measurement, control and systematic control of variables in an experiment or test. Thus an important step in primary science is the shift from simple observation of phenomena to increasingly accurate quantitative measurement and increasingly sophisticated use of data in addressing questions to establish, for example, causal relationships. This is very well exemplified by the use of tables and graphs (Goldsworthy et.al., 1999), especially line graphs which represent a numerical relationship between two variables. For example, as temperature increases towards boiling point, so does the rate of evaporation of water (Figure 1).

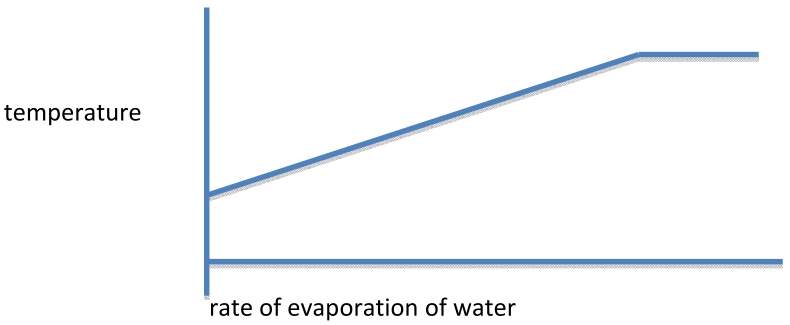

Figure 1: Graph Showing the Rate of Evaporation of Water as the Temperature of the Water is Increased to Boiling Point

Well organised, purposeful curricular links between subjects allow children's learning to be extended and deepened (Barnes, 2011, Rose, 2009). According to Ofsted (2010) this approach affords opportunities for independent enquiry that can be inclusive and relevant for all learners. However, as professional educators we should take care. Hattie has reviewed research about integrated curricula and noted that any positive affect can vary from subject to subject with mathematics benefiting more in one enquiry than science. Overall he noted that integration of subjects had a greater positive affect in primary education (Hattie, 2009). This paper recognises the value of subjects as one way (Alexander, 2010), we would say, a very powerful way of organising human knowledge. For learning to be meaningful we consider that curricular links and connections can assist learners making sense of the world.

Working Scientifically or Working Mathematically?

One of the strongest connections between mathematics and science is found through how learners work scientifically and mathematically. Working as a mathematician or as a scientist requires a curious and enquiring mind, which observes the world and asks why, how, could, should, would? It is as if a person wears special enquiring glasses, through which is seen a world of questions and enquiries. With this curiosity in place questions can be posed, conjectures proved or disproved, hypotheses tested, rules and theorem established.

In the English National Curriculum for science (DfE, 2013) working scientifically precedes the blocks of knowledge within each key stage. Many learners come to science with ideas and interpretations concerning the phenomena that they are studying. They often form these ideas as a result of everyday experiences. The objectives of the working scientifically English programmes of study (DfE, 2013) aim to harness, shape and develop the skills and understanding needed to test and interpret science ideas. For example, they remind us to ask questions, gather data and perform fair tests whilst learning about living things, materials or physical processes. Working scientifically includes the core characteristics of being a scientist, and reflects the three aims of the English science curriculum (developing science knowledge and conceptual understanding; developing understanding of the nature, processes and methods of science; understand the use and implications of science). However, the list of objectives within the working scientifically programme of study

(DfE, 2013) are so mathematical it would not be a surprise to find them in the mathematics curriculum. Consider these examples from the science programme of study:

- identifying and classifying;
- gathering and recording data to help in answering questions;
- using results to draw simple conclusions;
- reporting on findings from enquiries, including oral and written explanations, displays or presentations of results and conclusions;
- taking measurements (DfE, 2013).

The English mathematics programme of study (DfE, 2013), however, does not mirror the English science programme of study in that there is no separate section for working mathematically. Instead working mathematically is contained within the three aims of the mathematics curriculum (fluency, reasoning and problem solving). Historically there has always been a working mathematically strand in previous versions of the mathematics National Curriculum (e.g. DfEE, 1999), although it has appeared under various pseudonyms such as using and applying mathematics, or problem solving. The inclusion of working mathematically is important as it suggests that to be a successful learner in mathematics requires understanding and skills which allow us to solve real problems, to enquire, to reason and justify and to communicate and explain. Just as science education would be meaningless without working scientifically, mathematics education would lack meaning and purpose if we did not teach the understanding, skills and processes alongside the content. Jones (2003) writes that 'a mathematics curriculum without problem solving can be likened to a diet of PE in which children practice football and netball skills but never get to play a game'. Within the English mathematics curriculum (DfE, 2013) we need to look to the three aims of fluency, reasoning and problem solving to provide this element.

Mathematical and Scientific Skills

Mathematics and science are both subjects that require a specific set of skills and knowledge in order for learners to be successful. This section looks at how the skills of mathematics and science are more connected than perhaps we thought. However, we first summarise the skills associated within each subject (Table 2) before considering the connections between them.

Table 2 Science and Mathematical Skills

Science skills	Mathematics skills
- observing - asking questions - hypothesising - investigating - communicating and reflecting - interpreting evidence, drawing conclusions	- procedural recall, accuracy and fluency of number; - interpretation and use of concrete, pictorial and abstract representations; - application of mathematical knowledge and experience; - strategies for problem-solving and hypothesis-testing; - mathematical reasoning; - appreciation of the purpose and usefulness of mathematics, and willingness to use it. (Based on the skills identified by ACME (2011))

Is it possible that these mathematics skills and science skills are in fact one set of skills? These skills are about perceiving what is going on in the world, establishing relationships, making things predictable and using this to either expand knowledge and understanding or in other ways improve life? Looking at both sets of skills it is hard to see many differences between the skills of learning science and mathematics. Table 2 represents the considerable overlap. There are huge similarities between each set of skills. We suspect many people would not be able to decide whether 'investigating' or 'problem-solving and hypothesis-testing' is a mathematical or science skill! We would also like to suggest that being aware of these skills and connecting the subjects in this way actually enhances learning, not only because learners have more opportunities to practice and use these skills but subject specific skills in one subject enrich the other.

As well as understanding the similarities between the skills within each subject, the opportunities that subject specific content and activities provide also adds to these curricular connections. Schoenfeld (1994) makes the distinction between learning mathematics and doing mathematics. While there is a need for pupils to learn mathematical content and knowledge, there is also the need for them to apply and practice these skills. Science investigation provides the perfect vehicle for many of these skills. Practising mathematical skills in a real world context not only reinforces these skills, but goes on to extend and deepen knowledge. Learners make more of science and mathematics when they have posed questions about a topic and then sought answers themselves. This approach enables the use of mathematical and scientific language, it can make links very clear and enable the development of skills. Spendlove and Cross (2013) observe that 'learning through doing is both rich in content and process'. Science provides the ideal context to harness the skills learnt through mathematical problem solving, but in a real life context. To science, mathematics provides a means of describing, quantifying and articulating ideas and relationships. Progress in science education in the primary years can be seen as moving from predominantly qualitative observation, exploration and description towards increasingly planned, careful and precise quantitative methods. To mathematics, science offers a context to apply numerical skills and understanding.

So, there are many areas in the mathematics and science curriculum that overlap and use the same skills and knowledge. It is these areas that teachers might exploit. We acknowledge that there needs to be significant episodes of discrete mathematics and science subject teaching. For example, learners may need to practice pattern spotting in shape or explore using hand lenses before embarking on a nature hunt. We are not advocating that every mathematics or science lesson adopts full integration. However, there are many opportunities where connecting the subjects is natural, adds value to the learning and makes sense.

Connecting through STEM

A small number of English primary schools have adopted a STEM (Science, Technology, Engineering and Mathematics) approach. This varies but involves to some extent or another integrating these subjects across the entire curriculum or in a number of themes or topics that are developed. Primary schools use an age appropriate STEM approach to ensure that science, design and technology, computing and mathematics combine in all sorts of ways. A STEM approach encourages learners to see and use links across the four subjects.

One primary school uses the TASC (Thinking Activity in a Social Context) wheel (Wallace et. al., 2008) to scaffold learners' thought around different topics and problems, which link science, mathematics and design and technology. In a water topic learners designed a rain harvester to reduce the mains water required in the school garden. Learners made plans and designed model rainfall harvesters. This involved science, mathematics, design and technology and computing. Find out more about TASC at http://tascwheel.com/?page_id=289

A host of primary STEM projects are available at http://www.nationalstemcentre.org.uk/elibrary/ and primary STEM ambassadors are available to visit schools for free. Find out more from http://www.stemnet.org.uk

Connecting Mathematics and Science - pedagogically

Working mathematically will often involve thinking about the question and what the likely answer might look like and how it might be solved. In a very similar way working scientifically uses a question to consider a prediction and then a plan for an investigation to answer the question. Learners questions in science and mathematics are often naive so you will need to model or assist the learners in rephrasing the question. This

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iteration of the question can occur more than once and almost always results in deeper learning. This is because learners and teachers do not always stress or perceive the same information.

Rephrasing questions mirrors common practice in real science contexts as in this lesson on thermal insulation below.

In a lesson on thermal insulation one class suggested the following question:
"Which material is best?"
Their teacher asked them to explain the word best and to rephrase the question, which became:
"Which material keeps the ice lolly cold?"
She checked that they understood the words material and cold.
Later they rephrased the question to:
"Which material keeps the ice lolly colder for longer?"

Each iteration of the question improved it, that is, made it more scientific. Similarly, questions can be used to stimulate mathematical thinking too.

We could ask:
“What is the total of 5 and 8?”
However, we could change the question to:
“How many ways can we reach a total of 13?”
“Can a pattern help you to find all the possible ways to reach 13?”
“If 5 and 8 equal 13, what might come next?”

Although the two examples above are subject specific, they both utilise pedagogic constructs of questioning. Being able to ask different types of questions (and then solve them) is a skill that both science and mathematics rely heavily on. As the section on working mathematically or working scientifically shows, many of the pedagogical strategies used in either mathematics or science are transferable and allow learners to build on these skills in different contexts and subjects.

Connecting Mathematics and Science - contextually

In the example above the question required measurement of temperature and time so that mathematics was now required to assist the learners in their investigation. There are opportunities in all areas of mathematics and science that offer a platform through which to connect the subjects through either the content or context. The example here shows how the mathematical area of measurement is vital to learners solving this scientific question.

The learners can quantify the relationship between two variables (temperature and time). In order to vary these values systematically and establish usable patterns we need to quantify these variables. Younger primary learners will not always use numbers but will use qualitative descriptors and categoric data (e.g. temperature will be “cold, warm and hot”, force will be “tiny, small, medium and large”). With measurement, however, we move significantly from qualitative judgements to quantitative measures.

Thus measurement is an important aspect of working scientifically and working mathematically (Table 3). Science enables meaningful measurement in the context of an investigation and the opportunity to develop skills. Mathematics allows the use of number in measures to be systematic and to quantify values and changes we make or observe whilst providing learners real opportunities to use and apply numerical data in a context.

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Table 3: Qualitative and Qualtitative Measures (units listed here are all SI Units)

Phenomena	Can be described qualitatively	Is measured in units ...	Using a device called a...	These devices come in different forms
level of heat	With the sense of touch and the language of hot, hotter, cold and colder	centigrade (C)	thermometer	digital and analogue, maximum and minimum, data logger
sound	With the sense of hearing and the language of loud, louder, quiet, quieter, silent	decibels (Db)	decibel meter	analogue, digital including data logger
light	With the sense of sight and the language of dark, light, lighter, bright, brighter	lux (lx)	light metre	analogue, digital including data logger
force	With the sense of touch the pressure applied and the language of push, pull, bigger	newton (N)	Newton metre	analogue, digital including data logger
distance	With none standard measures e.g. carpet tiles, strides, handspans, lengths of string etc	millimetres (mm) centimetres (cm) metre (m), kilometre (km)	rulers, tape measures etc	analogue, digital
time	By estimating and counting e.g. 1 elephant, 2 elephant, 3 elephant for 3 seconds.	second, minute, hour, day, week, month, year	clocks, sand timers, tocker timers, waterclocks, etc	analogue, digital
capacity	By comparison, this container holds more/ least, largest, smallest etc	millilitre (ml) and litre (l)	measuring cylinder or jug or a syringe	analogue

Science also allows the use of perhaps a wider range of measures than would be used in most mathematics lessons. The importance of measures in the two subjects is demonstrated by their reliance on the internationally agreed measures known as SI units which, mathematicians and scientists have agreed and are thus regular standard units recognised throughout the world. It is important to use measures and therefore measuring equipment. Data loggers offer the opportunity to gather data on light, sound, temperature, pulse rate and more. They can operate away from the computer and will also download data to your computer quickly. In Figure 2 a class recorded data for twenty-four hours. Giving the learners opportunity to reason mathematically about why one value fluctuates considerably and others less so? In this case are learners studying mathematics or science?

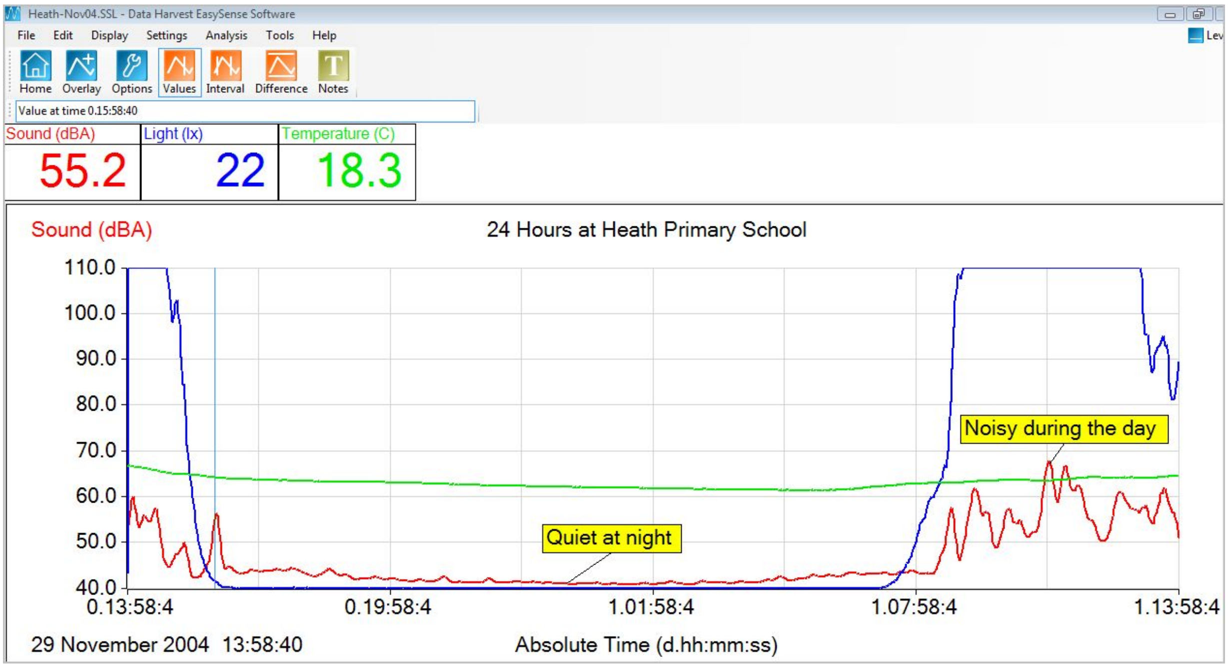

Figure 2: Data Gathered in Real Time Over Night in a Classroom (school name is fictitious) (reproduced with permission from Data Harvest Group (http://www.data-harvest.co.uk/catalogue/science/primary/datalogging))

Some data collected by learners will be categoric (discrete) such as pet type, hair colour or day of the week. These are categoric, for example, there is a value we call Tuesday and one we call Wednesday but nothing in between called say Tuesdaywednesday! Continuous data however exists on a continuous scale with numerous subdivisions and values which can be divided and sub divided. An example is time which can be scaled in days which could be subdivided into hours themselves divisible into minutes and so on.

CONCLUSION

Mathematics and science appear to be two powerfully complementary STEM subjects. Each subject on its own has a great deal to offer learners but when we connect them the potential to learn is huge with beneficiaries being the learners. Learners have the opportunity to see mathematics being used in the real world and to observe how science makes use of mathematics to help answer scientific questions. The authors do not advocate complete integration of the subjects as each represents a valuable way of looking at the world and organising knowledge. Rather we would advocate creative and thoughtful teachers who examine the curricula to identify contexts available which could strongly develop and connect mathematical and science understanding.

Learners need to understand mathematics and science so that they can contribute to the world we live in. Yet it would seem to be a missed opportunity if we did not pursue connections that are so obvious and easy to use. In pursuing both the mathematical and scientific needs of our learners we are helping them to view both subjects as being inter-connected, dependent on each other and stronger through their relationship together. We would offer the view that these are essential skills if they are to understand the world and move our society on into the next century.

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