What are the Implications of Psychology and Neuroscience Research for STEM Teaching and Learning?

A Mapping Study for the Royal Society

Paul Howard-Jones and Tim Jay, Graduate School of Education, University of Bristol

Executive summary

Our report summarises the current state of knowledge in psychology and neuroscience that can be useful for STEM teaching and learning, and sets out what this knowledge means for the classroom.

The evidence emphasises two key messages regarding a child's initial STEM building blocks:

- Young children do not arrive at school as "blank slates". They arrive with important mental skills for STEM learning. These include the ability to focus, think, and to resist an impulse. How an infant thinks about number and how he/she can imagine an object rotating are also important. Insights from current research can help detect and reduce problems in these areas early on.
- Attitudes to STEM also strongly influence outcome. Teachers and parents have an effect on the difference between boys' and girls' attitudes.

In terms of implications for teaching, evidence from the sciences of mind and brain support:

- Early training with number using computers.
- Practicing the rotation of objects in one's head.
- Using exercise to help brain function and memory.
- Writing about worries before a test.
- Spacing out periods of learning over time, instead of doing it all once.
- Mixing up types of problem and types of topic when learning. For example, mixing worked examples with solving problems.
- Using testing to help learning.
- Using learning games with the whole class that require luck as well as learning.
- When using pictures, providing explanations that are spoken (or recorded as spoken) rather than written.
- In science, using both direct instruction and approaches that involve inquiry
- Explaining scientific ideas by moving from more solid (or "concrete") examples of a scientific idea to more "abstract" forms (such as a diagram)

- Using actions and gestures. This can include asking students to act out actions they come across in their learning. It can also include teachers using gestures when explaining ideas to students

In summary, we find cause for cautious optimism in terms of number and quality of insights arising from psychology and neuroscience. Inclusion of neuroscience and more psychology in teacher training, and greater dialogue between education and neuroscience would support the application of these insights in STEM education.

Introduction and remit of the study

In this study, we show how insights from the sciences of mind and brain are offering opportunities to improve approaches to STEM education. In developing our recommendations, we have drawn from advances in cognitive psychology, developmental psychology, cognitive science, cognitive neuroscience and the emerging field of neuroeducation[1]. The following questions motivated and guided the study:

i) What do findings from psychology and neuroscience tell us about the relationships between age, gender, cognitive resources, attitudes, engagement and achievement in STEM subjects?

ii) What do teaching strategies based on findings from psychology and neuroscience look like?

iii) What examples are there of successful interventions in the design of teaching and learning that are based on psychology and neuroscience?

iv) Are there any specific issues or implications when using these teaching strategies for science and mathematics teaching and learning?

We present our findings in two parts. The first of these ("Precursors for achievement") focuses on the cognitive resources and pre-school experiences that underpin children's STEM potential. The second ("Teaching strategies") focuses on teaching and learning practices in the classroom that can help children fulfil this potential.

[1] Also known as "educational neuroscience", "brain, mind and education" or "neuroscience and education"

Method

This study began with an initial mapping task to identify and classify topics (see Appendix 1). From the results of this task, we selected a sub-group of topics where there was broad agreement in the classroom and/or laboratory-based peer-reviewed research for educational value. The notion of agreement, of course, becomes less meaningful when only a very few studies exist on a particular topic and we do, therefore, indicate where this is the case. Similarly, we indicate where, in some cases such as the *enactment effect*, the data arises from non-STEM subjects but, based on present understanding of underlying processes, should be applicable to STEM also. We also encountered some important topics where, at present, scientific opinions do not converge sufficiently to provide a clear message regarding educational value. One important example here would be the training of working memory capacity[2]. Such research may soon reveal valuable educational benefit but the intensity of the current scientific debate surrounding it prevents practical recommendations at present. Similarly, the role of sleep in learning is well established, as is the difficulty teenagers often encounter with their sleep patterns. However, evidence of clear improvements in school achievement have not arisen from studies in which teenagers are educated about their sleep (Azevedo et al., 2008; Bakotic, Radosevic-Vidacek & Koscec, 2009; Blunden, Chapman & Rigney, 2012; Brown, Buboltz & Soper, 2006; Cain, Gardisar & Moseley, 2011; Cortesi et al., 2004; de Sousa, Araujo & Macedo de Azevedo, 2007; Hoyland, Dye & Lawton, 2009; Tan et al., 2012) or allowed to start school later (Owens, Belon & Moss, 2010; Wahistrom, 2002). It is also worth noting that many concepts boasting a popular association with psychology and/or neuroscience have been omitted since their scientific basis, in terms of high quality scientific publications, we find difficult to establish (including some of the common "neuromyths" discussed in Appendix 2 such as 'teaching to learning styles' (Geake, 2008)).

[2] this Working memory is the ability to hold information in your conscious attention, and the amount of information (its capacity) is limited. For example, the average person can retain only around 7 digits in the working memory

Results and analysis

Precursors for achievement

This section covers both the foundations of children's understanding, and the ways in which children in a classroom can differ from one another in their response to instruction. A study by LeFevre et al. (2010) suggests children's achievement in mathematics is predicted well by a combination of number, spatial and language abilities. With these, we also consider executive function (the ability to concentrate, reason, and resist impulses[3]) and attitudes to STEM, due to the weight of evidence linking these to achievement in STEM subjects.

Number

Being able to use number rests on 3 key systems or abilities:

- Our non-symbolic number system - which allows us to quickly estimate the number of objects in a group (Dehaene, 1997). This develops throughout childhood (Halberda & Feigenson, 2008) and correlates strongly with achievement in mathematics (Halberda, Mazzocco & Feigenson, 2008). Four-month-old infants can tell the difference between sets of one, two and three objects (Wynn, 1998), but it takes children another two or three years of development before they can tell the difference between sets of five and six objects (Starkey & Cooper, (1980). Specific difficulty in learning maths has been linked to problems with this ability (Anderson & Ostergren, 2012; Mazzocco, Feigenson & Halberda, 2011; Piazza et al., 2010).
- Our symbolic number system – which involves using number symbols (1,2,3 etc.) and words (one, two three, etc). Children of around two to three years old know some words mean numbers but it takes another year or more before they know which word refers to which number (Wynn, 1992). Children usually have some abstract understanding of numbers (i.e. without the presence of real objects) by the age of five, particularly in the principles of counting (Gallistel & Gelman, 1992). This understanding is strongly linked with experience and ability with language.
- An ability to translate (or map) between non-symbolic and symbolic number systems. This develops throughout early childhood (Mundy & Gilmore, 2009) and the use of fingers in counting appears to play an important role in its development (Kaufmann, 2008; Kaufmann et al. 2008).

All these abilities are rapidly emerging at age five, when children in the UK begin formal education. While their relative importance (Rousselle & Noel, 2007) and the connection between them (Sasanguie et al., 2013; Gilmore et al., 2013) remains the subject of research, it is recognised that supporting development before, or soon after, starting school can reduce disadvantage relative to peers. A pre-school intervention (Klein, Starkey & Ramirez, 2003) for children in low-income families reduced the gap in

[3] Related to delayed gratification

mathematical knowledge between these and other children (Starkey, Klein & Wakeley, 2004). Furthermore, computer games designed to support the development of non-symbolic number sense, and mapping between this and symbolic numbers, have also reported success (Kucian et al., 2011; Wilson et al. 2006). Additionally, some improvement of mapping between number systems has been achieved by focusing on finger exercises (Gracia-Bafalluy & Noel, 2008). We are quickly developing ways of identifying children's differences in number and other abilities soon after birth. These methods are based on genetic information or measurements of brain activity, and they allow the earliest possible intervention (Plomin, 2008; Szucs & Goswami, 2007). However, the ethical issues involved with such screening programmes may need further thought.

Spatial ability

Spatial ability refers to our ability to think in three dimensions. In particular, our ability to accurately imagine what happens when we rotate an object in space (mental rotation) is an important predictor of achievement in maths (Casey, Pezaris & Nuttall, 1992; Geary et al., 2000) and science (Tracy, 1987). Spatial ability appears to explain some gender differences in STEM outcomes, though the connection is complex (Casey, Nuttall & Pezaris, 1997; Linn & Peterson, 1986). For example, it may partly be due to differences in test-taking strategies, since differences in mental rotation tests when individuals were timed disappeared in untimed versions of the test (Goldstein, Haldane & Mitchell, 1990).

Training of mental rotation can lead to durable improvement in this skill. One review estimates that training the entire population might double the number of those with spatial abilities as good as an average engineer (Uttall et al., 2012). However only a few studies have examined transfer of spatial training to STEM outcomes. These studies report positive results but suggest sustained practice may be necessary for long term improvement (Gerson et al., 2001; Miller & Halpern, 2013; Sorby, 2009).

Executive function

Several research studies link the ability to focus, think, and to stop an impulse (executive function) with achievement in maths (Bull, Espy & Wiebe, 2008; Clark, Pritchard &Woodward, 2010; Mazzocco & Kover, 2007) and science (Gropen et al., 2011). In particular, young children's levels of effortful control[4], false belief understanding[5], inhibitory control[6] and abilities to shift attention from one focus to another are strongly related to mathematics achievement at the beginning of primary school (Blair & Razza, 2007). Children with low achievement in mathematics often have particular difficulties with resisting impulses (Bull & Scerif, 2001). In general, efforts to develop training programmes to improve executive function have not been successful (Thorell et al., 2009). However, physical exercise has been shown to lead to strong and enduring gains in executive function in both adults and children (Davis et al. 2011). Such gains help explain the substantial amount of evidence that exercise can improve academic

[4] Being able to control one's response to an external event

[5] Understanding that an individual's belief or representation about the world may contrast with reality

[6] Being able to suppress an action

achievement (Hillman et al., 2009; Rasberry et al., 2011; Tomporowski et al., 2008).

Attitudes and achievement in STEM

Positive attitudes to STEM subjects strongly predict high levels of achievement in science, and this relationship is particularly strong for low-achieving girls (Weinburgh, 1995). In international comparisons, gender differences in mathematics achievement are generally small across the world but vary widely by country (Else-Quest, Hyde & Linn, 2010). The causes of such gender differences are largely social and cultural, and reasons for international variations are likely to be complex. National attitudes towards sex roles and STEM subjects appear to influence gender differences in achievement in those subjects; In the USA, high correlations between people in a country think about a typical scientist nation-level gender-science stereotypes and nation-level sex differences have been found in 8th grade (13-14 years old) mathematics and science achievement (Nosek et al., 2009). These cross-national studies back up smaller-scale findings showing that girls often underachieve in STEM subjects as a result of unfavourable stereotypes (Nosek, Banaji & Greewald, 2002; Stoet & Geary, 2012).

Parents' gender stereotypes predict primary school children's self-perceptions about ability in mathematics (Tiedemann, 2000). Female primary school teachers' levels of maths anxiety predict children's maths anxiety and their level of achievement in maths, but only for female pupils (Beilock et al., 2010). Students who are anxious about maths are likely to engage less with the subject and this may have an accumulating effect upon their engagement, progress and achievement (Ashcraft, Hause & Hopko, 2007; Hembree, 1990). Researchers have explored the effect of single-sex mathematics and sciences classrooms, with the hypothesis that all-girl classrooms might increase girls' confidence and in turn raise levels of acheivement and post-compulsory participation in STEM. While there are some signs that single-sex classrooms can increase girls' confidence (Gillibrand, Robinson, Brawn & Osborn, 1999), the prevailing evidence shows that there are generally no effects on achievement or participation (Baker, 2002; Daly, 1995; Forgasz & Leder, 1996). Although only a modest amount of research has focused on academic anxiety, there are many studies focused on memory and stress more generally, with neuroscience helping to explain why anxiety can sometimes support or detract from learning (Joels et al. 2006). When maths-anxious children perform calculations, they have greater activity in the amygdala (a brain region associated with emotional processing) and reduced activity in brain regions supporting working memory and the processing of numbers, compared with children who are not anxious (Young, Wu & Menon, 2012). The extent to which maths-anxious individuals display problems with their maths is predicted by the extent to which they use neural circuits for controlling emotion. This suggests that interventions should emphasize control of negative emotional responses to maths (Lyons & Beilock, 2012). A simple example of such an approach has been to encourage students to write about maths-related anxieties before a test. This was found to significantly boost scores of anxious maths students (Ramirez & Beilock, 2011).

Socioeconomic Status (SES) and STEM achievement

Relationships between childhood SES and cognitive abilities have only relatively recently been systematically studied (Hackman & Farah, 2009). A review of SES and cognitive

development (Raizada & Kishiyama, 2010) cites evidence for links between SES and a number of factors discussed above, including executive function, language skills, and numerical ability.

Teaching strategies

Teachers have a wide range of instructional strategies at their disposal. Depending on the subject and the level at which it is being studied, teachers must decide what material to present, and when and how to present it. This section reviews research that might inform these decisions.

Spaced learning and interleaving

Learning is improved when it occurs in several study sessions separated in time (or "spaced") rather than massed together (Cepeda et al., 2006). For example, instead of an hour's learning followed by an hour's break, outcomes will be enhanced by alternating between 10 minutes of learning and 10 minutes break for 2 hours. This has been observed in studies of pre-school children and infants (Rea & Modigliani, 1987; Toppino, 1991; Toppino & Digeorge, 1984), primary (Sobel, Cepeda & Kapler, 2011) and secondary school children (Carpenter, Pashler & Cepeda, 2009) and in a number of educational contexts including secondary school biology (Reynolds & Glaser, 1964), 5 year-olds' reading (Seabrook, Brown & Solity, 2005) and undergraduate mathematics (Rohrer & Taylor, 2006; 2007). A recent study of the effects of spacing science lessons out in time showed that it improved young students' ability (aged 5-7 years) across several types of learning and in relation to both simple and complex concepts (Vlach & Sandhofer, 2012). Any form of spacing appears to promote learning (Carpenter et al., 2012). No single value of spacing appears to be the best, with researchers reporting a range of optimum figures (Challis, 1993; Dempster, 1988). The optimal gap may increase as the gap between learning and testing increases, with the penalty for a too-short gap appearing far greater than the penalty for a too-long gap (Cepeda, Coburn et al., 2009; Cepeda, Vul et al., 2008). A brain imaging study showed that improved performance in a spaced approach relative to a massed approach was related to activity in a brain region that supports mental repetition when learning. This suggests the spaced learning effect is due to maintaining the learning content in consciousness longer during and between spaced sessions relative to when sessions are massed together (Callan & Schweighofer, 2010).

Interleaving is a type of spaced learning that incorporates other, unrelated, learning in the spaces. There are different ways in which interleaving can be used. For example, the teacher may decide to interleave two different types of content, or two different types of thinking process, etc. The interleaving of different learning content and processes creates a more complex situation in terms of explaining beneficial effects and not all approaches to interleaving have been explored. A study of 10-12 year-olds learning fractions (Rau et al., 2013) has shown that interleaving task types can be an effective instruction strategy. In a study involving adults, numerous paintings by each of 12 artists with similar styles were viewed, with the paintings either categorised by artist or interleaved. This type of interleaving was shown to improve the ability of learners to identify the creator of previously unseen paintings (Kang & Pashler, 2012). Some researchers suggest that, unlike temporal spacing, interleaving can highlight category differences and so enhance

processes of learning by example (Birnbaum & Kornell, 2013; Kornell & Bjork, 2008). This explanation is aligned with a neuroimaging study that suggests when tasks are interleaved this may encourage the pairing of each kind of task with its appropriate procedure (Taylor & Rohrer, 2010). When we are presented with the same information several times over a short space of time, we know the activity in regions of the brain related to memory can decrease over each presentation. Other brain imaging studies suggest that interleaving also has the advantage of reducing this suppression of neural activity (Xue et al., 20010; 2011).

Testing

Taking a test on studied material improves memory for material on a final test, compared to simply rereading that material (McDaniel et al., 2007; Roediger & Karpicke, 2006). Rather than enhanced learning from testing being due to better attention, studies suggest it is due to practising the act of remembering (Kang & McDermott, 2007). The testing effect for memory has been demonstrated for a wide range of material and contexts, including computer-mediated scientific explanations with adults (Johnson & Meyer, 2009), multiple choice questions during undergraduate lectures (Campbell & Meyer, 2009) and science quizzes with 13-14 year olds (McDaniel & Agarwal, 2011). Rehearsal of retrieval was recently shown to be more effective than concept mapping for undergraduate scientists (Karpicke & Blunt, 2011). Testing can improve memory for associated material that is not tested (Chan, 2010; Chan et al., 2006). It can improve performance on applying the learned information to make inferences (Butler, 2010) and can promote meaningful conceptual links (Karpicke, 2012), although some evidence suggests it may not apply to the retention of problem-solving skills (van Gog & Kester, 2012).

The ability to remember during a test appears strongly related to the brain's response to the reward available (Shohamy & Adcock, 2010), and this response is mediated by many factors, including expectation, context, peer presence and competition (Chein et al., 2011; Howard-Jones et al., 2010; Niewenhuis et al., 2005). Uncertain rewards[7] are a common feature of games, and these have been shown to increase motivation and emotional response to learning (Howard-Jones & Demetriou, 2009). As well as providing insight into issues such as scientific curiosity (Jirout & Klahr, 2012), the provision of uncertain rewards offers a theoretical basis for designing learning games (Howard-Jones et al., 2011a), since uncertain rewards can increase learning and understanding relative to rewards received only in return for learning (Ozcelik et al., 2013).

Multiple representations

Studies have confirmed the benefit of combining visual and text descriptions. Providing an auditory description (i.e. one spoken by the teacher or a recording rather than text) provides additional advantage – possibly because the learner does not have to split their visual attention between the text and diagram (Clark & Meyer, 2003). Additional learning

[7] Uncertain rewards may, or may not, arrive when a student has achieved learning. Students can be more motivated to learn by the offer of a 50% chance to win two points, than by the certain knowledge they will earn 1 point.

from providing auditory and visual information has also been attributed to increasing the limited capacity of working memory by using both its visual and auditory components. In addition, brain imaging studies suggest improved learning may occur by encouraging additional linking of information from the two sources (Olsen et al., 2012).

The tendency of our memory systems to seek meaningful links may also explain the learning potential of abstract representations compared with concrete ones (e.g. diagrams of systems compared with a solid working model). To understand an abstract representation, one must focus on the meaning of its different parts, rather than focus on its physical properties (Kaminski et al., 2013; Uttal et al., 2009). Abstract representations are better at supporting transfer of the concept to new situations, at least if these are abstract in nature (Goldstone & Son, 2005). However students, especially young children, find it easier to initially grasp a concept from its concrete representation, and this representation may also help the student apply the concept in new concrete contexts (de Bock et al., 2011). Recent research confirms abstract and concrete representations can complement each other in a "concreteness fading" approach (Moreno et al., 2011). Here, the teacher moves gradually from the concrete to the abstract (McNeil & Fyfe, 2012), emphasising how the parts of each representation map onto each other (Richland & Zur, 2007).

Alternatives to direct instruction

There is good evidence that direct instruction may be most efficient in ensuring understanding, and short and long-term retention (Alfieri et al., 2011; Kirschner et al., 2006; Klahr & Chen, 2003; Klahr et al., 2011). Learning can also be improved with the use of problem-solving practice and study of well-designed worked examples (Atkinson et al., 2000). Studies of the "worked example effect" - the fact that the study of worked examples is often more effective than problem-solving practice alone - are mainly laboratory-based. However, some studies have demonstrated this phenomenon in children's learning of science and mathematics in educational contexts. These include early findings of improved outcomes and considerably faster progress of middle-school children following a three-year curriculum of algebra and geometry (Zhu & Simon, 1987), improved understanding of physics principles amongst secondary school students (Ward & Sweller, 1990), improved reasoning about geometry by 12-13 year olds learning both individually and in groups (Retnowati et al., 2010), and faster learning of subtraction by 9-10 year olds (van Loon-Hillen et al., 2012).

Although in many contexts direct instruction can be very effective, other issues may arise when selecting between direct instruction and alternatives that include guided inquiry and problem-based learning approaches (Kuhn, 2007). For example, indirect instruction may allow students to better understand the links between concepts (Knippels et al., 2005) and to understand the learning process itself (Kuhn & Dean, 2005). For socioscientific issues (e.g. the ethics of stem-cell research), indirect instruction appears more effective in fostering understanding of the complex decision-making strategies involved (Bottcher & Meisert, 2013). Guided inquiry-based exploration[8] of a virtual geometry environment has also been shown to promote better engagement and learning than direct instruction

[8] Where the teacher guides the students towards answers already identified by the teacher

supported by text-books (Erbas & Yenmez, 2011). A neuroimaging study (Lee & Kwon, 2012) revealed two different networks involved with hypothesis-generating and hypothesis-understanding. The same study showed that, rather than the teacher providing hypotheses for testing, the students' ability to explain hypotheses was improved by engaging them in generating the hypotheses themselves, and this was linked to a strengthening (i.e. an increase in connectivity) in the associated brain networks. Taken together, the research suggests that a thoughtful combination of direct instruction and inquiry-based learning is most effective in the STEM classroom.

Mind and body

A recent review of 50 studies concluded that adding physical activity to the school day may enhance, and is unlikely to detract from, academic performance (Rasberry et al., 2011). There are also many studies linking exercise to changes in neural function together with associated cognitive benefit (Erickson et al., 2009; Hillman, Erickson & Kramer, 2008; Neeper et al., 1995; Vaynman, Ying & Gomez-Pinilla, 2004; Winter et al., 2007), including amongst children (Chaddock et al., 2010; Chaddock-Heyman et al., 2013; Chang et al., 2013; Kamijo et al., 2011).

Neuroscience is also providing insight into embodied cognition (Kiefer & Trumpp, 2012; Price, Peterson & Harmon-Jones, 2012), which proposes that the brain processes involved in classroom learning are inseparable from those involved with action. Embodied cognition provides insight into how actions influence our learning. It helps explain the long-established enactment effect, illustrated by students remembering action verbs better when they are performed rather than simply read (Engelkamp, Siefer & Zimmer, 2004), and this effect has been applied successfully in studies of learning a second language (Kelly, McDevitt & Esch, 2009; Macedonia & Knosche, 2011; Tellier, 2008). The close relationship between fingers and mathematics (Gracia-Bafalluy & Noel, 2008; Krinziger et al., 2008) is another example of embodied cognition and this idea has been extended by encouraging children to explore number lines with their whole body using dance mats. In this study, this type of spatial training was demonstrated as more effective than non-spatial training for enhancing children's performance on a number line estimation task (Fischer et al., 2011).

Brain imaging studies have also shown that when we observe others carrying out actions, mirror neurons (which fire when we observe the actions of others, as if we are carrying out the actions ourselves) extend the embodied cognition concept further, helping to explain why teachers' gestures can enhance memory for adults and children (Rizzolatti & Craighero, 2004; So, Chen-Hui & Wei-Shan, 2012). For example, when a teacher imitated their students' behaviour during interactions, students improved achievement in a subsequent quiz. They also reported higher perceptions of rapport, and more confidence and satisfaction about learning outcomes (Zhou, 2012).

Technology

The application of psychology and neuroscience in teaching may prove most fruitful when combined with the new technologies. The adaptive tutoring of students by computers (see "adaptive tutoring" in the STEM and Learning Technologies Literature Review) can provide rapid responses to the student, be less threatening than face-to-face

tuition from the teachers, and can be educationally personalised (Butterworth et al., 2011; Howard-Jones et al., 2011b; Royal Society, 2011). It can also be accessible inside and outside the classroom, which may help overcome some of the mismatch between technology experiences between home and school (as discussed in the STEM and Learning Technologies Literature Review). The potential for a scientific understanding of learning to be incorporated into such systems has been noted and is actively being pursued (Koedinger, Corbett & Perfetti, 2012). Technology can also allow greater interaction between students and teachers, including during whole-class teaching sessions. We already know achievement can be raised when all individuals within a class have the opportunity to respond to the teacher's questions via an audience response system (Anderson et al., 2013) but the research discussed above (such as the testing effect and peer influence on reward response) can help improve the development and use of such technology for learning. Indeed, a freely available app from "zondle" (discussed in the STEM and Learning Technologies Literature Review) allows the teaching of whole classes through a gaming environment involving uncertain reward (see above).

New technologies on the horizon include "tangible interfaces" which offer new types of haptic (i.e. involving touch) learning experience (Yeh et al., 2013). Audiovisual multimedia experiences stimulate an individual's brain activity in regions additional to those activated by auditory and visual stimuli alone, as he/she attempts to relate these two sensory sources (Beauchamp et al., 2004). On the other hand, haptic and visual neural processes converge earlier in the brain. Whether by touch or by vision, object recognition activates similar brain regions (Kim & James, 2010), suggesting hapto-visual experiences may enhance the transmission of a single concept such as a shape. Audio-visual experiences, in contrast, can enhance learning by encouraging meaningful relations between different streams of information (see multiple representations above). Scientific understanding of our response to artificial agents (e.g. robot tutors, robot collaborators and competitors) is another area likely to contribute to learning technology in the future (Krach et al., 2008).

Neurofeedback involves the use of technology by an individual to monitor their own brain activity. Studies have shown such feedback can help individuals influence the ratio of theta to alpha waves associated with attention and relaxation, thereby improving the creative performance of music students (Egner & Gruzelier, 2003) and dancers (Raymond et al., 2005). The technology to provide neurofeedback in school classrooms is becoming cheaper and more portable, but its value to STEM remains unexplored. Neurofeedback might also be shared with the teacher. Although ethical aspects would need careful consideration, the use of wearable brain image technologies in classrooms has been identified as a new challenge for the field of Mind, Brain, and Education (Battro, 2010). In addition to raising learners' awareness of their own cognitive states, wearable devices might also pass information to the teacher regarding individual or whole-class levels of attention in a classroom. A recent study used such a low-cost device to inform a robot about when it was necessary to recapture a student's attention. This significantly improved student memory for the learning content that the robot was presenting (Szafir & Mutlu, 2012).

Discussion, conclusions and recommendations

Cautious optimism

We conclude that, in terms of psychology and neuroscience offering a valuable and practical contribution to STEM teaching and learning, the increasing quantity and quality of relevant research gives cause for optimism. However, gaps exist in our present understanding that temper this optimism with caution. There are many concepts where we are still far from identifying the optimum approach (e.g. remedial training of quantitative ability), concepts which have not been fully trialled in classrooms (e.g. learning games using uncertain reward) or where the scientific underpinnings themselves require further research (e.g. interleaving).

Accessibility of research

On the other hand, many concepts (e.g. spaced learning) are ready to apply and have been ready for many years, even decades. This draws attention to another cause for concern; the longstanding difficulties in ensuring research influences teachers' instruction. A recent survey of teacher attitudes in the USA suggests the major barrier is communication, since the research is chiefly disseminated in scientific journals rather than in the training courses and professional publications accessed by teachers (Laski et al., 2013). There are now many examples of where neuroscientists are working to communicate their findings directly to teachers (Blakemore & Frith, 2005), but more initiatives in this area are needed. *We recommend that a key challenge for education in the UK is to improve the accessibility to teachers of the findings and implications of the research reviewed in this report.*

The challenge of transfer may, however, extend beyond simply providing teachers with information (Newcombe, 2013). Typically, each topic discussed here provides evidence for the educational usefulness of a particular concept. In daily practice, a teacher must apply professional judgement when drawing on a multitude of strategies, skills and routines that require judicious integration in order to support effective teaching and learning in the unique context of his/her classroom (Capel, Leask & Turner, 2013). Rather than a prescription for classroom practice, each insight from psychology and/or neuroscience is just one possible element for a successful STEM lesson. A teacher's judgement about how to integrate each concept into practice would benefit from a full understanding of the principles involved. *We recommend a greater emphasis on psychology and neuroscience in the training and continuing professional development of teachers.*

Greater collaborative engagement of scientists and educators in the production of messages, resources and future research may also improve the accessibility and value of this research, and help improve uptake of findings by teachers. Such collaboration would additionally provide a platform for solving the practical issues encountered when integrating scientific insights into classroom practice, and help find consensus on the novel ethical issues that arise in some areas. *We recommend greater dialogue and collaboration between scientific and educational communities.*

Appendix 1: Classification of topics from initial mapping task

1. We began by identifying key reviews and policy documents that focused on the value of findings of from psychology and neuroscience for education. These included:

   Newcombe, N. S., Ambady, N., Eccles, J., Gomez, L., Klahr, D., Linn, M., et al. (2009). Psychology's role in mathematics and science education. *American Psychologist, 64*(6), 538-550.

   OECD. (2007). *Understanding the Brain: Birth of a New Learning Science*. Paris: OECD.

   Pashler, H., Bain, P., Bottge, B., Graesser, A., Koedinger, K., McDaniel, M., et al. (2007). *Organizing instruction and study to improve student learning: A practice guide (NCER 2007–2004)*. Washington, DC National Center for Education Research, Institute of Education Sciences, U.S. Department of Education.

   Royal Society (2011). *Brain Waves Module 2:Neuroscience:Implications for education and lifelong learning*.

   Shaw, S., & MacLeod, S. (2013). *Improving young people's engagement with science, technology, engineering and mathematics (STEM)*. Slough: National Foundation for Educational Research.

2. We then conducted a search of the last 10 years of literature using all databases on *Web of Science* using the following term (which returned 3259) between 2003 and 2013

   (psychology or cognitive science or neuroscience or brain) and education and learning and teaching

   We were able to validate the efficacy of this search term by ensuring that it returned all topics already encountered in the key reviews and policy documents.

3. We also reviewed the abstracts of all articles in the last 10 years in some specialist journals of particular interest, including *Mind, Brain and Education, Trends in Neuroscience and Education,*

4. Having identified groups of key publications associated with emergent topic areas, we made "forward" searches identifying literature that had cited these publications, in order to identify subsequent reports and the most-to-update understanding of these, and potentially related topics.

5. To ensure the most up to date awareness of emerging research, we studied all abstracts submitted and attended presentations at:

   EARLI SIG on Neuroscience and Education, IoE London May 2012

   Translating Mind, Brain and Education in Quito, Ecuador May 2013

We concluded that the following range of concepts and findings from psychology and neuroscience research had potential value for the STEM teaching and learning, and we classify these in the following way:

	Classification	***Sub-classification***
precursors for achievement	quantitative ability	non-symbolic ability
		symbolic ability
		ability to map non-symbolic & symbolic quantity
	spatial ability	mental rotation
	executive function	effortful control, false belief understanding, inhibitory control, attention-shifting
	attitudes to STEM	gender differences and stereotypes, maths anxiety
	neural and genetic markers	neural markers, genetic markers
teaching strategies	spaced learning & interleaving	spaced learning, interleaving
	Testing	uncertain reward
	Technology	cognitive tutoring, audience response systems, neurofeedback
	multiple representations	tangibles, audio-visual, concrete, abstract, concreteness fading
	alternatives to direct instruction	inquiry, guided exploration, worked-examples
	mind and body	physical exercise, embodied cognition

Appendix 2: Common Neuromyths

Multiple Intelligences (MI) Theory

Gardner's MI theory proposed that, rather than a single all-purpose intelligence, it is more useful to describe an individual as possessing a small number of relatively independent intelligences(Gardner, 1983). Possible candidates for these intelligences include linguistic, musical, logical-mathematical, spatial, bodily-kinaesthetic, intrapersonal sense of self, interpersonal and Gardner has later proposed other possibilities such as naturalistic and existential intelligence(Gardner, 1999). MI theory is in direct opposition to the idea of a unitary general intelligence factor 'g', reflecting overall brain efficiency and the close interconnection of our mental skills. MI theory resonates with many educators, who see it as a robust argument against IQ-based education.

In a critical review of the evidence for MI theory, Waterhouse examined the empirical scientific evidence(Waterhouse, 2006). MI theory claims to be drawn from a wide range of disciplines including neuroscience. Indeed, Gardner has claimed "accumulating neurological evidence is amazingly supportive of the general thrust of MI theory". In terms of an empirical basis, one might point to neuroscientific evidence showing that achievement in different types of task is correlated with activity in different regions of the brain such that the behavioural influence of one region's efficiency may vary according to task, or the inadequacy of a single measure of intelligence to explain individual behavioral differences. Both types of evidence might be used to argue against the likely usefulness of a single IQ measure as a strong general predictor of educational achievement[9]. This is not the same, however, as suggesting that the limits of our mental and/or neural performance arise from a small distinct set of components, and that these limitations, in combination, accounts for the diversity of performance we observe across individuals tackling different tasks.

Gardner suggests that each intelligence operates from a separate area of the brain although, in response to Waterhouse, Gardner rephrased this claim more carefully. In his response, he refers to intelligences as being "composites of fine-grained neurological subprocesses but not those subprocesses themselves"(Gardner and Moran, 2006). Gardner refers to the type of test he believes would invalidate his MI concept, when he argues that if "musical and spatial processing were identically represented" in the cortex, "that fact would suggest the presence of one intelligence, and not two separate intelligences". Yet, many shared and overlapping brain processing pathways have been found between, for example, language and music skills(Koelsch et al., 2004), music perception and nonverbal reasoning(Norton et al., 2005) and distributed networks for emotion that are shared with reasoning, memory and action(Adolphs, et al.,

---

[9] However, general intelligence might also be distributed throughout the brain in terms of overall brain efficiency and, contrary to Gardner, some scientists point to the positive correlation between a measure of general intelligence 'g' , brain sizeMcDaniel, M.A., 2005. Big-brained people are smarter: A meta-analysis of the relationship between in vivo brain volume and intelligence. Intelligence 33, 337-346, Toga, A.W., Thompson, P.M., 2005. Genetics of brain structure and intelligence. Annual Review of Neuroscience 28, 1-23. and the level of brain activityGeake, J.G., Hansen, P.C., 2005. Neural correlates of intelligence as revealed by fMRI of fluid analogies. Neuroimage 26, 555-564. to suggest that 'g' may be an important concept in understanding individual performance.

2003;Morgane, et al., 2005;Phelps, 2006). Neither do two tasks recruiting the same shared region provide strong evidence for a single intelligence. The idea here is that if a single area is linked with two different activities, then performance in these two tasks might be effected only by the processing efficiency in this single brain region and that this could contribute to the notion that these two tasks require a single type of intelligence. Functional isolation in the brain would be very unusual, with processes employing different pathways between the same areas and to different regions. In short, the general processing complexity of the brain, makes it unlikely that a theory resembling MI theory will ever emerge from it. Cognitive neuroscience is exploring the brain in terms of processes (vision, hearing, smell, etc) but not in terms of *seeing intelligence*, *auditory intelligence* or *smelling intelligence.* In the realm of neuroscience, it neither appears accurate or useful to reduce the vast range of complex individual differences at neural and cognitive levels to any limited number of capabilities.

In Gardner's response to Waterhouse, provocatively titled "the science of multiple intelligences theory", he summarises two ways in which MI theory may come to be assessed in the future. The first is by intelligence testing, using systems of assessment he describes as "intelligence fair". Such tests may indeed raise awareness of how diverse our individual profiles of cognitive ability are, and provide evidence against the idea of a unitary measure of that ability. Less certain, is the possibility that they will also indicate a limited set of clearly defined and relatively independent intelligences.

Although Gardner is waiting chiefly for such behavioural evidence, and despite the absence of MI theory in the neuroscience literature, teachers often associate MI theory with neuroscience (Pickering and Howard-Jones, 2007).

Thus, in educational terms, MI theory appears like a liberator – providing teachers with the 'scientific' license to celebrate diversity. In terms of the science, however, it seems an unhelpful simplification as no clearly defined set of capabilities arises from either the biological or psychological research.

MI theory is very popular with educators and promotes the worth of children's individual and diverse talents rather than how generally "bright" they are. At the same time, MI theory may also be an example of an idea that has been inappropriately imbued with a sense of neuroscientific authority although, in fairness to Gardner, this is not wholly due to arguments put forward by its author.

Learning Styles

An individual's learning style can be considered as a set of learner characteristics that influences their reponse to different teaching approaches. A survey in 2004 identified 71 different models of learning styles and our own survey showed almost a third of UK teachers had heard of learning styles, with most of those who used this approach reporting it as effective(Pickering and Howard-Jones, 2007). As with MI theory, which is also often interpreted by educators as a means to identify preferred modes of learning, the promotion of learning styles has benefited from a strong association with neuroscience. Many learning style models have a distinctly biological justification, with one of their major proponents, Rita Dunn, commenting that "at least three fifths of style is biologically imposed".

Perhaps the best known inventory of learning styles within education is the one categorising individuals in terms of their preferred sense modality for receiving, processing and communicating information: visual, auditory or kinaesthetic (VAK). However, the educational enthusiasm for learning styles does not stop at identifying a preferred sense modality. Instead, it commonly goes one step further in assuming that there is some educational value in tailoring educational experience to suit the learning style reported by each individual. Perhaps the assumption that learning can be improved in this way is not wholly unreasonable. If a learner expresses a preference during the learning process, then a learner-centred response seems logical. However, if this 'preference' is via a very limited and closed questionnaire consisting of essentially 3 options, based wholly upon sensory modalities, the extent to which VAK can meaningfully personalise learning seems very questionable.

Very many educational projects have pursued improvement through tailoring programmes to meet individual learning styles but, as yet, there is no convincing evidence that any benefit arises. A review of such studies, concluded that matching instruction to meet an individual's sensory strengths appears no more effective than designing content-appropriate forms of education and instruction (Coffield et al., 2004). Furthermore, in a laboratory study of memory performance, participants' own self assessment of their learning style (as is commonly used) was shown to be out of line with more objective measures, and memory scores in different modalities appeared unrelated to any measure of dominant learning style(Kratzig and Arbuthnott, 2006). There was, instead, evidence that participants' self-rating as kinaesthetic learners was related to visual performance, that they were self-rating their learning styles in ways possibly promoted by the inventory itself, and objective evidence from memory testing that suggested visual and kinaesthetic/tactile tasks were tapping the same underlying memory process. The authors concluded that educators' attempts to focus on learning styles were "wasted effort".

The implicit assumption appears to be that, since different modalities are processed independently in different parts of the brain, differences in the efficiency of these parts results in a clear modality-based method of classifying how learners are able to process information most efficiently. However, as pointed out by Geake and already discussed in terms of MI theory, this flies in the face of what we know about interconnectivity of the brain(Geake, 2008). Geake refers to a recent piece of experimental research that succinct demonstration of the ineffectiveness of the VAK approach. In this piece of research, 5 year olds showed themselves able to distinguish between groups of dots even when the numbers were too large for counting(Gilmore et al., 2007). They were then asked to repeat the task in auditory mode by counting clicks, and reproduced almost identical levels of accuracy. Geake suggests this is because input modalities in the brain are very interlinked. As yet, no evidence arising from neuroscience, or any other science, supports the categorisation of learners in terms of their sensory modality or any other type of learning style. In the meantime, educators continue to be drawn to VAK as means to implement a new type of differentiation.

Another popular way of categorising learning style is in terms of "left-brain right-brain" theory (Springer and Deutsch, 1989). According to this theory, learners' dispositions arise from the extent to which they are left or right brain dominant.). It is true that some tasks

can be associated with extra activity that is predominantly in one hemisphere or the other. For example, language is considered to be left lateralised. However, no part of the brain is ever normally inactive in the sense that no blood flow is occurring. Furthermore, performance in most everyday tasks, including learning tasks, require both hemispheres to work together in a sophisticated parallel fashion. The division of people into left-brained and right-brained takes the misunderstanding one stage further. There is no reliable evidence that such categorisation is helpful for teaching and learning.

Educational Kinesiology (Brain Gym)

Educational kinesiology (or Edu-K, also often sold under the brand name of Brain Gym) was developed by Paul and Gail Dennison as a means to 'balance' the hemispheres of the brain so they work in an integrated fashion and thus improve learning (Dennison, 1981). This theoretical basis has been roundly criticised by established scientists and there is a lack of published research in high quality journals to make claims about programmes such as Brain Gym raising achievement. Of the studies published elsewhere, the lack of information about the exercises undertaken and/or the insufficient or inappropriate analysis of the results undermine their credibility (Hyatt, 2007). However, it may also be that programmes such as Brain Gym are contributing to learning, but for entirely different reasons than those used to promote them. There is an emerging body of multidisciplinary research supporting the beneficial effect of aerobic exercise on selective aspects of brain function that happen to be particularly important for education(Hillman et al., 2008). However, these advantages appear linked to the aerobic nature of the exercise, which is likely to be low in Brain Gym.

REFERENCES

Alfieri, L., Brooks, P. J. et al. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology,* 103(1), 1-18.

Anderson, L. S., Healy, A. F. et al. (2013). The clicker technique: Cultivating efficient teaching and successful learning. *Applied Cognitive Psychology,* 27(2), 222-234.

Andersson, U., & Östergren, R. (2012). Number magnitude processing and basic cognitive functions in children with mathematical learning disabilities. *Learning and Individual Differences,* 22(6), 701-714.

Ashcraft, M. H., Krause, J. A., & Hopko, D. R. (2007). Is math anxiety a mathematics learning disability? In Berch, D. B. and Mazocco, M. M. (*Eds.), Why is math so hard for some children? The nature and origins of mathematical difficulties and disabilities, pp.329-348.* Baltimore: Paul H. Brookes Publishing.

Atkinson, R. K., Derry, S. J. et al. (2000). Learning from examples: Instructional principles from the worked examples research. *Review of Educational Research,* 70(2), 181-214.

Azevedo, C. V. M. *et al.* (2008). Teaching chronobiology and sleep habits in school and university. *Mind, Brain, and Education* 2, 34-47.

Baker, D. (2002). Good intentions: An experiment in middle school single-sex science and mathematics classrooms with high minority enrolment. *Journal of Women and Minorities in Science and Engineering,* 8, 1–23.

Battro, A. M. (2010). The Teaching Brain. *Mind, Brain, and Education,* 4, 28-33.

Bakotic, M., Radosevic-Vidacek, B. & Koscec, A. (2009). Educating adolescents about healthy sleep: Experimental study of effectiveness of educational leaflet. *Croatian Medical Journal* 50, 174-181.

Beauchamp, M. S., Lee, K. E. et al. (2004). Integration of auditory and visual information about objects in superior temporal sulcus. *Neuron,* 41(5), 809-823.

Beilock, S. L., Gunderson, E. A., Ramirez, G., & Levine, S. C. (2010). Female teachers' math anxiety affects girls' math achievement. *Proceedings of the National Academy of Sciences*, 107(5), 1860–1863.

Birnbaum, M. S., Kornell, N. et al. (2013). Why interleaving enhances inductive learning: The roles of discrimination and retrieval. *Memory & Cognition*, 41(3), 392-402.

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child*

Development, 78(2), 647–663.

Blakemore, S. J. & Frith, U. (2005). *The Learning Brain*. London: Blackwell.

Blunden, S. L., Chapman, J. & Rigney, G. A. (2012). Are sleep education programs successful? The case for improved and consistent research efforts. *Sleep Medicine Reviews* 16, 355-370.

de Bock, D., Deprez, J., Van Dooren, W., Roelens, M. & Verschaffel, L. (2011). Abstract or concrete examples in learning mathematics? A replication and elaboration of Kaminski, Sloutsky, and Heckler's Study. *J. Res. Math. Educ.* 42, 109-126.

Bottcher, F., & Meisert, A. (2013). Effects of direct and indirect instruction on fostering decision-making competence in socioscientific issues. *Research in Science Education,* 43(2), 479-506.

Brown, F. C., Buboltz, W. C. & Soper, B. (2006). Development and evaluation of the sleep treatment and education program for students (STEPS). *J. Am. Coll. Health* 54, 231-237.

Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory, and executive functioning in preschoolers: Longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, 33(3), 205–228.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, 19(3), 273–293.

Butler, A. C. (2010). Repeated testing produces superior transfer of learning relative to repeated studying. *Journal of Experimental Psychology-Learning Memory and Cognition,* 36(5), 1118-1133.

Butterworth, B., Varma, S. et al. (2011). Dyscalculia: From brain to education. *Science,* 332(6033), 1049-1053.

Cain, N., Gradisar, M. & Moseley, L. (2011). A motivational school-based intervention for adolescent sleep problems. *Sleep Med.* 12, 246-251.

Callan, D. E., & Schweighofer, N. (2010). Neural correlates of the spacing effect in explicit verbal semantic encoding support the deficient-processing theory. *Human Brain Mapping*, 31(4), 645-659.

Campbell, J., & Mayer, R. E. (2009). Questioning as an instructional method: Does it affect learning from lectures? *Applied Cognitive Psychology,* 23(6), 747-759.

Capel, S., Leask, M. & Turner, T. (2013). *Readings for Learning to Teach in the*

Secondary School: A Companion to M Level Study. Oxon, UK: Routledge Falmer.

Carpenter, S. K., Cepeda, N. J., Rohrer, D., Kang., S. H., & Pashler, H. (2012). Using spacing to enhance diverse forms of learning: Review of recent research and implications for instruction. *Educational Psychology Review,* 24(3), 369-378.

Carpenter, S. K., Pashler, H., & Cepeda, N. J. (2009). Using Tests to Enhance 8th Grade Students' Retention of US History Facts. *Applied Cognitive Psychology,* 23(6), 760-771.

Casey, M. B., Nuttall, R. L., & Pezaris, E. (1997). Mediators of gender differences in mathematics college entrance test scores: a comparison of spatial skills with internalized beliefs and anxieties. *Developmental Psychology*, 33(4), 669.

Casey, M. B., Pezaris, E., & Nuttall, R. L. (1992). Spatial ability as a predictor of math achievement: The importance of sex and handedness patterns. *Neuropsychologia*, 30(1), 35–45.

Cepeda, N. J., Coburn, N. et al. (2009). Optimizing Distributed Practice Theoretical Analysis and Practical Implications. *Experimental Psychology,* 56(4), 236-246.

Cepeda, N. J., Pashler, H., Vul, E., Wixted, J., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin,* 132(3), 354-380.

Cepeda, N. J., Vul, E. et al. (2008). Spacing Effects in Learning: A Temporal Ridgeline of Optimal Retention. *Psychological Science*, 19(11), 1095-1102.

Chaddock, L., et al. (2010). Basal ganglia volume is associated with aerobic fitness in preadolescent children. *Developmental Neuroscience,* 32(3), 249-256.

Chaddock-Heyman, L. *et al.* (2013). The effects of physical activity on functional MRI activation associated with cognitive control in children: a randomized controlled intervention. *Front. Hum. Neurosci.* 7.

Challis, B. H. (1993). Spacing effects on cued-memory tests depend on level of processing. *Journal of Experimental Psychology-Learning Memory and Cognition,* 19(2), 389-396.

Chan, J. C. (2010). Long-term effects of testing on the recall of nontested materials. *Memory,* 18(1), 49-57.

Chan, J. C., McDermott, K. B. et al. (2006). Retrieval-induced facilitation: Initially nontested material can benefit from prior testing of related material. *Journal of Experimental Psychology-General,* 135(4), 553-571.

Chang, Y. K., Tsai, Y. J., Chen, T. T., & Hung, T. M. (2013). The impacts of coordinative exercise on executive function in kindergarten children: an ERP study. *Exp. Brain Res.* 225, 187-196.

Chein, J., Albert, D. et al. (2011). Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. *Developmental Science,* 14(2), F1-F10.

Clark, R. C. & Mayer, R. E. (2003). *e-Learning and the science of instruction: Proven guidelines for consumers and designers of multimedia learning*. Jossey-Bass.

Clark, C. A., Pritchard, V. E., & Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Developmental Psychology*, 46(5), 1176–1191.

Coffield, F., Moseley, D., Hall, E., Ecclestone, K. (2004). *Learning styles and pedagogy in post-16 learning: A systematic and critical review (Report no. 041543)*. London: Learning and Skills Research Centre.

Cortesi, F., Giannotti, F., Sebastiani, T., Bruni, O. & Ottaviano, S. (2004). Knowledge of sleep in Italian high school students: Pilot-test of a school-based sleep educational program. *Journal of Adolescent Health* 34, 344-351.

Daly, P. (1995). Science course participation and science achievement in single sex and co-educational schools. *Evaluation & Research in Education,* 9(2), 91-98.

Davis, C. L., Tomporowski, P. D., McDowell, J. E., Austin, B. P., Miller, P. H., Yanasak, N. E., Allison, J. D., & Naglieri, J. A. (2011). Exercise improves executive function and achievement and alters brain activation in overweight children: a randomized controlled trial. *Health Psychology*, 30(1), 91.

Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. Oxford, UK: Oxford University Press.

Dempster, F. N. (1988). The Spacing effect - a case-study in the failure to apply the results of psychological research. *American Psychologist*, 43(8), 627-634.

Dennison, P. E. (1981). *Switching on: A guide to Edu-Kinesthetics*. Ventura, California: Edu-Kinesthetics.

Egner, T. & Gruzelier, J. H. (2003). Ecological validity of neurofeedback: modulation of slow wave EEG enhances musical performance. *Neuroreport,* 14, 1221-1224.

Else-Quest, N. M., Hyde, J. S., & Linn, M. C. (2010). Cross-national patterns of gender differences in mathematics: A meta-analysis. *Psychological Bulletin*, 136(1), 103.

Engelkamp, J., Seiler, K., & Zimmer, H. (2004). Memory for actions: Item and relational

information in categorized lists. *Psychological Research,* 69, 1-10.

Erbas, A. K., & Yenmez, A. A. (2011). The effect of inquiry-based explorations in a dynamic geometry environment on sixth grade students' achievements in polygons. *Computers & Education,* 57(4), 2462-2475.

Erickson, K., et al. (2009). Aerobic fitness is associated with hippocampal volume in elderly humans. *Hippocampus,* 19(10), 1030-1039.

Forgasz, H., & Leder, G. (1996). Mathematics classrooms, gender and affect. *Mathematics Education Research Journal,* 8, 153–173.

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H. C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychon. Bull. Rev.* 18, 177-183.

Gallistel, C.R., & Gelman, R. (1992). Preverbal and verbal counting and computation. *Numerical Cognition.* 44(1-2), 43-74.

Gardner, H. (1983). *Frames of the mind: The theory of multiple intelligences*. New York: Basic Books.

Gardner, H. (1999). *Intelligence reframed*. New York: Basic Books.

Gardner, H., & Moran, S. (2006). The science of multiple intelligences theory: A response to Lynn Waterhouse. *Educational Psychologist,* 41, 227-232.

Geake, J. G. (2008). Neuromythologies in education. *Educational Research,* 50(2), 123-133.

Geake, J. G., & Hansen, P. C. (2005). Neural correlates of intelligence as revealed by fMRI of fluid analogies. *Neuroimage,* 26, 555-564.

Geary, D. C., Saults, S. J., Liu, F., & Hoard, M. K. (2000). Sex differences in spatial cognition, computational fluency, and arithmetical reasoning. *Journal of Experimental Child Psychology,* 77(4), 337–353.

Gerson, H. B., Sorby, S. A., Wysocki, A., & Baartmans, B. J. (2001). The development and assessment of multimedia software for improving 3-D spatial visualization skills. *Computer Applications in Engineering Education*, 9(2), 105–113.

Gillibrand, E., Robinson, P., Brawn, R., & Osborn, A. (1999). Girls' participation in physics in single sex classes in mixed schools in relation to confidence and achievement. *International Journal of Science Education*, 21(4), 349-362.

Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., Simms, V. &

Inglis, M. (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlated with maths achievement. *PLoS ONE* 8(6), e67374.

Gilmore, C., McCarthy, S., & Spelke, E. (2007). Symbolic arithmetic without instruction. *Nature,* 447, 589-591.

van Gog, T., & Kester, L. (2012). A test of the testing effect: Acquiring problem-solving skills from worked examples. *Cognitive Science,* 36(8), 1532-1541.

Goldstein, D., Haldane, D., & Mitchell, C. (1990). Sex differences in visual-spatial ability: The role of performance factors. *Memory & Cognition,* 18(5), 546–550.

Goldstone, R. L., & Son, J. Y. (2005). The transfer of scientific principles using concrete and idealized simulations. *Journal of the Learning Sciences,* 14(1), 69-110.

Gracia-Bafalluy, M. and Noël, M.P. (2008). Does finger training increase young children's numerical performance? *Cortex,* 44, 368-375.

Gropen, J., Clark-Chiarelli, N., Hoisington, C., & Ehrlich, S. B. (2011). The importance of executive function in early science education. *Child Development Perspectives*, 5(4), 298–304.

Hackman, D. A. & Farah, M. J. (2009). Socioeconomic status and the developing brain. *Trends in Cognitive Sciences,* 13, 65-73.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the‘ number sense’: The approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental Psychology*, 44(5), 1457.

Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature*, 455(7213), 665–668.

Hembree, R. (1990). The nature, effects, and relief of mathematics anxiety. *Journal for Research in Mathematics Education,* 21(1), 33-46.

Hillman, C., Erickson, K., & Kramer, A. (2008). Be smart, exercise your heart: Exercise effects on brain and cognition. *Nature Reviews Neuroscience,* 9, 58-65.

Hillman, C. H., Pontifex, M. B., Raine, L. B., Castelli, D. M., Hall, E. E., & Kramer, A. F. (2009). The effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. *Neuroscience*, 159(3), 1044.

Howard-Jones, P. A., Bogacz, R. et al. (2010). The neural mechanisms of learning from competitors. *Neuroimage,* 53(2), 790-799.

Howard-Jones, P. A., & Demetriou, S. (2009). Uncertainty and engagement with learning games. *Instructional Science,* 37(6), 519-536.

Howard-Jones, P. A., Demetriou, S. et al. (2011a). Toward a science of learning games. *Mind Brain and Education,* 5(1), 33-41.

Howard-Jones, P., Ott, M. et al. (2011b). *Neuroscience and technology enhanced learning*. London: Futurelab.

Hoyland, A., Dye, L. & Lawton, C. L. (2009). A systematic review of the effect of breakfast on the cognitive performance of children and adolescents. *Nutr. Res. Rev.* 22, 220-243.

Hyatt, K. J. (2007). Brain Gym: Building stronger brains or wishful thinking? *Remedial and Special Education,* 28, 117-124.

Jirout, J., & Klahr, D. (2012). Children's scientific curiosity: In search of an operational definition of an elusive concept. *Developmental Review,* 32(2), 125-160.

Joels, M., Pu, Z. W., Wiegert, O., Oitzl, M. S. & Krugers, H. J. (2006). Learning under stress: How does it work? *Trends in Cognitive Sciences* 10, 152-158.

Johnson, C. I., & Mayer, R. E. (2009). A testing effect with multimedia learning. *Journal of Educational Psychology,* 101(3), 621-629.

Kamijo, K. *et al.* (2011). The effects of an afterschool physical activity program on working memory in preadolescent children. *Dev. Sci.* 14, 1046-1058.

Kaminski, J. A., Sloutsky, V. M. et al. (2013). The cost of concreteness: The effect of nonessential information on analogical transfer. *Journal of Experimental Psychology-Applied,* 19(1), 14-29.

Kang, S. H., McDermott, K. B. et al. (2007). Test format and corrective feedback modify the effect of testing on long-term retention. *European Journal of Cognitive Psychology,* 19(4-5), 528-558.

Kang, S. H., & Pashler, H. (2012). Learning painting styles: Spacing is advantageous when it promotes discriminative contrast. *Applied Cognitive Psychology,* 26(1), 97-103.

Karpicke, J. D. (2012). Retrieval-based learning: Active retrieval promotes meaningful learning. *Current Directions in Psychological Science,* 21(3), 157-163.

Karpicke, J. D., & Blunt, J. R. (2011). Retrieval practice produces more learning than elaborative studying with concept mapping. *Science,* 331(6018), 772-775.

Kaufmann, L. (2008). Dyscalculia: Neuroscience and education. *Educational Research,* 50(2), 163-175.

Kaufmann, L., S. E. Vogel, et al. (2008). A developmental fMRI study of nonsymbolic numerical and spatial processing. *Cortex,* 44, 376-385.

Kelly, S. D., McDevitt, T., & Esch, M. (2009). Brief training with co-speech gesture lends a hand to word learning in a foreign language. *Language and Cognitive Processes,* 24, 313-334.

Kiefer, M., & Trumpp, N. M. (2012). Embodiment theory and education: The foundations of cognition in perception and action. *Trends in Neuroscience and Education,* 1, 15-20.

Kim, S., & James, T. W. (2010). Enhanced effectiveness in visuo-haptic object-selective brain regions with increasing stimulus salience. *Human Brain Mapping,* 31(5), 678-693.

Kirschner, P. A., Sweller, J. et al. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist,* 41(2), 75-86.

Klahr, D., & Chen, Z. (2003). Overcoming the positive-capture strategy in young children: Learning about indeterminacy. *Child Development,* 74(5), 1275-1296.

Klahr, D., Zimmerman, C. et al. (2011). Educational interventions to advance children's scientific thinking. *Science,* 333(6045), 971-975.

Klein, A., Starkey, P., & Ramírez, A. (2003). Pre-k Mathematics Curriculum: Early Childhood. Scott Foresman.

Knippels, M., Waarlo, A. J. et al. (2005). Design criteria for learning and teaching genetics. *Journal of Biological Education*, 39(3), 108-112.

Koedinger, K. R., Corbett, A. T. & Perfetti, C. (2012). The knowledge-learning-instruction framework: Bridging the science-practice chasm to enhance robust student learning. *Cognitive Science* 36, 757-798.

Koelsch, S., Kasper, E., Sammler, D., Schulze, K., Gunter, T., & Friederici, A.T. (2004). Music, language and meaning: Brain signatures of semantic processing. *Nature Neuroscience,* 7, 302-307.

Kornell, N., & Bjork, R. A. (2008). Learning concepts and categories: Is spacing the "Enemy of Induction"? *Psychological Science,* 19(6), 585-592.

Krach, S., Hegel, F. et al. (2008). Can machines think? Interaction and perspective taking

with robots investigated via fMRI. *PLoS ONE,* 3(7), e2597.

Kratzig, G. P., & Arbuthnott, K. D. (2006). Perceptual learning style and learning proficiency: A test of the hypothesis. *Journal of Educational Psychology,* 98, 238-246.

Krinzinger, H. *et al.* (2008) The role of finger representations and saccades for number processing: an fMRI study in children. *Frontiers in Psychology,* 2**.**

Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schönmann, C., Plangger, F., Gälli, M., Martin, E. von Aster, M.(2011). Mental number line training in children with developmental dyscalculia. *Neuroimage,* 57(3), 782-795.

Kuhn, D. (2007). Is direct instruction an answer to the right question? *Educational Psychologist,* 42(2), 109-113.

Kuhn, D., & Dean, D. (2005). Is developing scientific thinking all about learning to control variables? *Psychological Science,* 16(11), 866-870.

Laski, E. V., Reeves, T. D., Ganley, C. M. & Mitchell, R. (2013). Mathematics teacher educators' perceptions and use of cognitive research. *Mind Brain and Education* **7**, 63-74.

Lee, J. K., & Kwon, Y. (2012). Learning-related changes in adolescents' neural networks during hypothesis-generating and hypothesis-understanding training. *Science & Education*, 21(1), 1-31.

LeFevre, J.-A., Fast, L., Skwarchuk, S.-L., Smith-Chant, B. L., Bisanz, J., Kamawar, D., & Penner-Wilger, M. (2010). Pathways to mathematics: Longitudinal predictors of performance. *Child Development*, 81(6), 1753–1767.

Linn, M. C., & Petersen, A. C. (1986). A meta-analysis of gender differences in spatial ability: Implications for mathematics and science achievement. In J. S. Hyde & M. C. Linn (Eds.), *The Psychology of Gender,* (pp. 67-101). Baltimore, MD: Johns Hopkins University Press.

van Loon-Hillen, N., van Gog, T. et al. (2012). Effects of worked examples in a primary school mathematics curriculum. *Interactive Learning Environments,* 20(1), 89-99.

Lyons, I. M., & Beilock, S. L. (2012). Mathematics anxiety: Separating the math from the anxiety. *Cerebral Cortex,* 22(9), 2102-2110.

Macedonia, M., & Knösche, T. R. (2011). Body in Mind: How Gestures Empower Foreign Language Learning. *Mind, Brain, and Education,* 5, 196-211.

Mazzocco, M. M., Feigenson, L., & Halberda, J. (2011). Impaired acuity of the

approximate number system underlies mathematical learning disability (dyscalculia). *Child Development*, 82(4), 1224–1237.

Mazzocco, M. M., & Kover, S. T. (2007). A longitudinal assessment of executive function skills and their association with math performance. *Child Neuropsychology*, 13(1), 18–45.

McDaniel, M. A. (2005). Big-brained people are smarter: A meta-analysis of the relationship between in vivo brain volume and intelligence. *Intelligence,* 33, 337-346.

McDaniel, M. A., Agarwal, P. K. et al. (2011). Test-enhanced learning in a middle school science classroom: The effects of quiz frequency and placement. *Journal of Educational Psychology,* 103(2), 399-414.

McDaniel, M. A., Roediger, H. L. et al. (2007). Generalizing test-enhanced learning from the laboratory to the classroom. *Psychonomic Bulletin & Review,* 14(2), 200-206.

McNeil, N. M., & Fyfe, E. R. (2012). "Concreteness fading" promotes transfer of mathematical knowledge. *Learning and Instruction,* 22(6), 440-448.

Miller, D. I., & Halpern, D. F. (2013). Can spatial training improve long-term outcomes for gifted STEM undergraduates? *Learning and Individual Differences*, 26, 141-152.

Moreno, R., Ozogul, G. et al. (2011). Teaching with concrete and abstract visual representations: Effects on students' problem solving, problem representations, and learning perceptions. *Journal of Educational Psychology,* 103(1), 32-47.

Mundy, E., & Gilmore, C. K. (2009). Children's mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology,* 103(4), 490–502.

Neeper, S. A., Gomezpinilla, F., Choi, J., & Cotman, C. (1995). Exercise and brain neurotrophins. *Nature,* 373, 109-109.

Newcombe, N. S. (2013). Educating to use evidence in thinking about education. *Mind, Brain, and Education* 7, 147-150.

Nieuwenhuis, S., Heslenfeld, D. J. et al. (2005). Activity in human reward-sensitive brain areas is strongly context dependent. *Neuroimage,* 25(4), 1302-1309.

Norton, A., Winner, E., Cronin, K., Overy, L., Lee, D. J., & Schlaug, G. (2005). Are there pre-existing neural, cognitive, or motoric markers for musical ability? *Brain and Cognition,* 59, 124-134.

Nosek, B. A., et al. (2009). National differences in gender–science stereotypes predict national sex differences in science and math achievement. *Proceedings of the National Academy of Sciences*, 106(26), 10593–10597.

Nosek, B. A., Banaji, M. R., & Greenwald, A. G. (2002). Math = male, me = female, therefore math ≠ me. *Journal of Personality and Social Psychology*, 83(1), 44–59.

Olsen, R., Moses, S., Riggs, L., & Ryan, J. (2012). The hippocampus supports multiple cognitive processes through relational binding and comparison. *Frontiers in Human Neuroscience,* 6, 146.

Owens, J. A., Belon, K. & Moss, P. (2010). Impact of delaying school start time on adolescent sleep, mood, and behavior. *Arch. Pediatr. Adolesc. Med.* 164, 608-614.

Ozcelik, E., Cagiltay, N. E. et al. (2013). The effect of uncertainty on learning in game-like environments. *Computers & Education,* 67(0), 12-20.

Piazza, M., Facoetti, A., Trussardi, A. N., Berteletti, I., Conte, S., Lucangeli, D., Dehaene, S., & Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition*, 116(1), 33–41.

Pickering, S. J., Howard-Jones, P. A. (2007). Educators' views on the role of neuroscience in education: Findings from a study of UK and international perspectives. *Mind, Brain and Education,* 1, 109-113.

Plomin, R. (2008). *Genetics and the Future Diagnosis of Learning Disabilities*. Government Office for Science, London.

Price, T. F., Peterson, C. K., & Harmon-Jones, E. (2012). The emotive neuroscience of embodiment. *Motiv. Emot.,* 36, 27-37.

Raizada, R. D. S. & Kishiyama, M. M. Effects of socioeconomic status on brain development, and how cognitive neuroscience may contribute to levelling the playing field. *Front. Hum. Neurosci.* 4.

Ramirez, G., & Beilock, S. L. (2011). Writing about testing worries boosts exam performance in the classroom. *Science,* 331(6014), 211-213.

Rasberry, C. N. et al. (2011) The association between school-based physical activity, including physical education, and academic performance: A systematic review of the literature. *Prev. Med.* 52, S10-S20.

Rau, M. A., Aleven, V. et al. (2013). Interleaved practice in multi-dimensional learning tasks: Which dimension should we interleave? *Learning and Instruction,* 23, 98-114.

Raymond, J., Sajid, I., Parkinson, L., & Gruzelier, J. H. (2005). The beneficial effects of alpha/theta and heart rate variability training on dance performance. *Applied Psychophysiology and Biofeedback,* 30, 65-73.

Rea, C. P. & Modigliani, V. (1987). The spacing effect in 4-year-old to 9-year-old children. *Memory & Cognition,* 15(5), 436-443.

Retnowati, E., Ayres, P. et al. (2010). Worked example effects in individual and group work settings. *Educational Psychology,* 30(3), 349-367.

Reynolds, J. H., & Glaser, R. (1964). Effects of repetition and spaced review upon retention of a complex learning-task. *Journal of Educational Psychology*, 55(5), 297-308.

Richland, L. E., Zur, O. et al. (2007). Cognitive supports for analogies in the mathematics classroom. *Science,* 316(5828), 1128-1129.

Rizzolatti, G., & Craighero, L. (2004). The mirror neuron system. *Annual Review of Neuroscience,* 27, 169-192.

Roediger, H. L., & Karpicke, J. D. (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science,* 17(3), 249-255.

Rohrer, D., & Taylor, K. (2006). The effects of overlearning and distributed practise on the retention of mathematics knowledge. *Applied Cognitive Psychology,* 20(9), 1209-1224.

Rohrer, D., & Taylor, K. (2007). The shuffling of mathematics problems improves learning. *Instructional Science* 35(6), 481-498.

Rousselle, L., & Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition*, 102(3), 361–395.

Royal Society (2011). *Brain Waves Module 2:Neuroscience:implications for education and lifelong learning.* London: Royal Society.

Sasanguie, D., Defever, E., Maertens, B., & Reynvoet, B. (2013). The approximate number system is not predictive for symbolic number processing in kindergartners. *The Quarterly Journal of Experimental Psychology*, DOI:10.1080/17470218.2013.803581.

Seabrook, R., Brown, G.D., & Solity, J. E. (2005). Distributed and massed practice: From laboratory to classroom. *Applied Cognitive Psychology,* 19(1), 107-122.

Shohamy, D., & Adcock, R. A. (2010). Dopamine and adaptive memory. *Trends in*

Cognitive Sciences, 14(10), 464-472.

So, W. C., Chen-Hui, C. S., & Wei-Shan, J. L. (2012). Mnemonic effect of iconic gesture and beat gesture in adults and children: Is meaning in gesture important for memory recall? *Language and Cognitive Processes,* 27, 665-681.

Sobel, H. S., Cepeda, N. J., & Kapler, I. V. (2011). Spacing effects in real-world classroom vocabulary learning. *Applied Cognitive Psychology,* 25(5), 763-767.

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, 31(3), 459–480.

de Sousa, I. C., Araujo, J. F. & Macedo de Azevedo, C. V. (2007). The effect of a sleep hygiene education program on the sleep-wake cycle of Brazilian adolescent students. *Sleep Biol. Rhythms* 5, 251-258.

Springer, S. P., & Deutsch, G. (1989). *Left brain, right brain*. New York: Freeman.

Starkey, P., & Cooper, R. G. (1980). Perception of numbers by human infants. *Science,* 210(4473), 1033-1035.

Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly*, 19(1), 99–120.

Stoet, G., & Geary, D. C. (2012). Can stereotype threat explain the gender gap in mathematics performance and achievement? *Review of General Psychology*, 16(1), 93.

Szafir, D., & Mutlu, B. (2012). Pay attention! Designing adaptive agents that monitor and improve user engagement. In *Proceedings of the 31st ACM/SigCHI Conference on Human Factors in Computing* (pp. 11–20).

Szucs, D. & Goswami, U. (2007) Educational neuroscience: defining a new discipline for the study of mental representations. *Mind, Brain and Education* 1, 114-127.

Tan, E., Healey, D., Gray, A. R. & Galland, B. C. (2012). Sleep hygiene intervention for youth aged 10 to 18 years with problematic sleep: a before-after pilot study. *BMC Pediatr.* 12.

Taylor, K., & Rohrer, D. (2010). The effects of interleaved practice. *Applied Cognitive Psychology,* 24(6), 837-848.

Tellier, M. (2008). The effect of gestures on second language memorisation by young children. *Gesture* 8, 219-235.

Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science*, 12(1), 106–113.

Tiedemann, J. (2000). Parents' gender stereotypes and teachers' beliefs as predictors of children's concept of their mathematical ability in elementary school. *Journal of Educational Psychology*, 92(1), 144.

Toga, A. W., Thompson, P. M. (2005). Genetics of brain structure and intelligence. *Annual Review of Neuroscience,* 28, 1-23.

Tomporowski, P. D., Davis, C. L., Miller, P. H., & Naglieri, J. A. (2008). Exercise and children's intelligence, cognition, and academic achievement. *Educational Psychology Review*, 20(2), 111–131.

Toppino, T. C. (1991). The spacing effect in young children's free-recall - support for automatic-process explanations. *Memory & Cognition,* 19(2), 159-167.

Toppino, T. C., & Digeorge, W. (1984). The spacing effect in free-recall emerges with development. *Memory & Cognition,* 12(2), 118-122.

Tracy, D. M. (1987). Toys, spatial ability, and science and mathematics achievement: Are they related? *Sex Roles*, 17(3-4), 115–138.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2012). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin,* 139(2), 352-402.

Uttal, D. H., O'Doherty, K. et al. (2009). Dual representation and the linking of concrete and symbolic representations. *Child Development Perspectives,* 3(3), 156-159.

Vaynman, S., Ying, Z., & Gomez-Pinilla, F. (2004). Hippocampal BDNF mediates the efficacy of exercise on synaptic plasticity and cognition. *European Journal of Neuroscience,* 20, 2580-2590.

Vlach, H. A. & Sandhofer, C. M. (2012). Distributing learning over time: The spacing effect in children's acquisition and generalization of science concepts. *Child Development* 83, 1137-1144.

Wahistrom, K. (2002). Changing times: Findings from the first longitudinal study of later high school start times. *NASSP Bulletin* 86, 3-21.

Ward, M., & Sweller, J. (1990). Structuring effective worked examples. *Cognition and Instruction,* 7(1), 1-39.

Waterhouse, L. (2006). Multiple intelligences, the Mozart effect, and emotional

intelligence: A critical review. *Educational Psychologist,* 41, 207-225.

Weinburgh, M. (1995). Gender differences in student attitudes toward science: A meta-analysis of the literature from 1970 to 1991. *Journal of Research in Science Teaching,* 32(4), 387–398.

Wilson, A. J., Dehaene, S., Pinel, P., Revkin, S., Cohen, L, & Cohen, D. (2006). Principles underlying the design of "The Number Race", an adaptive computer game for remediation of dyscalculia. *Behavioral and Brain Functions,* 2(19).

Winter, B. *et al.* (2007). High impact running improves learning. *Neurobiology of Learning and Memory,* 87, 597-609.

Wynn, K. (1992). Children's acquisition of the number words and the counting system. *Cognitive Psychology*, 24(2), 220–251.

Wynn, K. (1998). Psychological foundations of number: numerical competence in human infants. *Trends in Cognitive Sciences*, 2(8), 296–303.

Xue, G., Mei, L. L. et al. (2011). Spaced learning enhances subsequent recognition memory by reducing neural repetition suppression. *Journal of Cognitive Neuroscience,* 23(7), 1624-1633.

Xue, G., Mei, L. L. et al. (2010). Facilitating memory for novel characters by reducing neural repetition suppression in the left fusiform cortex. *Plos One,* 5(10).

Yeh, S. C., Hwang, W. Y. et al. (2013). Study of co-located and distant collaboration with symbolic support via a haptics-enhanced virtual reality task. *Interactive Learning Environments,* 21(2), 184-198.

Young, C. B., Wu, S. S., & Menon, V. (2012). The Neurodevelopmental Basis of Math Anxiety. *Psychological Science,* 23(5), 492-501.

Zhou, J. (2012). The Effects of Reciprocal Imitation on Teacher–Student Relationships and Student Learning Outcomes. *Mind, Brain, and Education,* 6, 66-73.

Zhu, X., & Simon, H. A. (1987). Learning mathematics from examples and by doing. *Cognition and Instruction,* 4(3), 137-166.

Vision & Commentary

The literature review surveyed contemporary research focused on ways in which our understanding of psychology and neuroscience can inform STEM teaching. This section looks to the future and explores ways in which the relationship between psychological theory and STEM teaching practice might develop in order to support children's learning over the next 20 years.

This commentary emerges from the literature review in the sense that suggestions that appear here are either potential extensions of current research or are gaps that we have identified in the current literature with a strong likelihood of being filled in the next two decades. It is aligned with recent articles (e.g. Ansari & Coch, 2006; Fischer, Goswami & Geake, 2010) that call for closer relationships between education practitioners and researchers, and researchers in psychology, cognitive science and neuroscience. However, it goes further by making some specific recommendations for targeted development in STEM teaching practice and research that have become apparent through conducting the literature review.

Reflecting the structure of the literature review, we begin with comments relating to the skills and abilities required by children to access STEM learning successfully, and we then move to strategies for teaching STEM in schools.

Early Years STEM Learning

Emerging from the literature review, further research is likely to illuminate how different individuals respond to instruction during early years education. The literature review reveals the fact that children start school with potentially very different levels of ability in some key areas that predict achievement in STEM subjects (including linguistic ability, quantitative ability, spatial ability and executive function). We are beginning to understand the way in which these skills combine to provide a foundation for STEM Learning, but in the future education is likely to benefit from:

Improved methods of identifying the individual needs of children. Tests for various abilities are already used in research, but these are not always convenient or appropriate to apply in classroom practice. This can be due to the time required to administer the tests, or to the need to administer them on a 1-to-1 basis. In the future, novel methods of measuring precursor abilities in classroom contexts, with good levels of reliability and validity, will provide schools and teachers with new and more effective methods by which to target differentiated support and instruction.

Improved methods of supporting children with low levels of precursor skills and abilities. Given that these skills and abilities are strong predictors of future

> learning, it may be important that children identified as having low levels of particular abilities on entering formal education are supported in ways that focus on these abilities. Research cited in the literature review indicates some limited success has already been demonstrated in raising levels of these precursor skills, but further pursuit of research in this area will help identify more effective interventions for children with different levels of need and at different ages.

Some research has already taken seriously the need to focus on individual differences in response to STEM instruction, and to explore interventions that can address diverse needs for support. An excellent example of this approach is Dowker's (2005a; 2005b) componential model of arithmetic, that led to the development of the Catch-Up Numeracy programme. This research was not included in the literature review as its theoretical basis appears more educational than psychological or neuroscientific. However it provides clear evidence that a focus on individual differences in children's learning can lead to improved outcomes.

In the next 20 years, improved understanding of discrete predictors of achievement in STEM (e.g. spatial ability, quantitative ability, linguistic ability) and, perhaps more importantly, the ways in which they interact, will stimulate new insights into ways in which curriculum material can best be introduced, and new insights into ways in which material can be differentiated according to children's abilities.

STEM Instruction Strategies

In the future, a part of teachers' formal training and professional development will include a focus on concepts from neuroscience and psychology that have relevance for education. There will also be improved access to non-specialist summaries of related research via new technologies. These initiatives will empower teachers to implement a range of novel research-based approaches in the classroom that benefit their learners. They will also provide an effective first line of defence against neuromyth and its deleterious effects on educational practice.

It is anticipated that appreciation of the bidirectional role of socio-emotional well-being and education will grow. In STEM areas, this may be manifest through the curriculum, e.g. in terms of student understanding of brain function in relation to sleep, nutrition and mental health, but also in terms of teaching strategies that account for STEM-related anxieties. This content will also improve student understanding of their learning processes, with use of cheaply-available neurofeedback devices supporting greater metacognitive awareness.

The educational benefits of starting school later for adolescent children may not justify the associated disruption to school and family routines. However, collaborative parental and school approaches to improving teenagers' regulation of their own lifestyle may prove more successful and become common practise. The school day across primary and

secondary schools will be punctuated by short exercise breaks that are designed to improve executive function and learning, in addition to supporting physical health and well-being.

Learning schedules will space and interleave topics. Here, as elsewhere, laboratory and classroom-based research studies will inform the details of practise, with research data used to select the arrangement and timing of topics and tasks such as to optimise outcomes.

In the digitally-connected STEM classroom, all students will be responding simultaneously during teacher-class interaction. They will be engaging in challenges and simulations that fully engage the brain's reward, attention and learning processes, often in contexts that provide an immersive gaming experience. Such experiences will form an important part of learning outside of school, through homework and off-site research and learning projects.

Multimodality will be used to teach certain aspects of STEM concepts to greater effect. For example, tangible interfaces will improve the efficiency of learning 3D concepts. This will be achieved through, for example, the experience of touching, feeling and manipulating 3-dimensional molecular models, increasing the efficiency and fidelity by which shape information is received and processed in the brain. Learning resources will use audio and visual modalities to reduce working memory burden, and to also increase the rate of learning encouraging the linking of different streams of information represented by the two modalities.

Teachers will judiciously choose from approaches across a spectrum of inquiry-based and direct instruction methods, mindful of the types of knowledge and cognitive skills that are being targeted. Students will learn from experiences that combine concrete and abstract representations in ways that enable initial grasp, the rapid development of deep understanding and an ability to transfer this understanding to novel abstract and concrete situations.

Towards the Future

The anticipated progress discussed above will only arise from enterprise that crosses traditional disciplinary boundaries. In particular, there is a need to develop methods for research and the development of practice that combines concepts and insights at the intersection of psychological, neuroscientific and educational domains, to interrelate neurocognitive processes with the social activity and learning processes of the classroom (Jorg, Davis & Nickmans, 2007; Howard-Jones, 2010; Jay, 2013). While Jorg, Davis &

Nickmans (2007) advocate a complexity science approach, and Jay (2013) puts forward a postdisciplinary approach, a common aspect to both is the assertion that important potential findings in research are inaccessible as long as traditional disciplinary boundaries are observed, and the complex interactions amongst internal and external cognitive and social processes are ignored. The kind of work that could result from these approaches could include studies that aim to understand the interactions between cognitive development and social interaction that lead to children learning how to use number words. This could have important implications for the teaching of number, as it would allow educators a better understanding of ways in which pre-school experience contributes to learning. For example, we know that children do better at maths if there is more use of number words in their home environment, but we do not yet understand the causal mechanism for this phenomenon. With better understanding of these processes, parents could be better informed about the kinds of talk that are most helpful for children, and educators could be better informed about strategies for supporting children who have not had these kinds of home experiences before starting school.

References

Ansari, D., and Coch, D. (2006). Bridges over troubled waters: education and cognitive neuroscience. *Trends in Cognitive Sciences 10*(4), 146-151.

Dowker, A. (2005) Individual differences in arithmetic – Implications for Psychology, Neuroscience and Education (Psychology Press): It is "misleading and usually counterproductive, to label individuals as globally 'good' or 'bad' at arithmetic."

Dowker, A. (2005) What Works for Children with Mathematical Difficulties? (DfES Research Report RR554)

Fischer, K., Goswami, U., and Geake, J. (2010). The future of educational neuroscience. *Mind, Brain and Education 4*(2), 68-80.

Howard-Jones, P. (2010). *Introducing neuroeducational research: Neuroscience, education and the brain.* Abingdon, UK: Routledge.

Jay, T. (2013). The possibility and importance of postperspectival working. *Educational Research Review 9,* 34-46.

Jorg, T., Davis,B., and Nickmans, G. (2007). Towards a new, complexity science of learning and education. *Educational Research Review 2*(2), 145-156.