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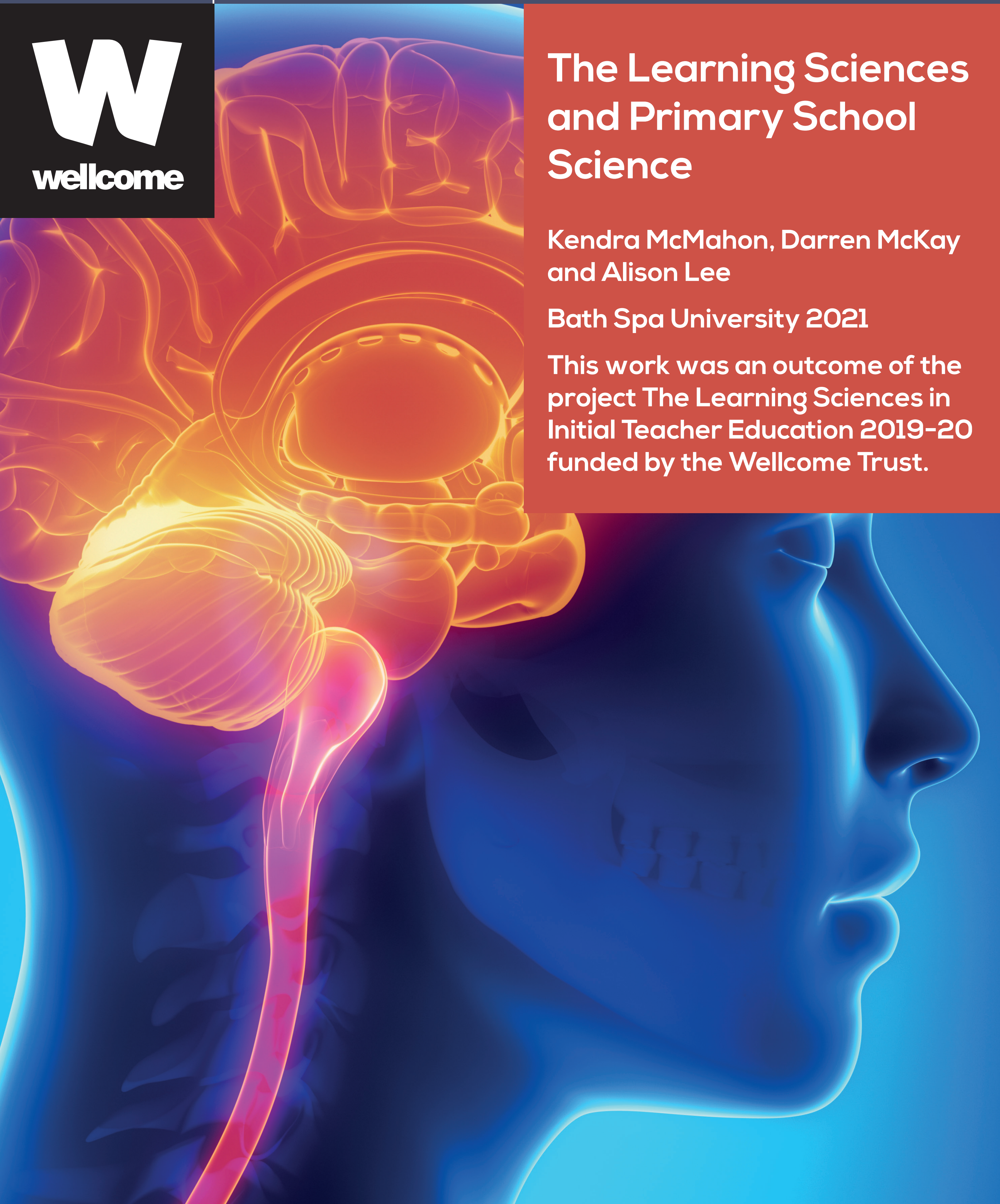

The Learning Sciences and Primary School Science

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Contents

Introduction: Why focus on the Learning Sciences in primary science?

This document is one outcome of the project The Learning Sciences in Initial Teacher Education (ITE) 2019-20 funded by the Wellcome Trust. The project explored how initial teacher education could and also should engage with the 'Learning Sciences' in order to provide a good preparation for teachers in their professional journeys. The curriculum in ITE typically includes generic elements such as Professional Studies and subject specific elements. In other documents we have addressed generic issues, but here we are considering subject-specific implications of the learning sciences exemplified through a focus on science.

Science is not a random choice; it seems appropriate that this scientific perspective on learning should first be explored in a subject with which it is epistemologically congruent. Also, and perhaps for that reason, we found that colleagues interested in science were particularly drawn to exploring these issues. It seemed like a good place to start.

We think there are three main reasons to explore the Learning Sciences in relation to science in primary schools:

- Firstly, there is a local and pragmatic reason: in England, the Department for Education (DfE) and school inspectorate (Ofsted) are supporting the application of some concepts from cognitive psychology and this means that schools should expect to be familiar with those key ideas, and what they suggest for teaching and learning. We need to know what this means for teaching and learning in primary science.
- Secondly, there is a global interest in how the surge in international research in the field of neuroscience might benefit education. We want to be enthusiastic and open minded about this, but also cautious.
- Thirdly, science educators are well placed to help their colleagues to engage with these new ideas, drawing on their science literacy and understanding of the nature of science to recognise limitations as well as potential benefits.

We are taking a positive and practical approach. We want to identify and understand the key ideas, and think about what they might mean for teaching and learning in primary science.

In this document we first consider the meaning of the Learning Sciences, then get to grips with the strategies for teaching and learning that have been advocated from cognitive psychology and that appear in current English education policy documents. Finally we take a broader look at the potential of the Learning Sciences, including neuroscience, to inform our thinking as primary science educators. We consider how neuroplasticity offers a physical perspective on constructivist theories of learning including the importance of children's existing ideas. We begin to explore how neuroscience helps to explain the importance of hands-on experiences. Examining this cutting-edge field of science required us to draw on our understanding of the nature of science and we also reflect on this.

What do we mean by the Learning Sciences?

There are fields working at the intersection of science and education with an array of terms: the Science of Learning, Educational Neuroscience and the Learning Sciences. These might be used interchangeably, but have some subtle differences in emphasis. Furlong and Witty (2017) make a helpful distinction between the 'New Science' of education characterised by randomised control trials and systematic reviews to establish 'what works' and the interdisciplinary approach of the Learning Sciences aiming to support learning in real world contexts, often through design-based research. There are differences here in what counts as 'scientific knowledge'. Is it only proper, valid science if there are controlled variables and large samples or we do also value case studies of particular instances and exploring the messier complex interactions between factors? By valuing both, we are taking an approach perhaps more similar to that of medicine, or clinical neuropsychology (Lee et al. forthcoming), in which clinical experience and experiments both contribute to knowledge and to practice. Taking this approach is also consistent with what is understood about the brain; there are biological features common to all humans, but there are also considerable differences between the brains of individuals as they develop in response to the unique environment and experiences of the person.

Beware authors implying that science can tell teachers what to do - it can't! Science is providing an additional set of tools for making sense of learning. It does not provide a prescription for how to teach. Most authors argue that the relationship is two-way; as well as neuroscience offering insights for education, education will raise questions that suggest avenues of research for neuroscience. Interdisciplinary research can take generalisations that seem to hold true in laboratory conditions and examine what happens in the complex social reality of particular classrooms.

What are the messages from the DfE and Ofsted?

A range of policy documents in England; The Education Inspection Framework (Ofsted, 2019a), The, Early Career Framework (DfE 2019a) , and The Core Content Framework for Initial Teacher Training (DfE 2019b) draw on the contribution that findings from cognitive psychology could make to the learning of individuals. (See Ofsted 2019b for their research summary). From this viewpoint, learning is defined as changes to long term memory and factors affecting retention and recall of knowledge are explored. For example, the Ofsted Education Inspection Framework (EIF) grade criterion (for Implementation) says that:

> *'over the course of study, teaching is designed to help learners to remember in the long term the content they have been taught and to integrate new knowledge into larger concepts'*
>
> (Ofsted, 2019a; p10)

Cognitive psychology provides models that help explain what might be going on when learning takes place. However, it doesn't explicitly include the contributions of neuroscience which provides explanations at a different level, the physical structures of the brain. It is not clear why cognitive psychology has been prioritised in English documentation, but there may be justifiable caution about creating a direct 'bridge' between neuroscience and teaching strategies. Also the emphasis on memory is congruent with the English focus on a 'knowledge rich' curriculum. We see both psychological and neuroscience explanations as potentially useful and much contemporary research integrates them.

In this document we will first present some recommended teaching strategies that have been developed from research in cognitive psychology and consider what these might look like for primary science in particular. Then we will go further and explore what a wider view of the learning sciences including neuroscience might have to offer our understanding of teaching and learning in primary science.

What are the key ideas from cognitive psychology?

In the last decade, summaries of the literature of cognitive psychology converged in recommending teaching and learning strategies that are supported by research (Weinstein et al., 2018; Pomerance et al., 2016; Dunlosky et al., 2014; Deans for Impact, 2015) and are evident in English policy documents. These are retrieval practice, spaced practice, interleaving, dual coding, using of concrete examples, elaboration and making links with prior knowledge. There has also been much discussion on how teaching can help to adjust the cognitive load experienced by learners (see for, example, Shibli and West, 2018) so we begin with a consideration of cognitive load.

First, each teaching/learning strategy listed below is described in general terms. Next, the cognitive psychology that underpins it explained and considered in terms of existing ideas in primary science education. We then offer some examples of what each teaching/learning strategy might look like in practice in primary science contexts.

Teaching/learning approaches supported by cognitive psychology

- Reducing cognitive load
- Plain classroom environment
- Retrieval practice
- Spaced practice
- Interleaving
- Dual coding
- Using concrete examples
- Elaboration
- Making links with prior knowledge

What could the cognitive psychology concepts mean for teaching science in primary schools?

Reducing Cognitive Load

Teaching and Learning Strategies

In practice ‘reducing cognitive load’ means structuring knowledge and teaching into small chunks. It means planning activities that do not require too much memory capacity. It also means providing supports such as a writing frame or word bank. It also means making sure that teaching is paced so that children have a secure set of ideas before they are expected to use them independently.

Underpinning Cognitive Psychology concepts

Cognitive Load theory is based on the premise that before entering long-term memory and forming ‘schemas’ (knowledge structures, such as science concepts, or skills) information from the senses must first be processed in a kind of mental holding space known as the ‘working memory’. (Working memory is also known as ‘short term memory’.)

It is worth noting that working memory isn’t a single clearly identifiable structure in the brain; MRI scans show that many different parts of the brain are active when people are given tasks requiring working memory. Perhaps a better way of thinking of it is a model of what our brains are doing when we are working on a problem that requires some kind of reasoning.

The working memory has limited capacity. It is often described as being able to hold 5-9 chunks of information. Individuals seem to vary on this. Demands on this capacity are called the ‘cognitive load’. If the working memory is overloaded with too many ‘chunks’ at once then the next step of forming long term memories (encoding) will not happen. In other words, information won’t be remembered, and concepts won’t be formed.

Models of working memory include different parts: a phonological loop (to manipulate speech -based information), a visuospatial sketchpad (though no one has found corresponding anatomical structures in the brain) as well as a ‘central executive’ that coordinates activity and directs attention. Reducing the cognitive load is also partly about reducing conflicting demands on attention. Humans have a limited capacity and can only focus attention on one thing at a time. It is worth noting that working memory can increase; it is a learned skill rather than a pre-set function. Psychologists call any improvement an increase in cognitive load capacity.

Primary Science examples:

- Use focused assessment to elicit pupils’ current conceptual ideas, skills and knowledge of science processes in order to judge what cognitive load new teaching might involve; (see for example, the TAPS Project https://pstt.org.uk/resources/curriculum-materials/assessment).
- Present new material in steps e.g. teach pupils how to draw a table for results before asking children to do it independently.
- Use worked examples e.g. first make classification keys with sweets/toys then apply to plants you find in the school grounds.
- Scaffold children’s enquiries with planning boards and gradually handover responsibility for making the decisions to pupils.
- In an enquiry think about the demands of working scientifically and the concept matter. If both are challenging, then the task may be too hard.
- Focus teaching on one aspect of Working Scientifically during an investigation, Consider which choices are for children to make.
- Limit what has to be recorded: use focused recording e.g. drawings, written responses to specific questions, instead of lengthy ‘write-ups’.

Plain classroom environment

Teaching and Learning Strategies

Having a simple, visually uncluttered classroom helps children to focus on the intended learning.

Underpinning Cognitive Psychology concepts

Often as educators we like to think we are providing a 'rich' and stimulating classroom environment. This might take the form of eye-catching displays, or having different materials on hand for children to choose from. However cognitive psychologists are suggesting that this is over-stimulating, contributing to cognitive overload, and is distracting - making more demands on children's attention and so making it hard for them to focus on the learning at hand.

It seems humans can only be doing one bit of conscious 'thinking' at a time. In other words, we only have one 'working memory'.

So how do we 'decide' what is allowed into the limited working memory space? Humans are complicated! Our attention is drawn to novelty and to what interests us as individuals. We focus on what we are motivated to do. As teachers know well from classroom experience, directing pupil attention is a complex matter. One issue in practical work is that pupils may be drawn to features that are not the things the teacher is hoping they will notice. We may have to make features 'salient' by drawing attention to them.

There is an assumption here that the teacher is deciding what the focus is. Although this is usually the case when there is a science curriculum, sometimes we might want to stimulate children's curiosity to ask a range of diverse questions, or to select items to explore that match their own interests. We might encourage children to notice something that no-one else has noticed! The theory helps us to think about when to offer rich, stimulating choices and when to limit choices and focus attention.

Classrooms often make powerful use of 'shared attention' - cognitive psychology has shown that we are drawn to what interests other people and follow their gaze. Again, the teacher usually tries to lead this social process, but as educators and scientists we should also be open to what others notice that we haven't.

Primary Science examples:

- Limit the number of items in a collection for a sorting activity.
- Use wall display space sparingly and thoughtfully.
- Use 'slow reveal' of an object under a cloth, or in a feely bag to focus attention.
- Use mini plenaries to make important features of practical work 'salient'.

Retrieval Practice

Teaching and Learning Strategies

Retrieval practice is ‘bringing information to mind from memory’ (Weinstein et al. 2019, p 85). We might think of retrieval practice as recapping or revisiting, but the crucial factor is that it is the pupil that does this, and puts in the effort to retrieve the memory. It is not the same as the teacher repeating content or a pupil simply looking at something again. So it could take the form of a low stakes quiz, or responding to questions.

Underpinning Cognitive Psychology concepts

Retrieval practice also depends on the concept of working memory. As well as drawing on input from the senses, working memory can be working on long term memories. This involves ‘retrieving’ them from the long term memory into the working memory. But human memories are not fixed like in a book or a computer - memory is ‘reconstructive’ - so every time you retrieve a memory you are recreating it using the context of the current experience as a trigger. There is something about the effort involved in retrieving the memory that strengthens it. Teachers can aim to provide many different contexts for retrieving memories to develop a range of connections with that memory, making it more useful and more meaningful.

Cognitive psychologists are not looking at the mechanism for this, just the outcomes, but neuroscience suggests how this might happen at the level of brain cells (neurones). Memories are represented by groups of neurones connected together by synapses. Any kind of doing, including thinking, means that certain groups of neurones are active - they are ‘firing’. Those that fire simultaneously can be connected together (by synapses) creating physical associations between them. Sometimes these connections are consolidated to form a long lasting connection. Whether or not this consolidation will happen depends on whether there are associations with existing strong connections (in other words - connections with prior knowledge). Sleep is also important for consolidation!

It is important that the retrieval process is ‘low stakes’ as too much anxiety interferes with memory formation. So it could be a quiz, but not a high pressure test. But, retrieval practice can feel difficult and uncomfortable and we need to help children tolerate this.

Working memory is also freed up when concepts are so secure in long term memory that they are a single ‘chunk’ and so take up just one bit of the capacity of working memory. It is this idea that is part of the justification behind the drive for children to create stable, long term memories of key facts. Willingham (2009) gives examples of this: knowing your multiplication tables and letter sounds. The argument made is that: “Each subject area has some set of facts that, if committed to long-term memory, aids problem-solving by freeing working memory resources and illuminating contexts in which existing knowledge and skills can be applied. The size and content of this set varies by subject matter.” (Deans for Impact, 2015 p5). However, arguably there is not an obvious set of frequently needed memorisable facts in primary science. As we want to avoid pupils seeing science as a series of disconnected facts - this may be one of the factors that can put children off science - we need to think about this claim very carefully.

It might be helpful to learn key vocabulary e.g. about parts of the body, or components of an electric circuit, to support shared understanding in discussion. However, rather than identifying key facts to memorise, a better way of thinking might be to use Harlen et al.’s (2010) account of how ‘Big ideas’ of science are built by connecting and extending smaller ideas. For example, we start by helping young children recognise differences between different materials in their everyday lives. Later, experiences of changing and mixing and separating materials helps to develop their thinking that materials are made up of small bits of other materials and at secondary school this provides the basis for an understanding of atoms and molecules in particle theory.

Instead of ‘retrieval practice’ some psychologists call this the ‘generation effect’, a term which has fewer overtones of rote learning, as it is about generating thought by using the memories (Shimamura, 2018) and link it with ‘elaboration’ as part of consolidating learning for deeper knowledge.

Primary Science examples:

- Securing science specific vocab, e.g. mini quiz to label parts of a different flower, list on mini whiteboard 4 methods of seed dispersal, card sort classification activity (mammal/reptile etc).
- Review skills of equipment use - e.g. ruler (remember to start from zero), thermometer (keep it in the water), pupils recall rules before going to the nature area.
- Review e.g. explain to your partner what condensation means, write in your own words what made that material suitable for the purpose , odd one out quiz, exit notes - 2 things you learned today, explain to a puppet how to separate a mixture of materials;
- Undertaking self and peer assessment against known criteria.

Spaced Practice

Teaching and Learning Strategies

Spaced or distributed practice is that thing that many people had good intentions to do - plan a revision schedule for an exam that involved planning to look at each element for a short time and revisit it at intervals. For teachers, it is about planning to revisit content after a gap in time.

Underpinning Cognitive Psychology concepts

The research has shown that if you compare ‘massed practice’ - studying for a long single block of time, with the same total time, but ‘distributed’ over different occasions then people are better able to remember the content. It isn’t entirely clear why this time interval is important - but it is consistent with retrieval practice and consolidating memories. There is a considerable body of evidence from cognitive psychology to support this strategy. It seems in line with existing educational good practices of reviewing and revisiting content at the start of lessons and topics and provides another rationale for doing this. It is not clear from the research what the ideal time gap is. In practice in primary science, finding enough time for revisiting can be a challenge. One issue to bear in mind is that the research involved well defined, narrowly defined chunks of knowledge such as a vocabulary list and is less convincing for learning complex tasks and knowledge.

At the school level, spaced practice might mean a science subject leader has to fight to keep science in every topic and in weekly timetables. And it means we should certainly not be doing all the science for a year in one big ‘Science week’!

Primary Science examples:

Plan to revisit Working Scientifically skills like drawing a table or a conclusion (in long term and medium term planning).

Interleaving

Teaching and Learning Strategies

Interleaving means switching between work with similar, but different kinds of content, typically maths problems (E.g. finding the area of different shapes), within one session.

Underpinning Cognitive Psychology concepts

It is not clear why interleaving has led to better learning outcomes in many studies, particularly in maths and in learning motor skills such as playing a musical instrument. It may be that the juxtaposition helps pupils to focus on the distinct features of a problem or activity. But it isn't clear where the balance lies between the value of interleaving and the detrimental effects of task switching. At the moment, the applications of interleaving to primary science seem limited to us.

Primary Science examples:

Plan a topic e.g. fairground topic/ Romans topic - that draws on a range of science content e.g. forces/materials and structures.

Dual Coding

Teaching and Learning Strategies

The two elements that are combined in dual coding are visual and verbal materials. The strategy is to use both modes together to complement one another, such as in a labelled drawing.

Underpinning Cognitive Psychology concepts

We said above that models of working memory include different parts: a phonological loop (for speech -based information) and a visuospatial sketchpad (for visual and spatial information). We can't deal with two visual processing tasks at the same time, e.g. looking at a sheet in front of us and at a screen. Similarly, we can't do two speech based tasks at the same time e.g. listen to the teacher talking and hear the video clip of the moon landing. Importantly, reading text on a screen is the equivalent of hearing a voice (reading is an internal voice) so pupils can't read text on a slide while listening to a teacher talk. They can only do one or the other.

BUT, we can do a visual task at the same time as a speech-based task. So having a discussion about a picture or diagram that you are looking at works well. Also it seems that combining the two modes (speech and visuospatial) makes it easier to recall memories. This strategy seems particularly relevant for science education as we are frequently using multimodal materials with drawing and diagrams to help us explain ideas verbally.

It is worth noting that this is a strategy that can benefit all children. This helps us to dismiss the old idea that a child has a certain learning style and we should teach them using just one mode (visual, auditory or kinaesthetic). A one-mode approach does not lead to improved learning.

However, there is a danger of cognitive overload if we have too much detail or use representations within a diagram to carry too much information that the children are not yet sufficiently familiar with, such as symbols for an electric circuit. It helps if labels are placed right next to what they are labelling rather than having long arrows to follow, or more demanding still, using a key.

Understanding dual coding also tells us what not to do - don't have a PowerPoint slide with lots of words for children to read and then at the same time be saying something different, it is better to have a diagram or picture or key words that can be quickly read.

Primary Science examples:

- Annotated drawings/diagrams, e.g. drawing and labelling light diagrams.
- Demonstration plus talking (e.g. use body apron to explain the digestive system).
- Labelled pictures of sequence of events in seed formation and dispersal.
- Using a graphic organiser to plan the stages of an investigation (e.g. Discovery Dog).

Using Concrete Examples

Teaching and Learning Strategies

Abstract ideas are easier to understand if we give an example.

Underpinning Cognitive Psychology concepts

It helps to explain an abstract idea if we give an example the children can relate to and understand. It also helps if we give multiple examples. For example the abstract concept of a habitat could be made more meaningful by giving examples such as a pond, or a tree, or a mountain top and the plants and animals that might live in these places. Perhaps we could interleave looking at several different habitats and draw out common elements that make up a habitat such as the food and shelter that is available. (And the examples have to be well chosen; if we talk about a bird's nest in a tree as a habitat, the concept of habitat becomes too associated with being an animal's 'house'.)

Cognitive psychologists tell us we have to be wary that pupils may remember the example, but not the overarching principle. The example may be so engaging that it distracts from the main aim. We also need to be aware that what cognitive psychologists call 'surface details' may be more memorable than what we are trying to convey. The deep message may be obvious to us as (relative) experts in the topic, but not to the pupils. This is one of the challenges of 'Wow moment' based teaching.

But in primary science starting with concrete, specific and contextualised examples and building towards 'bigger ideas' is a very relevant approach. Good curriculum design will support this.

Primary Science examples:

Bigger idea – *materials are made of smaller parts and the properties of the material depend on the nature of those parts and how they are put together.* This could be built towards by making a range of concrete experiences: pulling apart a knitted jumper; looking at T-shirt jersey fabric through a powerful magnifier; looking at woven fabrics and pulling out threads; testing the strength of different kinds of threads; looking at different kinds of rocks closely to see the different grain shapes and how they fit together; testing the properties of different rocks.

Bigger idea – *the pitch of a sound is related to the size of the vibrating parts.* This could be built towards by: listening and comparing sounds with higher and lower pitches; using a range of musical instruments that have different ways of setting or changing the pitch of a note; making homemade musical pitched instruments such as elastic band and margarine tub guitars or a xylophone from glass bottles filled with different levels of water.

Elaboration

Teaching and Learning Strategies

To help pupils elaborate a teacher might ask them to make links to previous learning: What does this make you think of/remind you of?; How is this similar to/different from..?; What does this remind you of..; how might you use this?;.. Teachers could ask children to paraphrase something in their own words, or summarise it to extract the key ideas.

Underpinning Cognitive Psychology concepts

One way of thinking about elaboration is as making additions to a memory. Elaboration has echoes of supporting 'deep learning' and thinking about meaning. It is about organizing and integrating ideas. It is about connecting new information with existing knowledge. To an educator, this is a fundamental aim of education! But this complexity makes it hard to study using the kind of science that is seeking to isolate and test variables. This reductionism may underlie the discomfort that many feel about applying cognitive science to teaching and learning in schools.

Thus cognitive psychologists consider elaboration to be very important, but hard to define and thus difficult to use in practice (Weinstein et al., 2019). This might be why it is conspicuously absent from some government documentation.

Elaboration is a very important element of teaching and learning, and very much so in science. It needs and supports questioning and curiosity, scientific attributes that we want children to develop. It could be seen as the neuropsychological basis for dialogic teaching - connecting children's ideas with those of the scientific community. (This guidance has been structured with an eye to elaboration - we consider a concept and provide more detail about it while connecting it with primary science ideas and think about how to apply it in different contexts.)

Primary Science examples:

- Applying knowledge of friction to explain how the movement of balloon rockets changes on different strings.
- To develop the concept of a leaf, expand the range of examples by looking at lots of different kinds of leaves.
- When learning about the structure of a flower such as apple blossom - can you connect that with an apple?
- Link to pupils own experiences - .e.g. link experiences of growing plants at home, and experience of caring for a pet with MRS GREN.
- Go beyond knowing that a snake is a reptile to knowing more about how snakes move, reproduce, eat…
- Compare playing in the water tray and the sand tray.
- Describe feelings after running - link to heart and to lung function.
- Concept mapping - e.g. for evolution.
- Raising questions using KWL grids, (see TAPS pyramid https://pstt.org.uk/resources/curriculum-materials/assessment).
- Use pupil voice wall (see TAPS pyramid).

Making Links to Prior Learning

Teaching and Learning Strategies

Reviewing previous learning and eliciting children's existing ideas provides 'hooks' on which children can then build the new concepts.

Underpinning Cognitive Psychology concepts

Although this one is given last here, partly because it isn't new to teachers - it should really come first for primary science! However, the cognitive psychology reminds us that finding out children's current ideas is not just for teachers to assess them and plan how to build on them. The very process of activating previous memories makes it more likely that new experiences and ideas will be linked to them.

For cognitive psychologists individual knowledge is memory - everything that is learned is memory. Long term memory is created by first encoding an experience then consolidating it. It only becomes a long term memory if it is consolidated. And every time a memory is retrieved it is reconstructed. This is the point at which it will be changed by having new associations made with it. Then the memory will be reconsolidated. So we can see that by bringing to mind previous learning we are making it possible for these old memories to be modified by connecting them with new ones.

Neuroscience is beginning to make sense of what is happening to the material of the brain when we make memories. There is a phrase; 'neurones that fire together, wire together' that nicely summarizes what is happening at the level of the brain cells. There might be clusters of neurons in different parts of the brain that are activated at the same time, some may be old patterns and some may be as a result of new experiences, and then connections between them are created or strengthened. But much of how memories are formed and where they physically are in the brain is still a puzzle for neuroscience.

Primary Science examples:

- Start a lesson by asking children to talk about what they did in the last science lesson (e.g. use picture of materials used to prompt).
- Ask children to draw to explain their ideas e.g. about why the sole of a trainer is good for the purpose of running.
- Invite a group of children to work together to draw what they know about the digestive system.

This list is not exhaustive. We touched here on the role of the emotions in learning but there is much more to consider. There are other well-established ideas in cognitive psychology which we have not discussed here such as the role of narrative and cognitive biases, which also have relevant concepts and findings for primary science.

Beyond Cognitive Psychology: thinking about broader ideas from the learning sciences in a science education context

In this section we explore two important (and related) issues in learning science in primary schools: how we can help children to understand scientific concepts and understanding the value of getting 'hands-on'. Taking these as starting points, we will look at what insights neuroscience could offer. Here the links with practice are less immediate and have not been directly tested. Knowing about the brain won't tell us how to teach, but it can deepen and change our understanding of children's minds.

Neuroplasticity, Interconnectedness and Constructivism

Arguably the most important concept from neuroscience for teaching is neuroplasticity - the brain is constantly changing and will continue to change throughout our lives. There is however a trade-off between this responsive changing and having stable connections between brain cells that mean we don't constantly have to relearn everything! So some parts of the brain are more plastic than others, and some connections are very robust. Some areas of the brain change much less after a 'sensitive period' of development. An example of this is acquisition of a first language. Emotionally significant moments are memorable. Other memories/connections are strengthened (consolidated) by repetition. Cells that fire together, wire together (Hebb's rule, 1949). Much of this happens naturally as we respond to repeated events in our everyday environment. In school we have to deliberately provide this repetition through revisiting and recalling ideas. We grow our own brains in response to interactions with our environment.

The term 'neuroplasticity' means that the brain is continually changing connections between brain cells, with some of these changes becoming more stable than others. It can be thought of as a response to our interaction with the environment and as the traces of the activity of our own brains. We make associations – continuously throughout our lives, a process that only slows in old age. This offers a view of learning that emphasizes building and strengthening connections between ideas. For science educators, this supports the broadly 'constructivist' account of learning that has dominated science education.

Another important idea about the brain is its interconnectedness. Although there are some areas of the brain that have specific jobs to do such as the visual cortex, and areas associated with hearing and speech and directing attention, there are many areas that are less specific in function. Importantly there are large areas known as association cortex which integrate activities from other areas of the brain. Association cortex is where different senses are combined; things are learned, stored and reconstructed (remembered). Also it is in association cortex that attention is shifted and planning occurs. So for example, the experience of lighting a candle and observing it would involve visual areas, movement (motor) areas, smell (olfactory) areas, and emotional responses, possibly pleasure, or fear and memories of previous experiences of candles such as a birthday. Many scientists now think of the brain more as operating in complex networks than isolated regions. (See Fig 1) This helps us to think about how the different senses and thinking that are engaged during a science lesson might be interconnected.

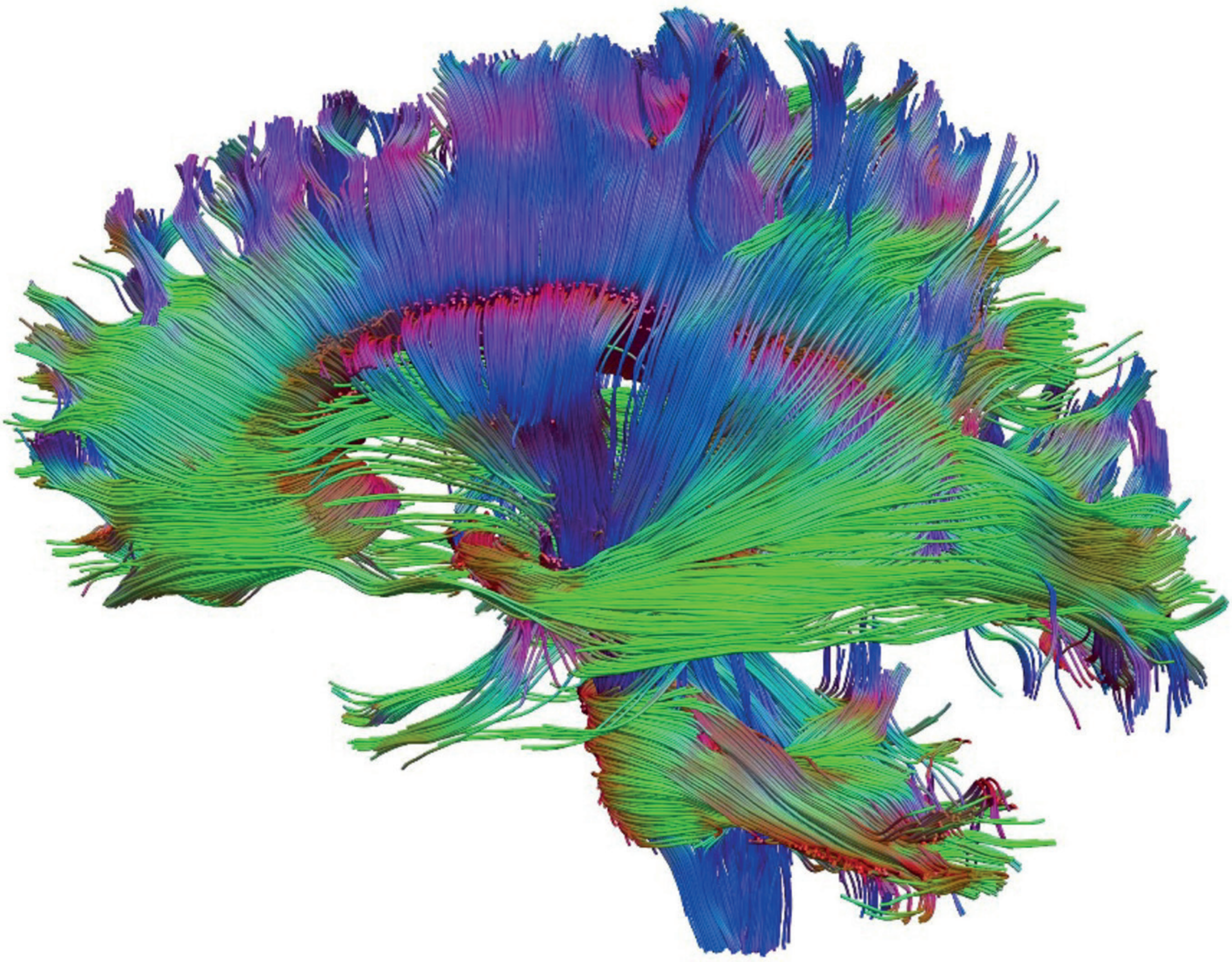

Figure 1 Imaging of connections in the human brain

Credit: Healthy human adult brain viewed from the side, tractography. Credit: Dr Flavio Dell'Acqua. Attribution 4.0 International (CC BY 4.0)

The importance of children's existing ideas

Science education has been good at identifying the existing ideas that children have about the world and that these can be quite different from scientific ideas: the sun and the moon change places for day and night; a shadow is a reflection; giraffes have long necks because they stretched to reach the trees; putting a coat on a snowman will make it melt faster. Constructivist theories of science education have focussed on how teaching can help children to build on or replace their existing ideas with others that are more in line with how scientists understand the world. Neuroscience supports the idea that learning is about building connections - associations - between existing ideas to form new concepts.

However neuroscience is also modifying our understanding: changing children's concepts is not about replacing naive ideas and misconceptions with new ideas but about inhibition of the old ones- suppressing them with alternatives. The neuroscience studies that lie behind this shift in thinking looked at what happens when physics experts and novices were presented with counterintuitive situations (heavy and light objects falling). They found that the experts showed significant activity in brain areas associated with inhibition and concluded that the physics experts' misconceptions were still there, but were being suppressed. We can only help children to build new ideas and strengthen these- we can't get inside a child's head and disconnect the old ones! (See Bell and Darlington, 2018).

We have probably all had the experience of reverting to one of our old ideas (e.g. that venous blood is blue - it isn't!), particularly when we aren't in a science context. This is consistent with the brain carrying out parallel processing - so we tend to form domain-specific connections and so we are not always good at transferring understanding from one context to another (Bell and Darlington, 2018, Vaughn, Brown and Johnson, 2020). We can help by revisiting science concepts in different contexts - retrieving and elaborating. We can help children to recognise where the 'old way of thinking' might kick in and to be alert. Concept Cartoons (Naylor and Keogh, 1998) are very helpful for this as they juxtapose different ideas for us to compare with our own.

The difficulty in changing ideas once they are constructed is a good argument for the importance of primary science and building solid foundations for those conceptions early. Ultimately all conceptions are rooted in active, physical experiences and this will be explored in the next section.

Understanding hands-on learning in science

Brains are in bodies, which are in an environment (both physical and cultural). All animals including humans learn by interacting with/acting on the environment. This concept is sometimes referred to as 'embodiment'.

The basis of every abstract concept is a set of physical interactions with the world mediated by our senses. A trace of this experience is encoded as an 'episodic memory' - a memory of an event that binds together our thinking in that moment with the sensory information of sight, sounds, smells and feelings. As we encounter similar events in lots of different contexts our brains pick out common patterns to create a semantic memory - a meaning. This meaningful chunk is then related to existing knowledge - and is consolidated.

For example, we can imagine a child dripping water onto different fabrics. They might feel the texture of each fabric, they might see how the surface of the fabric looks, and whether water bobbles on the surface or quickly sinks through, they might feel how wet the underside of the fabric feels. They might hear the sound of classmates joyfully playing with the droppers or the teacher rebuking them! This might be taking place in the warm sunshine outside or on a cold, dark day. All of these things will be encoded together.

Imagine then in a mini plenary the teacher invites children to describe the textures of the fabrics, and maybe to group them or sort them in some way. She might ask them to talk with another child and to describe what they noticed when the water was dropped onto the fabric. Then, the teacher might introduce some words: waterproof, water resistant, porous, and invite the children to link this vocabulary with their experiences. In this way language helps create the abstraction in a particular form and to develop a shared set of meanings - knowledge moves from being individual to being cultural and back again (Vygotsky 1978).

Although much conceptual science knowledge, even in primary schools, is abstract and symbolic, and so expressed through language (e.g. mammals, electric circuits, evaporation) much knowledge does come directly from first-hand experience. Think about what is learned about forces by handling a pair of bar magnets, how the graininess of salt before it dissolves in water is felt and seen and how growing plants is linked to the experience of time. This is not a new idea for primary science, but the fundamental importance of the body interacting with the material of the world is supported by cognitive neuroscience. All abstract concepts are built on sensory experiences.

One challenge for 'hands-on' primary science that has re-emerged through interpretations of cognitive science is that 'discovery learning' will not lead children to understand the world in the way that scientists do. Kirschner and Hendrick (2020, p.165) have reopened this discussion of 'Why discovery learning is a bad way to discover things/Why inquiry learning isn't'. They have two main challenges.

First they challenge the idea that children learning with minimal guidance in problem-based, inquiry-based lessons leads to effective learning. This is consistent with the social constructivist view; scientific knowledge is not 'in the stuff', but is a set of ideas that human culture has developed over hundreds of years. These ideas won't be 'discovered'; teacher guidance is needed to help children connect their sensory experiences of phenomenon with the established scientific ideas (Driver et al., 1994). However, we must remember that science hasn't explained everything and in primary science we want children to be curious and creative: to notice things and ask questions and make suggestions that may well go beyond the science learning objective set in the curriculum. Rethinking the relationship between children and the materiality of the world is important in supporting creativity in science (Digby, 2021).

Secondly, Kirschner and Hendrik challenge the assumption that children will learn science by 'being scientists' - making observations and carrying out fair tests and surveys. This is more complex. As just discussed, unguided discovery is unlikely to lead to children developing scientific concepts, but guided enquiries can provide evidence to challenge existing ideas and open children to alternatives. For example, children in a class who put cress seeds to germinate on damp kitchen towel under three different covers: transparent, translucent and opaque, were surprised to see that the amount of light reaching the seeds had had no effect on germination. Then they started to make connections with how seeds often germinate under soils and speculated about how plants get their food before they can photosynthesise. The structured enquiry became a provocation for elaboration. Teacher guidance is needed for children to learn to plan and carry out a scientific inquiry. But the realities of doing an enquiry are also associated with ideas and feelings - curiosity, excitement, having fun, frustration, tedious repetition, and resisting the temptation to take short cuts - that are part of learning what it means for humans to do science.

What can neuroscience tell us about science as a process?

One of the most important aims of science education is to develop scientific literacy within a society. By scientific literacy, we mean that not only do we want children to gain understanding of the concepts explaining natural phenomena, we want children to gain an understanding of the nature of science, or how science works, so that, as citizens, they can take part in evaluating the quality of science that lies behind claims. We want them to understand that the way the evidence is produced affects the outcomes of a study.

In neuroscience the development of different brain scanning techniques have led to new insights such as which areas of the brain are most active during different tasks. But, brain scanning is a good example of how we need to understand a little more about the limitations of the methods in order to judge how generalisable conclusions may be. There are two issues of how science works that we need to be aware of in interpreting brain scans: firstly that the tools or apparatus used to make observations will determine what observations are made and secondly that carrying out any experiment removes the subject from its normal context.

One kind of brain scan is a functional magnetic resonance imaging (MRI) scan. This kind of scan involves a big tube that people would slide into. They produce the pictures that you are likely to have seen of a grey brain with brightly coloured patches (e.g. Fig 3). These images together with concepts from cognitive psychology - of memory, attention and perception - have mapped functions to areas of the brain.

The colourful picture we are presented with from an fMRi scan is not a kind of direct 'photograph', similar to an x-ray. The images have been produce through statistical manipulation. Often this has involved combining results from many people and so may obscure the range of individual differences. We can't be sure that what we are seeing is meaningful. Sometimes the processing involves removing data that is seen as unimportant noise– perhaps by focussing only on the target areas of the brain. The decisions about what data is included or excluded is made by people and so it is subjective and based on prior theories and expected findings. In science the tools or apparatus, which includes analytic processes, will determine what observations are made and conclusions are drawn.

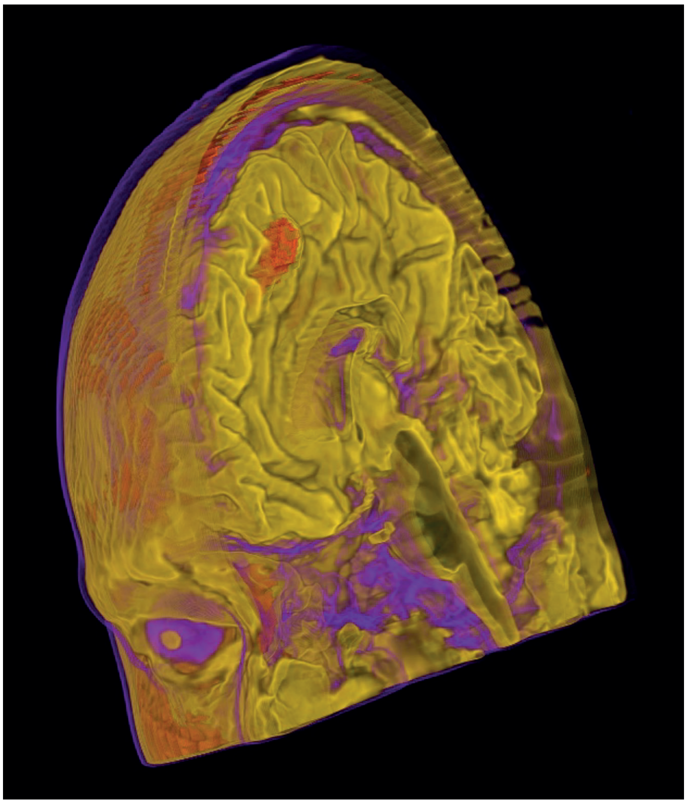

Figure 2 fMRI image of the Brain Human brain activation due to voluntary action.

Credit: Parashkev Nachev. Attribution 4.0 International (CC BY 4.0)

Carrying out a scan removes the subject from their normal context. People don't normally perform tasks when lying on their backs in a dimly lit room, with no human eye contact and the clunks and bumps of machine noise around them. Our bodies behave differently when we are lying down - our breathing slows and blood flow changes, gravity affects the distribution of fluid including (cerebrospinal) fluid in the brain. Functional magnetic resonance imaging or functional MRI (fMRI) measures brain activity by detecting electrical changes associated with blood flow. This is based on previous findings that when neurons are more active then there is increased blood flow to them. So what was already a proxy measure, will be affected by context.

Although as teachers it is useful to understand this as part of our own science literacy, it is obviously not part of the primary curriculum. We can however take opportunities to discuss how doing a science investigation is not always the same as 'real life'. Taking apart a rose flower to look at its reproductive parts is useful, but it is not the same as observing it in a hedgerow or garden filled with insects to visit it. We might explore factors affecting seed germination such as water, light and temperature, but on an arable farm these factors interact along with other factors such as the soil, wind conditions or slope of the field.

When learning about the human body we might also take the opportunity to help children think about organs of the body as interacting systems, not as separate isolated entities. How do the digestive and circulatory systems interact? The image in Fig 3 comes from a teacher education session on human body systems that was tweaked a little by asking the trainees to also think about how the brain was involved in each system (digestive, cardiovascular, musculoskeletal). It helps develop the idea that the brain is part of the body - it is embodied. In science we often deliberately simplify the context - we control the variables, but, particularly when studying living things, it is also valuable to consider phenomena in the complexity of a real environment or system.

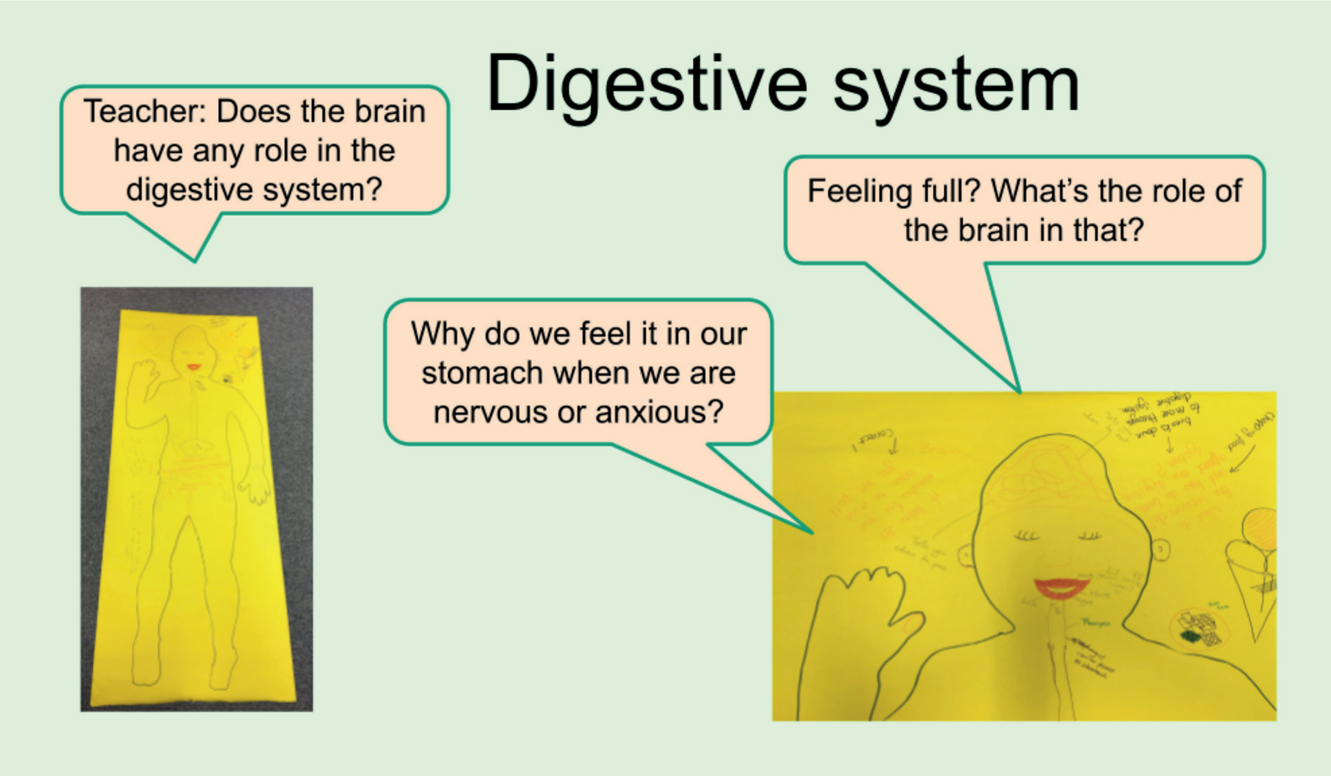

Figure 3 An example of teacher intervention to develop the idea of the brain as part of the body.

For more details see https://data.bathspa.ac.uk/articles/presentation/Teaching_resource_for_tutors_of_trainee_primary_teachers_The_brain_within_the_whole_body/7928699

There are different kinds of brain scans. The tube-like fMRI was mentioned above; there also electroencephalograms (EEG) in which the person wears what looks like a swimming cap or hair net to keep lots of electrodes touching the scalp. These electrodes pick up the electrical activity on the surface. This activity is the summation of the activity of tens of thousands of neurons and their millions of synaptic connections. This is useful (for example in investigating epilepsy), but is more akin to using a thermometer to measure the temperature of a cup of tea than a close look at the water molecules.

We are unlikely to be using EEG in primary classrooms (unless we are at the Synapse School collaborating with Stanford University), but we can learn about how different measuring tools give different insights into a phenomenon. For example, the sensitivity of a measuring instrument matters. We can show this by teaching children how to choose the right Newton meter for the force to be measured. If you try to compare the force of gravity on a classroom chair and a pencil case with a Newton meter that has a very sensitive spring, you will get the same measurement - at the end of the scale - and a broken Newton Meter. If you try to measure the force of gravity on a feather using another Newton meter you might conclude that there is no force acting on the feather.

Or is it that the instrument is not sensitive enough? We can talk with children about choosing appropriate tools to measure temperature or sound. It would be interesting to ask children whether they think learning to tell the time and using clocks changes their experience of time.

The image of brain networks in Fig 1, comes from another kind of process; diffusion tensor imaging. The resulting image of the brain functioning as networks (rather than separate patches of activity as shown in fMRI images) might affect how we think of the brain.

There are many examples of brain-based claims for commercial products that stretch the science beyond breaking point. Lots of these are in education. Many teachers may have been seduced into using activities such as touching the nose with one hand and the ear with the other and swapping over to 'connect the cerebral hemispheres'. Although the activities might be fun, and will certainly activate the brain - everything we do does - the cerebral hemispheres are well connected anyway. Brain training apps may help you to get better at the specific task in the app, but do not lead to a better general performance. (Though there is evidence that playing computer games can lead to a transferable improvement in visuo-spatial skills.) Science education has an important contribution to make in preparing teachers, and all of us, to develop a sense of when we need to dig deeper into a brain-based claim.

Going forwards

We want to support an open-minded, but critical approach to what the learning sciences have to offer teaching. It is also a good reminder of the importance of understanding the nature of science. We should hold in mind that education is an incredibly complex biological and social and cultural phenomenon. As neuroscientist Stephen Rose reminds us: is not brains that learn, it is people (Rose, 2018).

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