Do we have cognitive (psychology) overload?

• Kendra McMahon

What could 'the Learning Sciences' mean for primary science education?

This article is based on a session at the ASE Futures Conference in June 2021 and reflects the dialogue in the session, including those added to the chat box. Many thanks to the science educators who contributed but are not named here.

Abstract

In the recent Ofsted review of research related to science education (Ofsted, 2021), research in cognitive psychology frames learning science as the organisation of knowledge in memory. Science educators have expressed concerns that the importance of language, emotions and hands-on learning and enquiry in primary science may get lost in this view of learning as memory. Perhaps a wider view of 'the learning sciences' that includes neuroscience can take us forward.

After a brief explanation of the background to our recent research project addressing these issues, and a response to the Ofsted review, this article has two main parts:

1. **How can we use ideas from cognitive psychology in primary science?**
2. **How insights from neuroscience research can take us further, although there are critiques of this too.**

Background to the project

The Learning Sciences in Initial Teacher Education Project was funded by the Wellcome Trust and involved teacher educators and education researchers, and also colleagues from beyond our department with expertise in psychology and neuroscience. This collaboration was vital in making sure that we considered scientific and educational viewpoints together. This article builds on one of the project outcomes; the open access booklet entitled *The Learning Sciences and Primary School Science* (McMahon *et al*, 2021), available as a tutor resource at https://www.bathspa.ac.uk/learning-sciences

There are three reasons that we need to think about the learning sciences in primary science. One of these reasons is pragmatic: the DfE and Ofsted are supporting a learning sciences perspective. In particular, cognitive psychology is framing many ideas in policy documents, including the *Core Content Framework* for initial teacher education (DfE, 2019b) and the *Early Career Framework* (DfE, 2019a). But there is a bigger picture. There is also a global interest in neuroscience and education and we should be excited and open-minded about this, but also cautious. We already have our own valuable expertise from professional experience and educational research. And, because of the need for a critical and thoughtful approach, I believe that science educators are particularly well placed to make sense of this for other colleagues. We are used to thinking about issues of science literacy and this is much needed at this point.

Response to the Ofsted Research Review

There are some very helpful ideas that emerge from the review, which:

- Supports a relational view of science knowledge as interconnected (this was also emphasised by Ofsted Science Lead Jasper Green in his talk to the ASE Futures conference);

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- Recognises the need for time for science to embed and consolidate knowledge;
- Emphasises the importance of an interplay between disciplinary knowledge (nature of science and science enquiry) and substantive knowledge (conceptual content); and
- Frames 'science enquiry' as disciplinary knowledge that is both conceptual (e.g. measurement is always an approximation) and procedural (e.g. how to use a thermometer), rather than presenting it as a set of disconnected skills.

The review values practical work, but argues that it must have a clear purpose and that, in order for it to be valuable, children must have the necessary prior knowledge and skills to learn from the activity. Here the review explicitly draws together a range of science educational research (though much is based in secondary schools), with an explanation grounded in the cognitive view of knowledge being built on prior learning. However, the memory-based model of learning underplays research into the importance of the sensory/perceptual and emotional/social dimensions of learning (Turvey et *al*, 2019). As primary science teacher educators, this means that we must prepare teachers to understand and articulate clearly what it is that they expect children will gain from doing particular practical activities. The need to support trainee teachers to specify the 'learning objective' (not just the activity) will feel familiar, but we may also need to focus more sharply on exploring the purposes of a repertoire of different kinds of practical work.

Image credit: Henrietta Howells, NatBrainLab. CC BY

The Ofsted review also points out that scientific enquiry and enquiry-based instruction are not the same. In my experience, explaining this distinction is not an easy task. Discovery learning is totally rejected and the review does (perhaps grudgingly?) say that *'at times pupils will need to carry out their own scientific enquiries'.* The review supports what it terms 'Teacher-directed instruction'. Unfortunately, using this term reverts to the unhelpful dichotomy between 'telling' and 'child-centred learning', which was unpacked by Robin Alexander years ago and is resolved in dialogic teaching characterised by *'active student engagement and constructive teacher intervention'* (Alexander, 2020, p.13).

Good teaching employs a range of different levels and forms of scaffolding for different purposes and for different children as they progress (Darling-Hammond *et al*, 2019). One of the conference participants shared an example in which she clearly told the children that the purpose of the practical work was for them to explore and have fun, with an invitation to produce a photograph of something they had found interesting. This led to

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engagement, joy and children with observations of their own to share with others. A lack of nuanced understanding of the purposes of a repertoire of different kinds of teacher guidance for practical work could give too much support to the persistent 'transmission' view of education, moving too far away from supporting children in feeling ownership of their own lines of enquiry.

How insights from cognitive psychology can inform primary science

Dan Willingham's simple memory model is what underpins much of what we can see in the policy documents and its representation as a diagram by Oliver Caviglioli (Figure 1) is now familiar in education in England.

In this model, you must first give some aspects of the environment your attention. This means that there is a possibility for particular experiences to enter your working memory. The working memory is a theoretical space, not a clearly identified brain area, and psychologists using this model conceive it as where you can do mental work and manipulate ideas. The content of your working memory does not only come from the environment, but can also come from your own long-term memory. Some of the activity that was going on in your working memory becomes stored in long-term memory as a trace of that activity. Much is forgotten. In their very accessible book, Weinstein *et al* (2019) provide a view of learning drawing on cognitive psychology. They explore the cognitive processes of perception and attention, as well as memory. Their view of 'attention' involves both 'situational interest' (e.g. providing an engaging context) and 'increased salience' (e.g. pointing out a particular feature of a plant that you want children to focus on, or using your voice to emphasis new vocabulary). They explain that *'the amount of information requiring our attention'* is known as 'cognitive load' and that too much is termed 'cognitive overload'. The sections below come back to some of the issues examined here, such as how memory is not as fixed as it might seem.

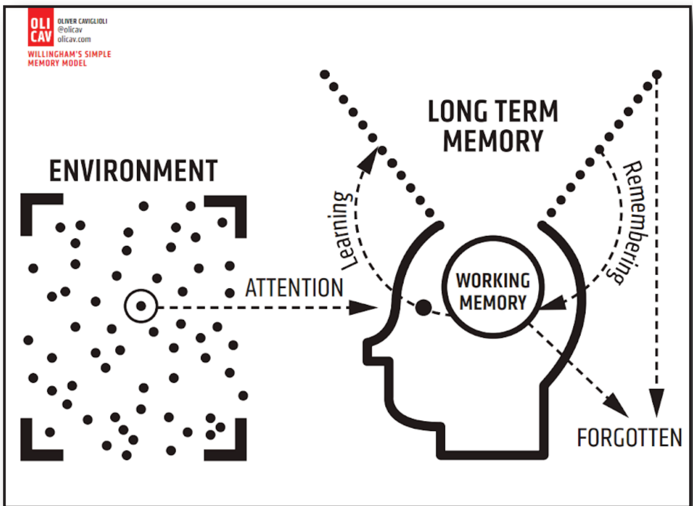

Figure 1. A simple model of memory illustrated by Caviglioli.

This section draws on the booklet (McMahon *et al*, 2021) (Figure 2) exploring how insights from cognitive psychology might help us with teaching and learning in primary science. The three strategies considered here are: reducing cognitive load, retrieval practice, and making links with prior knowledge. The booklet discusses these, and also spaced practice, interleaving, dual coding, plain classroom environment and using concrete examples.

Reducing cognitive load

Although the strategy is listed as reducing cognitive load, what matters more is thinking about the appropriate amount of cognitive load that an activity might generate for a particular learner. This is related to the idea that working memory is limited; it can only handle a limited number of chunks of information at a time. This is why we need to make sure that relevant prior

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knowledge is already in place before children tackle a new activity, so that we are not overloading working memory in what we are asking children to do next. For example, if you are going to be using a thermometer, then you need to spend a bit of time teaching children how to read the scale and that you need to keep it in the water (or the ice or the potato) for a length of time. A relatively easy activity might be to keep the thermometer in a cooling potato and take a reading every ten minutes. It might be harder if you have three different pots of water and you are trying to compare the temperatures, perhaps to check that they are similar as you are dissolving different materials. So, considering cognitive load is about being aware of how many different things children are learning to do at once and thinking about what you need to teach in advance. This is also where planning carefully sequenced lessons (Ofsted, 2021) comes in. Of course, the strategy of introducing new knowledge when the teacher judges that a learner is ready is familiar in the form of education concepts such as working in the zone of proximal development (Vygotsky, 1978), and formative assessment (Black & Wiliam, 1998).

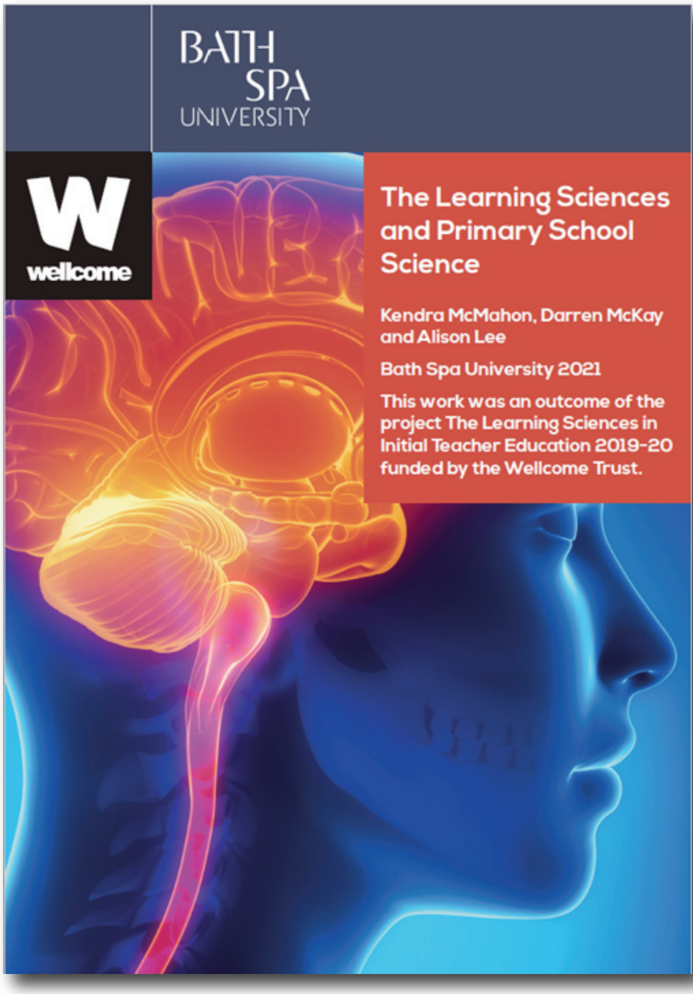

Figure 2. *The Learning Sciences and Primary School Science* downloadable booklet.

Retrieval practice

Retrieval practice is bringing information to mind from memory (Weinstein *et al*, 2019). In our everyday lives, we know that the experiences we have again and again are the ones that become ingrained as habits or patterns of thought. The image of desire lines on a field that is trodden over and over again (Figure 3) is a useful metaphor for what is going on in neural terms. We reinforce connections between brain cells by frequently activating those same connections. For everyday knowledge, this happens naturally. But, for school knowledge there is unlikely to be this frequent reuse of pathways unless we plan for it. Rather than simply repeating an experience, retrieval practice requires effort in bringing a memory to mind and this has a stronger and more lasting impact – things are more likely to be remembered.

Roediger and Karpicke (2006) compared the effect of a) just reading a text again with b) being asked to list pieces of information from it and given points for each correct item. In effect, this second strategy was a relaxed test situation. Those who were 'tested' remembered more of the text when formally tested a week later. This is a bit like when you were revising and you made yourself some flashcards, and put the question on the front and the answer on the back. We know that, if you

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look straight at the answer on the back without trying to recall it, without going to the effort, we do not learn as well. This is even when you do not get the answer right. The reason that this effortful retrieval works to help with retaining and consolidating ideas is not entirely clear, and the forming and retrieving of memories is an ongoing area of research.

In practice, we quite often encourage trainee teachers to start the lesson by reviewing previous learning, and the concept of retrieval practice helps to explain why it is the children who should be doing the recalling and not the teacher (e.g. 'Let's recap from last week – in what different ways can seeds be dispersed?'). To involve all children in this, we often use talk partners to remember ideas from a previous lesson or to put into their own words something that they have newly encountered (e.g. 'With your talk partner, list three things we need to remember when using a thermometer.'). Retrieval practice is sometimes labelled 'the testing effect'. It has to be a 'low stakes' form of testing, so a relaxed quiz or self-assessment would work, but too much anxiety interferes with the process.

Figure 3. *'Desire lines' across a park as a metaphor for reinforcing neural connections.*

Less emphasised in the policy documents is that we do not actually lay down objective, definitive memory traces (Weinstein *et al*, 2019). It is not a stable record like a computer or video recording, because every time you retrieve that memory, every time you are thinking about it again, you change it a bit. This is because memory is reconstructive (Weinstein *et al*, 2019); as you recall it, you are reconstructing the memory and probably making slightly new connections. The implications of this for teaching is that, when we use retrieval practice, we need to use it thoughtfully. We need to think about what new connections are being made. Can we use the retrieval to also extend and elaborate? Perhaps we can use the idea in a different context so that we are not supporting narrow repetition, but helping to create those interconnected pathways and related lines of thought that we want to.

Making links with prior knowledge and elaboration

Making links with prior knowledge is fundamental to the constructivist view of learning that has dominated primary science. In cognitive psychology terms, when we are eliciting children's existing ideas we are helping them draw those ideas from their long-term memories, into their working memories, to help them make new connections across different contexts. We are helping them to build elaborated networks of connections across related disciplinary or substantive knowledge. In neuroscience terms, we are creating pathways by creating and strengthening connections between neurons, summarised by that phrase *'cells that fire together wire together',* which originated from the neuroscientist Donald Hebb.

The fact that memory is reconstructive also means that details from your imagination can be built into your memories. Children could be thinking about

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all sorts of things. As well as the links that we are hoping that they make, they may also be building in what they heard someone behind them just say. The mental model that they have been constructing may not be the same picture that teachers want them to construct. We need to keep checking in and seeing what mental pictures are being created.

How insights from neuroscience can take this further

Using insights from neuroscience helps us to move beyond a cognitive psychology perspective focused on memory research and helps us think about the sensory, the perceptual and action in concept building. It provides insights into how the social/emotional and cognitive aspects of learning work together. There is also interesting new research on conceptual change that is highly relevant to practice and was not included in the Ofsted research review.

The brain as an interconnected whole, not separate compartments

As teachers, whether it is implicit or explicit, we have some kind of mental model of what it is we are trying to achieve from our teaching. As science progresses, a view in which different bits of the brain do different separate things is shifting into a view in which the brain is seen as acting more holistically. The Human Connectome Project is mapping pathways within the brain and gives us new images of connections between different brain areas (Figure 4). These images resonate with a view of learning as involving perception and action and a more relational view of knowledge and understanding as interconnections between different modes and elements.

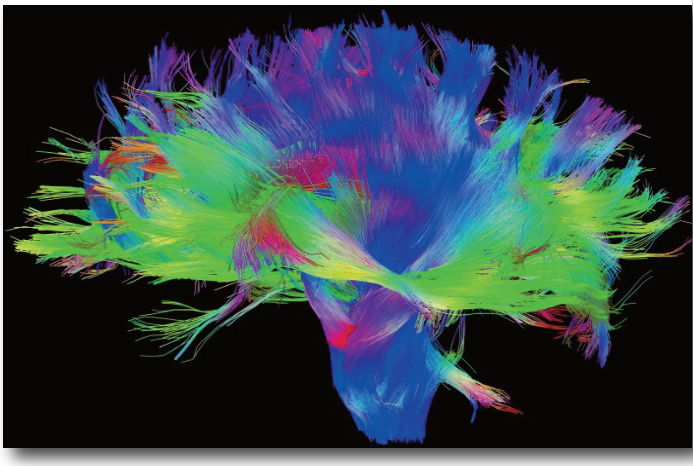

Figure 4. *Diffusion Tensor Imaging of connections in the brain from the Human Connectome Project.*

From this standpoint we are not viewing science knowledge as being in a particular little box that is separated from emotions or from what we see and do, but that it is constructed from connections between different parts of our brain. In primary science, we have got the material 'stuff', the phenomena (e.g. we can feel and see on a thermometer that a baked potato cools down over time) and we are curious about it (What is heat? Why do things cool down?). We also have everyday and scientific ideas about phenomena (e.g. heat is the opposite of cold; heat is a form of energy; putting a coat on keeps us warm; insulating materials can slow the transfer of heat to the air). Teaching involves bringing emotions, ideas and sensory experiences together for and with learners. My neuropsychologist project colleague Alison Lee has a particular interest in the association cortex, which are parts of the brain with the particular job of bringing together information from other parts of the brain. In association cortex areas, different senses are combined to make recognition/memory easier. Action is planned and attention is shifted. It is here that things are learned, stored and reconstruction happens when we remember. It is exciting that we can physically map the places in the brain where different sensory modes (touch, smell, taste, hearing, vision) are brought together. This is

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helpful to us in supporting our arguments about what constitutes good practice to support learning.

It makes sense of what might be happening during teaching that brings together discussion and practical work. For example, we might invite children to use their hands (to feel both a hot baked potato that has been wrapped up for an hour and another that was not wrapped up) and then ask questions to connect the sensations with ideas (e.g. What do you notice? What might the wrapping have done?).

What is developing a scientific concept?

One way of imagining the beginning of a scientific concept is as elaboration of 'phenomenological primitives' or P-prims (Amin *et al*, 2014). Through everyday experiences of living we develop these very basic forms of knowledge that can be called P-prims. They are situated in a particular context. We do not really think about them or label them with words, we just come to know by living. When young children wrap up to keep warm it is a physical experience – we put on a coat or jumper and we feel the effects. There might be language loosely associated with this experience; there is certainly action, movement and associated sensations. Rather than the coherent schemas that Piaget imagined developing naturally, the suggestion is that these P-prims tend to stay as separate bits and pieces of situated knowledge. Other authors use the terms 'image schemas' or 'core intuitions' to try and conceptualise the implicit knowledge that emerges from embodied, sensorimotor experiences (Amin, 2021). It is helpful to know that current research is still wrestling with these ideas!

Educational neuroscientists Tolmie and Dündar-Coecke (2020) suggest that science concepts start with 'image schemas' that are formed through our physical interactions with the environment. Image schemas do not involve language, but are embodied and prelinguistic. Some examples of image schema that Tolmie and Dündar-Coecke give are: above, path, container, thing, matching, and full/empty.

Developing a concept requires linking sensory perceptions and image schema with causal explanations. These causal explanations are not perceptible – our senses alone cannot 'tell' that the coat helps to reduce heat loss – we need an imaginative leap to reach this understanding. We layer a social developed representation, particularly language, on top of the perception and action-based image schemas, for example by creating the concept of heat as an entity that can move. The introduction of words, metaphors, diagrams (which are all kinds of external representations) on top of those initial image schemas develops the concepts. For example, to explain why putting on a coat makes you feel warmer we might use the metaphor of a coat as a barrier that blocks the pathway of the heat away from our body. Particularly for young children, this account supports a role for education in providing diverse sensory and embodied experiences and using language and other representations to make them meaningful. Direct experience AND social interactions are needed to build concepts.

As children get older, teachers can support children in making further connections between different concepts to form abstractions. We might ask children to explore the properties of materials that are good at keeping heat in and label that property as heat insulation. We could make more connections by exploring how insulating our homes properly makes a useful contribution to reducing global heating and look at the building materials that are used in this process.

Again, Tolmie and Dündar-Coecke (2020) explain that there is not a natural tendency for building coherent knowledge structures. It seems, in line

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with theories of situated learning (Lave & Wenger, 2012), that we build concepts in the kind of mental space for which it is usefully situated as a result of experience, so they end up being separate. This means that a key role for teachers is to build those bridges in order to make links, first between the perceptual and then conceptual and abstract capacities that we want children to have. This sounds like we are aiming for the relational, connected knowledge that Ofsted's Jasper Green is advocating.

What is conceptual change?

Another area in which neuroscience is contributing to our understanding of learning is the process of restructuring children's existing ideas. Neuroscience is changing our ideas about what it means for children to change their concepts. In science education, we have long talked about 'replacing misconceptions', or, using my preferred terminology, restructuring 'alternative frameworks' to align with more scientific ideas. But that might not be what is actually going on.

Rather than replacing and restructuring earlier concepts, those with scientific understanding seem to be suppressing their previous ideas. Masson *et al* (2014) used brain scanning to compare the brain activity of physics and non-physics graduates carrying out a physics task. The 'expert' physics graduate showed high levels of activity in brain areas responsible for inhibition. The authors concluded that the reason that the experts are able to bring their science knowledge to the fore is not that they have managed to completely replace their old, naïve ideas, but that they have built new ones and now know when to apply them and inhibit the old ideas; they can bring the right sort of ideas to mind for the right situation.

This subtly shifts our understanding of what we are trying to do as science educators and how we respond to the everyday, and sometimes unscientific, ideas that children have. We can continue to use them as starting points on which to build new concepts, but we can place more emphasis on recognising when an 'old idea' might get in the way and when we need to activate a 'new way of thinking'. Sometimes we can draw attention to whether everyday or scientific thinking is needed. In everyday thinking we talk about closing the door to keep the cold out, and that is fine in that context, but in a scientific context we talk about cold as an absence of heat and the insulation properties of materials (see the chapter in the *ASE Guide to Primary Science Education* written by Derek Bell and Helen Darlington (2018) for more discussion on how children can hold everyday and scientific ideas in parallel).

The 'Stop and Think' approach taken by the Unlocke Project (www.unlocke.org) is looking at the potential implications of this cognitive inhibition for teaching. The Unlocke project uses computer-based multiple-choice scenarios, similar to a concept cartoon, in which children have to choose the best response to a scientific problem. The computer programme enforces a wait time, so the children are forced to stop and are encouraged to engage more scientific ways of considering the problem (Bell *et al*, 2021). The evidence seems to be that this helps children to slow down and bring to mind more scientific explanations. An Education Endowment Foundation trial of this is now underway. Without the computer programme, teachers could explain to children that we commonly first go to our old ideas and simply encourage children to 'stop and think'.

The emotional and social dimensions of learning

Taking a broad view of the learning sciences also helps us to recognise that the cognitive comes together with the emotional and the social domains of learning. Teachers already know this of course, but we can improve our understanding by drawing further on ideas from neuroscience. For example, there are widely held ideas that could be seen as a new neuromyth, that we have an evolutionarily primitive 'reptilian' and emotional area of our brain and we need to use our more evolved rational thinking in order to control this. As the brilliant title of this article points out, *'Your brain is not an onion with a tiny reptile inside'* (Cesario *et al*, 2020) and that all parts of the brain evolved in parallel and they interact all of the time, and emotions are essential in driving and directing cognition (Damasio, 2006).

A fascinating quality of humans is that we actually have fewer genes than you might imagine you would need to specify a whole human mind. It may be that this under-specification evolved as an advantage that makes it possible for people to learn and change in response to their environment. That is what makes humans so flexible and adaptable. By 'the environment', we mean the social/cultural environment as well as the physical environment and humans have an *'unparalleled proclivity for socially mediated learning'* (Immordino-Yang *et al*, 2019, p.187). This is in line with educational theories on social learning proposed by Vygotsky (1978) and Bruner (1996).

Immordino-Yang *et al* (2019) explain that humans have three major brain networks that are interacting all the time. The first is the executive control network, which is responsible for goal-focused tasks. There is also the default mode network that is less talked about in education. The default mode network comes into play when we stop being goal-focused. It is sometimes called the daydreaming network and supports reflection and creativity. It seems to be responsible for our sense of who we are (and what matters) as well as helping us to have a sense of others (theory of mind or 'mentalising'). Another network, the salience network, is responsible for switching between the other two modes (the goal-focused and the more reflective thought). Current policy documents are placing a lot of emphasis on how we can keep this executive control network in charge at all times by managing children's attention and reducing distractions. I would like to see more recognition of the value of interaction between the default mode network and the executive control network; as teachers, we could support flights of fancy as well as helping children to pay attention to key features. After all, science is about imagination as well as evidence.

Summary of insights from neuroscience

From a constructivist perspective, children's scientific understanding is ultimately built on sensory experiences of the material world.

These sensory/perceptual experiences are mediated by cultural symbols that create meaning (e.g. words and images).

We need to build bridges between the sensory and conceptual to support expert understanding.

Teachers and learners engage social, emotional and cognitive processes all at once.

Learners hold everyday and scientific ideas in parallel. We need to help them activate/suppress the right ones in scientific contexts.

We can think of the brain as integrated networks.

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Problems and critical perspectives on neuroscience and education

Perhaps not surprisingly, there are plenty of critical perspectives on the role of neuroscience in relation to education. Some are saying that neuroscience is of no direct use to teachers and that it must be bridged by psychology. So, from this view maybe neuroscience can inform psychology, but it is psychology that should inform education (Bruer, 1997).

This could explain why ideas from neuroscience are not so visible in policy documents. There are also concerns from within the neuroscience community. People are more persuaded by a claim that is accompanied by a picture of the brain (McCabe & Castel, 2008) and we are all susceptible to the *'seductive allure of neuroscience'* (Weisberg *et al*, 2008). We need to be really careful and critical whenever we are presented with claims to knowledge that are brain-based.

There are also educationally-based concerns about the current dominance of a scientific view of learning. We do not want a version of evidence-informed practice that is about telling teachers what to do; we want professional expertise and situated judgement to be valued. As Biesta (2020) argues, education is a complex system involving people who have their own ideas, so we cannot reduce it to a simple cause-effect understanding of what works. As science educators we need to understand the limitations of scientific perspectives too.

Having a broad view of the learning sciences can help us go forwards

My contention is that we need a broad view of 'the learning sciences'. This article has begun this by discussing how neuroscience can extend what we can gain from cognitive psychology. These ideas are useful, but alone do not provide the whole picture. The learning sciences are wide-ranging and interdisciplinary, including the fields of linguistics, computer sciences, anthropology and education, which will offer further insights to those added here. As Biesta (2020) argues, research is not just there to advocate techniques for teaching; it can develop our cultural ideas about what learning is. We need to be wary about how the dominance of the cognitive psychology model of learning is shifting our ideas about teaching and learning.

Although the simplicity of a single model of learning based on working memory and long-term memory may be appealing for beginner teachers (Willingham, 2017), as science educators we should be honest about the fact that there are different perspectives. Managing this complexity of views is not easy and we are all vulnerable to cognitive overload!

We hope that the open access materials on our webpages offer helpful starting points for initial teacher education (www.bathspa.ac.uk/learning-sciences). We should maintain a dialogic framing of scientific knowledge, including scientific accounts of learning, as unfinished and disputed.

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