Education Endowment Foundation

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Neuroscience and Education:

A Review of Educational Interventions and Approaches Informed by Neuroscience

Full Report and Executive Summary

University of BRISTOL

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Executive Summary

Introduction

This review considers the extent to which insights from the sciences of mind and brain influence, or are close to influencing, classroom practice. It summarises the existing education evidence about approaches and interventions that are based, or claim to be based, on neuroscience evidence. In this way, the review also identifies areas of neuroscience that have successfully informed education, as well as areas of neuroscience that could inform education in the future if further work were undertaken to translate them into classroom-based approaches or interventions.

This review is part of a programme of work, undertaken in collaboration with the Wellcome Trust, which also includes a survey of teachers, parents and students and a review of the neuroscience literature. We hope that looking at the topic of neuroscience and education from the perspectives of practitioners, educational researchers and neuroscientists will provide a rounded understanding of the current use of neuroscience within education, as well as the challenges and questions that are arising.

Within this programme of work, this education literature review aims to identify neuroscience-informed educational interventions and approaches that:

- are likely, according to current findings, to have a positive impact on attainment and are therefore worth testing at a large scale;
- need further testing to determine their likely impact on educational attainment; or
- do not seem to have a promising impact on attainment.

The review also presents evidence about educational interventions that claim to be based on neuroscience findings, even where this link is less clear or less well evidenced. Note that some ideas presented within the review require further translational work before classroom application.

This programme of work has been conducted to inform applicants to a joint Education Endowment Foundation (EEF) and Wellcome Trust funding round focused on neuroscience and education projects. The review is therefore structured around 18 topics, with each topic being judged by the strength of evidence regarding educational effectiveness and the distance that needs to be travelled for the neuroscience knowledge to be applied within the classroom. Such readiness is an important factor that applicants might wish to consider when selecting an approach and developing a suitable intervention. This review is only intended as guidance and we will not automatically fund projects that fall under the topics explored; similarly, we may well fund projects that fall under topics not covered within this review, if the strength of evidence and classroom applicability is compelling.

This document does not require the reader to have a high level of specialist knowledge. However, many readers may benefit from acquiring the few anatomical terms presented in Appendix 1 in relation to brain regions. A list of acronyms can be found in Appendix 2.

The review does have some limitations, including the omission of literature within topics where the extent of published research prevents exhaustive review, or where the reference to neuroscience is insufficient (e.g. NeuroLinguistic Programming). Cognitive enhancing drugs have not been considered, on the basis of legal and ethical restrictions on their use. For related reasons, only passing reference is made to Transcranial Electrical Stimulation (TES), where potential ethical issues are only just receiving critical scrutiny. Interventions involving the effects on academic achievement of learning about the brain[1,2] have also been omitted. This is on the basis that their underlying principles are not informed directly by neuroscience, even though the materials used in such interventions do include neuroscientific information.

Why Neuroscience and Education?

Anything that has an impact on learning will ultimately have a brain basis; the idea that our understanding about how the brain works could impact upon educational practice is therefore an attractive one. This idea has gained traction in the last 10–15 years (particularly in the last five years), with considerable discussion and a step change in the number of articles connecting the brain with education (see Appendix 3).

The demand for neuroscience-informed education comes from both directions, with neuroscientists emphasising the potential of their work to improve education and educators being keen to learn what neuroscience has to offer. This enthusiasm does, however, mean that the topic needs to be approached with care, to ensure that neuroscience ideas are not adopted at too early a stage or before they have been properly translated for classroom use. This enthusiasm also means that interventions with a 'neuro tag', whether or not they are linked to neuroscience or indeed have any evidence of educational impact, are likely to propagate within education and be welcomed by schools and teachers – raising the importance of both dispelling myths and accurately disseminating evidence.

This then is an area of education that requires all of the parties involved – neuroscientists, cognitive psychologists, educational researchers and teachers – to work together, which should include ensuring that the neuroscience is properly interpreted and applied through educational interventions and approaches that are meaningful and feasible to implement. These interventions and approaches should then be rigorously tested to assess their educational impact.

Neuroscience and education is, therefore, an area of great potential that the EEF and Wellcome Trust can usefully contribute to by facilitating interdisciplinary working and the generation of high-quality evidence.

Main Findings

The review considers neuroscience, and the extent of its educational application, under 18 topics. Five of the topics deal with the curriculum areas of mathematics and reading, where a significant amount of neuroscientific understanding has accumulated. The other topics consider areas of neuroscience with more general influence; these cannot easily be constrained to a single curriculum subject. It should be noted that the curriculum area of mathematics has been split into four topics; this is because of differences in the amount of evidence and the applicability of different ideas within this subject.

Each of the 18 topics consists of two parts, the first part dealing with the *Neurocognitive processes* and summarising the scientific concepts, and the second part dealing with the *Education application*, which summarises the current extent of, or distance to, educational application.

The main findings of the review are summarised in the following sections and in Table 3, with each of the 18 topics given one rating to indicate the strength of evidence about the educational effectiveness, and another rating to indicate the distance that must be travelled by those seeking to apply the idea within the classroom. The criteria used to generate these ratings are shown in Table 1 and Table 2.

According to the strength of the evidence and the distance to application, the 18 topics have been grouped to reflect their stage of development and also the work that needs to be done to increase understanding.

Group 1: The five topics in this group are the most developed in terms of educational application and also have the most promising evidence about their impact on educational outcomes.

Group 2: The nine topics in this group have a good scientific basis, but may require further work to ensure they are appropriately applied within the classroom. They would also benefit from further evidence about their educational effectiveness.

Group 3: The four topics in this group have the least evidence about their educational impact and also require the greatest amount of translational work.

Group 1

The five topics in this group benefit from a theoretical basis that can be clearly constructed from findings in the scientific literature, from laboratory studies showing improvements in tasks related to academic achievement and classroom-based trials. Both the strength of evidence and the number of classroom-based trials do however vary, with some examples requiring further testing to determine best practice in applying the neuroscience knowledge within the classroom.

- **Mathematics – Maths anxiety.** Recruiting neural circuits for cognitive control of anxiety, with negative effects on working memory and the processing of number.

  A considerable amount is known about the effects of stress on learning, allowing for appropriate theorisation in this area. This work has given rise to a classroom-based intervention that demonstrates the potential effectiveness of a simple strategy. However, at present, only this single classroom study exists.

- **Reading.** Mapping letter symbols to sound and comprehending meaning.

  A vast amount of research has been undertaken on the neurocognitive processes that underlie reading, allowing appropriate and extensive theorisation. In addition, a significant number of laboratory-based and classroom trials of reading approaches and software informed by this understanding have been carried out. There are, however, many remaining questions that further projects may usefully address, including testing these approaches at larger scales to assess their benefits for a range of pupils.

- **Exercise.** Participating in physical activity to increase efficiency of neural networks.

  There is a strong basis in the neuroscience literature for justifying an exercise intervention, and many studies exploring the effects of exercise on academic achievement. The mixed results of these academic studies, however, suggest that some factors influencing outcomes are yet to be identified and there is a need to design future interventions carefully with this in mind.

- **Spaced learning.** Learning content multiple times with breaks in between.

  This application can be applied immediately in the classroom. Although it has in the recent past been strongly associated with neuroscience, it should be noted that the vast majority of what we know about the underlying processes derives from the psychological literature. The convergent nature of the many studies that have been undertaken in this literature do however provide clear guidance for its optimal application, including the ideal length of learning periods and the gaps between these. Outstanding questions still remain, such as the extent to which it can support learning processes beyond simple recall.

- **Testing.** Being tested on studied material aids memory.

  There is a strong educational and scientific evidence base for the effectiveness of testing in improving learning. Further work might usefully focus on how it is best used and the factors that influence its effectiveness.

Group 2

These topics benefit from a theoretical basis that can be clearly constructed from findings in the scientific literature, from laboratory studies showing improvements in academic learning, and/or from some exploratory research in classrooms. However, these topics often require more translational work and piloting of the approaches to test their feasibility within the classroom.

- **Mathematics – Non-symbolic and symbolic representations of number.** Having the ability to approximate number quantities and understanding representations of number such as “3”, linking these two abilities is also important.

  Such interventions can be based on the burgeoning literature regarding early number development, and there are now many studies involving young children that are producing promising results. However, these results have not presented a clear impression of the most important types of representation to target and further research is needed to understand their impact within the classroom.

- **Mathematics – Finger gnosis training**. Distinguishing between different fingers and using them when counting.

  There is a good range of scientific literature supporting this approach, but results for impact on mathematical learning are represented by a single classroom-based study in which the long-term impact of the approach was not tracked.

- **Sleep, nutrition and hydration**. Ensuring proper cognitive function and the consolidation of the day’s learning through proper sleep, nutrition and hydration.

  This topic boasts a sound theoretical basis, particularly with respect to sleep, with a strong common-sense rationale for interventions. However, effects of interventions on academic achievement have not yet been demonstrated. Interventions under this topic could include adapting the school day to suit the body clocks of teenagers to allow them to sleep for longer, or educating teenagers about sleep and how to ensure that they get enough sleep.

- **“Brain training” of executive function.** Using specific programmes to enhance functions such as reasoning, working memory and inhibition control.

  There is conflicting evidence for the effects of training on executive function, and little evidence for the effects of such training on academic achievement. The number of studies reporting positive effects on executive function, and the clear links between executive function and academic achievement, provide good justification for the exploratory testing of an intervention targeting achievement.

- **Embodied cognition.** Influencing cognitive processes and learning through our actions and the actions of others.

  Neuroscience helps establish an appropriate theoretical basis for applying concepts of embodied cognition in interventions based on a teacher’s gestures. However, evidence of effects on achievement is limited to a study of one-to-one interactions.

- **Interleaving.** Alternating different topics, as with spaced learning (in Group 1), ideas are revisited several times.

  The laboratory and classroom-based evidence shows clear value in some interleaving approaches. There are also several studies suggesting the neuroscientific processes that may underlie this effect. However, the range of different potential approaches to interleaving suggests a myriad of unanswered educational and scientific questions about this technique.

- **Learning games.** Using uncertain reward within computer games to make learning engaging.

  There is a clear theoretical basis and laboratory-based evidence for a classroom-based approach and some exploratory research in classrooms that may be helpful in informing pedagogy, but evidence of impact on improved engagement and enhanced academic achievement is limited to young adults.

- **Creativity.** Producing novel ideas and assessing their appropriateness.

  Neuroscience is providing some insight into strategies found to foster creativity in the classroom, but there is a lack of studies showing impact on tasks closely related to children's academic achievement. Further scientific progress in demonstrating the potential academic efficacy of concepts will be required before school-based interventions can be appropriately evaluated.

- **Neurofeedback**. Monitoring one's own brain activity with a view to influencing it.

  The technology for the use of neurofeedback in schools is becoming cheaper, and studies with undergraduates and children point to its effectiveness in improving performance and the value of assessing intervention. However, the emergent nature of its theoretical basis and questions about optimal approaches to its application suggest such an intervention has exploratory aspects.

Group 3

Topics within this group face significant challenges in terms of either their theoretical basis or their limited evidence predicting their likely impact on children's learning. This means that additional scientific questions need to be answered or that more developmental work needs to be done to allow the idea to be applied within the classroom.

- **Mathematics – Mental rotation skills.** Imagining how an object would look rotated from its current presentation, this ability has been linked with general intelligence.

  Mental rotation skills are strong predictors of achievement in science, technology, engineering and maths (STEM) subjects and results from a single study show that improving mental rotation does lead to improvement in attainment. However, this has only been tested with undergraduate students. Another way of improving these skills might be through video games. However, the effect of such games on STEM education has not been tested.

- **Genetics.** Looking at the cognitive influences of genes

  The present state of the science appears ready to inform usefully the tests of other educational interventions, particularly in understanding the composition of the cohort in terms of its likely sensitivity to any intervention. However, this knowledge is some way from being applied within the classroom.

- **Personalisation**. Selecting teaching approaches for different students.

  Although neuroscience is contributing an increasing number of insights regarding individual differences, we know little of how to attend to these differences when designing learning technology, or of the magnitude and nature of the advantages that may be achieved.

- **Transcranial Electrical Stimulation (TES)**. Applying small, non-invasive electrical currents to the brain by placing electrodes on the scalp.

  This research is producing exciting outcomes with apparent potential to raise academic achievement, but a complete understanding of the underlying processes, effects and risks is still some way off. Significant scientific progress is required in these areas before its value in improving academic achievement amongst mainstream school-aged children can be appropriately evaluated.

Table 1: Criteria for rating the strength of evidence for the educational effectiveness of interventions and approaches informed by neuroscience

Strength of evidence for educational effectiveness	Rating
There are either mixed experimental results or limited present evidence for the transfer to students' educational learning outcomes.	Low
There are convergent experimental results for outcomes known to influence students' educational learning outcomes, and/or some evidence for impact on students' educational learning outcomes.	Medium
Multiple studies report convergent findings of positive impact on students' educational learning outcomes.	High

Table 2: Criteria for rating the distance to application for educational interventions and approaches informed by neuroscience

Distance to application	Rating
Significant challenges exist in terms of the development of knowledge and understanding, and/or in terms of the design and production of state-of-the-art specialist resources, and/or in terms of ethical issues.	Distant
Application is likely to require some limited bridging studies, and/or limited specialist resourcing (e.g. specialist software) and/or training.	Moderate
The intervention could be applied immediately.	Near

Table 3: Neurocognitive processes and their potential educational application

Ratings for the strength of evidence for their educational effectiveness and their distance to application are provided, following the criteria in Table 1 and Table 2

Topic	Neurocognitive processes	Educational application	Strength of evidence for educational effectiveness (low, medium, high)	Distance to application (near, moderate, distant)	Page Number
1. Mathematics – Non-symbolic and symbolic representation of number	Neuroscience has helped reveal the importance of both non-symbolic and symbolic representation of quantity in both the earliest and later stages of mathematics education. Students must learn to link these representations.	Reflective of the emergent state of understanding in this area, mixed results have been obtained from the studies attempting to train children's non-symbolic representations, with some studies also reporting impact on symbolic representation and transfer to other numeracy skills.	Medium	Moderate	13 - 16
2. Mathematics – Finger gnosis	Fingers may have a special relationship with concepts of number.	An intervention study showed that finger gnosis training can improve some aspects of early number development.	Medium	Near	
3. Mathematics – Mental rotation skills	Mental rotation skills predict maths and science achievement and these skills are amenable to training, including by the playing of action video games.	A longitudinal study showed STEM benefits from spatial training amongst undergraduates.	Low	Distant	
4. Mathematics – Maths anxiety	Maths anxiety interferes with neurocognitive processes crucial to learning, with effects mediated by an individual's recruitment of cognitive control networks.	A study reported that the effects of teenage maths anxiety can be reduced by writing about it.	Medium	Near	

5. Reading	Children begin to learn to read by mapping letter symbols to sounds. As well as converting written words and sentences to sound, children must learn to comprehend meaning. Many sub-skills contribute to fluent reading.	Computer-based training focused on phonological skills has helped those experiencing difficulty to develop their reading skills. Several multicomponent interventions have also been successful, emphasising the complex nature of the reading process and the potential value of considering individual differences in such interventions.	Medium	Near	17 - 18
6. Exercise	Exercise increases efficiency of neural networks that are important for learning. Episodes and regimes of exercise can improve cognitive function and memory.	Almost entirely, exercise interventions have had either no effect or positive effects (in equal proportion) on learning, suggesting substantial likelihood of its academic value. The most important factors influencing the academic outcomes of exercise are still the subject of research.	Medium	Near	19 - 20
7. Sleep, nutrition and hydration	Sleep is important for rest and for consolidating the day's learning in long-term memory. Technology, caffeine, psychosocial factors and biological changes are known to disrupt sleep patterns, particularly in adolescents. Habitual ingestion of caffeine reduces cognitive function. Small amounts of dehydration can reduce cognitive ability.	Later starts in schools that begin the day early have been shown to improve attendance and engagement in lessons. Simply providing information to teenagers about sleep, including its chronobiology, raises awareness but fails to change habits. Great involvement of such interventions with home-life and culture has shown, tentatively, more promise. Studies assessing the effects of providing supplementary water suggest little educational benefits in UK schools.	Low	Near	21 - 23

8. Genetics	Genes have a major influence on brain function/structure, suggesting genetics can play an important role in the understanding of individual differences.	Some genetic markers already have current practical value in deepening our understanding of the effects of educational interventions.	Medium	Distant	24
9. Embodied cognition	Neuroscience has helped us understand that our body plays a crucial role in our cognitive processes (embodied cognition). Embodied cognition provides a theoretical basis for understanding how actions influence our learning (e.g. the enactment effect). Some of our neurons mirror the actions made by others (so-called mirror neurons) and these processes may inform an embodied cognition approach to understanding, for example, how a teacher's actions influence a student's learning.	Embodied cognition not only helps explain the well-established enactment effect, but may also provide insight into how students learn from the actions of their teachers.	Medium	Moderate	25 - 26
10. "Brain training" of executive function	Many studies exist demonstrating that the executive functions of adults and children can be trained, and there is clear potential for such training to contribute to education. However, there have been difficulties in replicating successful outcomes and there is debate regarding how far transfer can be achieved to tasks dissimilar to those used in training.	Results for impact on executive function are promising. However, there is currently a lack of good-quality evidence to indicate that this transfers to academic outcomes.	Medium	Moderate	27 - 28
11. Spaced learning	The spacing of learning sessions improves outcomes compared with massing sessions together. A neuroimaging study suggests the effect is due to enhanced maintenance rehearsal in spaced, as opposed to massed, presentations of learning material.	The spacing effect on memorisation is well established, and the benefits of spacing may extend to deeper types of learning.	High	Near	29 - 30

12. Interleaving	Interleaving topics can increase the efficiency with which learned material is remembered and also the effectiveness of some other learning processes. Interleaving may operate by reducing the suppression of neural activity in memory regions that occurs when similar stimuli are repeatedly presented.	Though considerably less established than the spacing effect, a small number of studies reveal educational potential.	Medium	Moderate	31
13. Testing	It has been established, in a range of contexts, that testing can improve memory for learned material and may also improve some other types of learning. Currently, there are several candidate neural processes for the testing effect – all of which may contribute to outcomes.	Insight from neuroscience and psychology, particularly when combined with technology, may help improve application of testing in today's classroom.	High	Moderate	32
14. Learning games	Popular games provide rapid schedules of uncertain reward that stimulate the brain's reward system. The brain's reward response can positively influence the rate at which we learn. Beyond just the magnitude of the reward, a range of contextual factors influence this reward response.	Efforts to develop and implement learning games are already drawing on concepts about brain and mind, although there have been no rigidly-controlled comparisons of their effectiveness compared with other teaching approaches.	Medium	Moderate	33 - 34
15. Creativity	There is a burgeoning field of creative neurocognition that has provided insights into individual differences in creativity and creativity-fostering strategies.	The tasks used in laboratory studies do not closely resemble those assessed in education, but neuroscience is providing insights into strategies found to foster creativity in the classroom. At present, no attempt has been made to create novel classroom strategies arising from these insights.	Low	Moderate	35

16. Personalisation	Responding to learner preference does not automatically lead to improved learning. Cognitive neuroscience is providing insight into individual differences likely to influence learning outcomes.	It is known that providing choice can improve motivation, but little attempt has been made to inform such personalisation with insights from authentic neuroscience.	Low	Moderate	36
17. Neurofeedback	Neurofeedback enables individuals to alter their mind state by monitoring their own brain activity. It has been demonstrated as beneficial in studies of creative performance, although a full understanding of how this occurs is still emerging.	The technology to provide neurofeedback in classrooms is becoming more portable and affordable Its value in these contexts has been explored in a classroom study of children's music performance, although many questions remain regarding how implementation should be designed to ensure optimal outcomes.	Medium	Moderate	37
18. Transcranial Electrical Stimulation (TES)	Although a full scientific understanding of the effect remains elusive, applying small currents to the scalp can benefit some cognitive functions and learning processes.	Positive effects are now being reported for learning tasks relevant to education, but remaining questions regarding risk and ethics make TES classroom interventions unlikely in the near future.	Medium	Distant	38

Mathematics

Neurocognitive processes

- Neuroscience has helped reveal the importance of both non-symbolic and symbolic representation of quantity in the earliest (and later) stages of mathematics education
- Students must learn to link these representations
- Mental rotation skills predict maths and science achievement and these skills are amenable to training, including by the playing of action video games
- Fingers may have a special relationship with concepts of number
- Maths anxiety interferes with neurocognitive processes crucial to learning, with effects mediated by an individual's recruitment of cognitive control networks

Non-symbolic and symbolic representation of number

Cognitive neuroscience has made a substantial contribution to understanding how numerical abilities develop in young children and the foundational role of non-symbolic and symbolic representation in acquiring formal mathematical skills. We now understand that quantitative ability involves a number of components, and these include:

- a non-symbolic number system (or numerosity) which is the ability to quickly understand and approximate numerical quantities[3], and is considered to be evident in animals and present very early in human development.
- a symbolic number system which is the ability to understand representations such as "3" or "three", whose development is strongly linked to that of early language, beginning around 2-3 years old
- ability to map between non-symbolic and symbolic systems, which appears linked to the use of fingers and develops through early childhood

A brain imaging study suggests we still use our approximate non-symbolic number system (which involves a region in the parietal lobe) when estimating quantity as adults, but we switch to a more language-dependent symbolic system when calculating exactly[4].

Studies in typically developing children also attribute a crucial role to numerical magnitude representations in predicting individual differences in mathematics achievement e.g. [5,6,7]. However, these studies have involved several sub-domains of mathematics assessed without time-constraint. A study focused on arithmetic, where deficits in fact retrieval are often regarded as the hallmark of mathematical difficulty[8,9], suggests access to numerical meaning from Arabic symbols ("1", "2", "3", etc) is key for children's arithmetic strategy development [10]. This study joins other evidence showing a critical role for this access, and makes a clear case for also exploring interventions based on connecting Arabic symbols to the quantities they represent[11,12].

Dyscalculics suffer from severely impaired number representation, with 10-year-old dyscalculics scoring at the level of 5-year-old normally achieving children[13]. Neuroimaging findings corroborate deficits of number representation observed in the behaviour of children with developmental dyscalculia, implicating functional impairments and structural alterations in parietal brain regions associated with representing the number line[14-16].

Mental rotation skills

Spatial abilities, and particularly mental rotation, are established as predictors of achievement in mathematics[17] and science[18] and these appear to mediate gender differences in STEM (Science Technology Engineering and Mathematics) achievement[19]. Training in mental rotation training can lead to stable gains[20]. Action video games, via processes that have been explained by the action of neural modulators on brain plasticity[21,22], have also been shown to improve mental rotation skills[23,24].

Fingers gnosis

Another insight from neuroscience comes from research into the role of fingers in early mathematical development. Finger gnosis (being able to distinguish between different fingers in response to, say, one or more being touched) has been identified as a predictor of mathematical ability [25]. Using functional Magnetic Resonance Imaging (fMRI), a study has shown a variation with age of the brain regions activated when fingers are used to approximate[26]. 8 year-old children produce an increase in activity in parietal regions associated with number sense when fingers are involved, but not adults. The authors of this study suggest fingers represent concrete embodied tokens involved in the estimation of number magnitude, i.e. they have an intimate involvement with our number sense. On this basis, children should not be discouraged from using them and teachers may be able to exploit the natural role of fingers more fully [27]. The disproportionate number of split-five errors made in later years, due to intermediate results represented by hands being forgotten, also bears witness to the continuing influence of our fingers on our mathematical training. An fMRI study with 6-12 year olds suggests that finger counting mediates the step from non-symbolic to symbolic and exact number processing [28]. Finger counting, therefore, appears to be an important example of co-called *embodied cognition* (the idea that human cognition has its roots in sensorimotor processes and so is still very influenced by our bodily experiences – see Embodied Cognition below)[29].

Maths anxiety

Evidence for anxiety about using numbers can be found in very young students [30] through to secondary education[31]. Such students are less likely to engage with the subject and suffer accumulating effects upon their progress[32]. Whatever the present level of sufferers' ability, anxiety can have detrimental effects on achievement beyond a willingness to engage [33]. This may be due to the effects of anxiety on working memory[34]. When performing calculations, children with maths anxiety have greater activity in the amygdala (associated with negative emotional processing, see Appendix 1, Figure A5 for location) and reduced activity in brain regions supporting working memory and the processing of number, compared with children who are not anxious [35]. Such neural differences should not be seen as evidence of a biologically determined condition. Indeed, it appears maths anxiety can be culturally transmitted from teacher to student[36]. A recent neuroimaging study found the difficulties experienced by young adult students who were anxious about maths was predicted by how much they recruited neural circuits for cognitive control [37]. The authors of this study suggest their results indicate the need for interventions emphasising control of negative emotional responses to mathematical stimuli.

Educational application

Can training improve children's non-symbolic representation of number and its relation to symbolic representation – and does this help their mathematics?

- Reflective of the emergent state of understanding in this area, mixed results have been obtained from the small number of studies attempting to train children's non-symbolic representations, with some studies also reporting training impact on symbolic representation and transfer to other numeracy skills.
- A single intervention shows finger gnosis training can improve some aspects of early number development.

A recent educational intervention with 6-7 year olds compared the effects of training exact and approximate number systems and found that each approach led to equal improvements in arithmetic ability, supporting the notion that two distinct systems are involved with representing approximate and exact information about quantity [38]. Potentially, the combination of technology with a scientific understanding of learning has much to offer education, with the promise of learning software with a sound theoretical basis and that adapts to learners needs. Researching how to combine technology and neuroscience in the development of new educational approaches has been identified as an important area for future investment[39]. "The Number Race'' was one of the first examples of attempts to do this, with a design that drew on the concepts discussed above. Its creators [40] suggest their work provides evidence for how this type of software can help close the socioeconomic gap in mathematics achievement[41]. The "Number Race" was designed to focus on 1) number sense, including numerical comparison (deciding which is the bigger of two numbers) and the link between number and space; (2) links between non-symbolic and symbolic representations of number; and (3) understanding of, and access to, basic addition and subtraction facts[40]. Although involving only a small sample number (N=9), the Number Race software was initially shown to improve performance on non-symbolic as well as symbolic tasks in an intervention targeting 7-9 year-olds with mathematical difficulties[42]. A study of 30 low-numeracy kindergarten children playing 10-15 minutes daily for 3 weeks revealed improvements in comparison of Arabic numbers but not in other areas of number skills[43]. Evaluation with 53 young children (ages 4-6) with low socioeconomic status revealed improvements in tasks comparing digits and words but no improvement on non-symbolic measures of number sense[44]. This suggests the underlying improvement in processes was better number sense *access* and/or *linking* of non-symbolic representations of number to symbols.

Kucian and colleagues developed a game called "Rescue Calcularis" which requires young children to land a spaceship on number line, with the aim of helping them develop their own internal number line representation. In a 5-week intervention, 16 children diagnosed with dyscalculia (8–10 years old) and 16 matched controls played this specially designed computer game for 15 minutes a day at home[45]. The outcomes of the training were evaluated using behavioural tests and neuroimaging of brain function when children were performing a number line task. Both groups, with and without developmental dyscalculia, showed an improvement in various aspects of spatial number representation and mathematical reasoning five weeks after training. The intensive training led initially to a general activation decrease of relevant brain regions probably due to reorganisation and fine-tuning processes(which was greater for dyscalculics), and then to an increase in task-relevant regions after a period of consolidation. A further evaluation of this software was carried out with 40 children having difficulties in learning mathematics – as indicated simply by their below average performance in arithmetic[46]. Playing 20 minutes per day, five days per week for 6 weeks improved arithmetic performance, especially subtractions (where performance is considered to represent a main indicator for development of spatial number representations and numerical understanding).

Two other technology-based resources exist for developing early mathematics ability which, according to their creators, are informed by neuroscience: Fluency and Automaticity through Systematic Teaching with Technology (FASTT Math) and "Number Worlds". However, as Kroeger et al.[47] point out, current reports of positive results for these resources are difficult to interpret due to underreporting of methodological and analytic detail.

Other researchers have used non-technological means to encourage children to connect symbols to meaning. Gabriel and Coché [48] asked 9-11 year olds (N=292) to use wooden disks to help them represent and manipulate fractions while playing card games for 30 minutes twice a week over 10 weeks. Relative to usual instruction, this improved children's conceptual understanding of fractions and their ability to associate fractional notations with numerical magnitude through a learning-by-doing approach. At the recent EARLI SIG[1] meeting, Brankaer et al. [49] reported improvements in children's symbolic number comparison after using a domino game designed to foster connections between magnitude and symbol, relative to using a control domino game.

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[1] *The European Association for Research on Learning and Instruction has a Special Interest Group (EARLI SIG) dedicated to neuroscience and education.*

Can finger gnosis training improve early number development?

An intervention study has considered the evidence linking fingers and mathematical processes and focused on finger gnosis as a means to improve numerical ability. This is despite many mathematics educators recommending the fostering of mentally based numerical representations so as to induce children to abandon finger counting. Gracia-Bafalluy and Noel [50] assessed new arrivals at 3 Belgian primary schools for finger gnosis and formed 3 groups: children with poor finger gnosis[2] who followed the finger-differentiation training programme (G1), a control-intervention who were trained in story comprehension (G2), and a group with high finger gnosis scores who just continued with normal school lessons (G3). Initially, children in G3 performed better in finger gnosis and enumeration than G1 and G2. Children in G1 then trained for 2 half-hour sessions per week over 8 weeks. Training consisted of games played with coloured stickers on each finger nail. For example, in one game the children followed each coloured pathway in a labyrinth with the correspondingly coloured finger. After the training period, the children in G1 were significantly better than those in G2 at finger gnosis, using their fingers to represent a numerosity (i.e. the number of objects in a set), quantification tasks and the processing of Arabic digits. These positive results have not resolved the debate between neuroscientists and mathematics educators regarding the role of fingers[51].

Can mental rotation training improve STEM achievement?

- A single longitudinal study shows STEM benefits from spatial training amongst undergraduates
- At present, no attempt has been made to acquire direct evidence of video games improving STEM achievement via enhanced mental rotation abilities

A longitudinal study suggests training benefited undergraduate students who initially exhibited poor spatial skills. These students achieved higher grades in engineering, mathematics, and science courses and were more likely to progress in their studies, compared with those who had not participated in the training[52]. Given the positive effects of video games on mental rotation ability, and the role of this ability in STEM achievement, it might be reasonably hypothesised that the playing of off-the-shelf and/or bespoke video games might improve STEM achievement. However, the existence and size of any effects have never been investigated.

Can understanding of math anxiety improve achievement?

- A single study has reported that the effects of teenage maths anxiety can be reduced by writing about it

An intervention focused on controlling negative emotional response has reported improved achievement. Writing about anxieties may be one way to rehearse such control. Following on from laboratory-based studies, a school-based intervention was carried out among students aged 14-15 years (N=106) [53]. These students first rated their own anxiety and were then randomly allocated into two groups. For 10 minutes, immediately before a maths test, one group wrote about mathematics-related anxieties and the other about a topic not in the test. Amongst students who had had rated themselves as more anxious, those who wrote about their anxieties significantly outperformed maths anxious students in the other group, performing similarly to less maths anxious students.

[2] *Knowledge and awareness of fingers*

Reading

Neurocognitive processes

- Children begin to learn to read by mapping letter symbols to sounds
- As well as converting written words and sentences to sound, children must learn to comprehend meaning
- Many sub-skills contribute to fluent reading

Symbols and sounds

A vital first step in learning to read is mapping letters and letter strings on to the sounds of language (known as phonemes). Dyslexia is most commonly attributed to problems with this "phonological decoding" process. Several interventions have had some success in ameliorating these difficulties, together with remediation of the function of associated brain regions [54,55]. Such studies have helped raise awareness of the general importance of phonological decoding for reading acquisition and contributed to the prevalent adoption of "phonics" approaches to reading. They have also helped prompt the development of technology-based reading resources combining neuroscience and educational understanding. One example is Graphogame - a non-commercial system developed at the University of Jyväskylä (Finland) which introduces the association of graphemes and phonemes to young children according to the frequency and consistency of a grapheme in a given language[56]. In Graphogame, online algorithms analyze a child's performance and rewrite lesson plans 'on the fly' depending on the specific confusions shown by the learner[57]. The difficulty of the content is adjusted so that the challenge matches the learner's ability. Using fMRI and EEG together (allowing both good spatial and temporal resolution in measurements), it has been shown that practice with the game can initiate print-sensitive activation in regions that later become critical for mature reading - the so-called 'visual word-form system' [58].

Multiple sub-skills

While phonological decoding remains the prime candidate for early problems with reading, reading proficiency also requires comprehension and this is the other key source of difficulty for many children. To be a proficient reader, one must decode accurately, and read fluently and with understanding[59]. A recent imaging study with adults revealed reading-related brain regions respond differently when reading fluency is manipulated by varying the speed with which text is presented [60]. This again suggests fluent reading should be understood as the product of multiple contributing reading sub-skills. It also suggests that varying reading speeds may be an effective means by which to subtype differing forms of dysfluency through behavioral and neural measures, and so support the personalisation of remediation programmes. Others have called for the incorporation of neuroimaging techniques as part of such a subtyping processs[61].

Educational application

Can training on the neurocognitive components of reading improve outcomes?

- Computer-based training focused on phonological skills has helped those experiencing difficulty to develop their reading skills.
- Several multicomponent interventions have also been successful, emphasising the complex nature of the reading process and the potential value of considering individual differences in such interventions

Several studies have shown the effectiveness of Graphogame in developing reading skills amongst those with difficulties[56,62]. One study showed only 3 hours of use improved reading-related skills and that the training effects were reflected in brain activity[63]. Implementation of GraphoGame in the

language of English, with its nontransparent orthography, is more challenging than for Finnish. A recent study compared the direct translation of Graphogame into English with a version that additionally introduced first the largest rhyme families with the most consistent orthographic rime spellings[64]. Groups of 6–7-year olds identified by their teachers as being relatively poor at reading played one of the games as a supplement to normal classroom literacy instruction for five sessions per week for a period of 12 weeks. In comparison with children in an untreated control group, both games led to gains in reading, spelling, and phonological skills that were maintained at a four-month follow-up.

Multicomponent approaches such as the RAVE-O (Retrieval, Automaticity, Vocabulary, Engagement with Language, Orthography) have also shown some success. The creators of RAVE-O claim considerable influence from neuroscience as well the developmental and linguistic sciences[65]. In a 70 day intervention of 2 hour a day training, the effectiveness of two multiple-component intervention programs for children with reading disabilities (one including elements of RAVE-O) showed improvements relative to single component phonological approaches [66]. Another multicomponent intervention with at-risk readers also showed remediation of reading difficulties, together with improved electrophysiological correlates of attention that were originally deficient in the at-risk group[67].

One group of researchers has focused on the importance of rapid auditory temporal processing skills and, again, there is some evidence for amelioration of behaviour and neural function with training[68]. This research gave rise to a computer-based training programme called “FastForWord”. However, after screening 130 evaluation studies for quality, a meta-analysis of the six remaining interventions concluded there was no evidence for the effectiveness of FastForWord as a treatment for children’s reading or expressive or receptive vocabulary weaknesses[69].

Perhaps even more controversially, Helen Irlen proposed dyslexia arises from visual stress. According to Irlen[70], visual stress is present in 65% of people diagnosed with dyslexia and in 12% of the non-dyslexic population and it derives from 'a structural brain deficit involving the nervous system' (Irlen, 1991, p. 57). The Irlen Method of dealing with reading problems (in categories that have been referred to as Irlen syndrome, Meares-Irlen syndrome, scotopic sensitivity syndrome, and visual stress) involves the wearing of tinted glasses. A lack of high quality evidence to support such approaches prompted McIntosh and Ritchie to mount a double-blind study, which failed to provide evidence of positive benefit[71]. This study also suggested the likelihood of a placebo effect associated with tinted overlays, further undermining the credibility of previous results derived from less judiciously constructed research designs. A 1-year follow up has confirmed no disproportionate gain in reading progress across the year compared to controls[72].

Exercise

Neurocognitive processes

- Exercise increases efficiency of neural networks that are important for learning
- Episodes and regimes of exercise can improve cognitive function and memory

Exercise and neural networks

There are authentic beneficial effects of aerobic exercise on selective aspects of brain function [73]. In adults, regular exercise has been shown to improve the efficiency of those frontal, posterior, and temporal networks important for learning[74] including the fronto-parietal networks that help guide our attention[75].

Exercise and memory

Physical exercise also increases blood flow and connectivity in the hippocampus (see Appendix 1, Figure A5), a key region for memory formation and consolidation, and hippocampal volume is related to physical fitness in children[76] and adults[77]. In adult studies, exercise has been shown to increase a range of white and grey matter regions, and such increases in the size of the hippocampus have been related to improved spatial memory and more Brain Derived Neurotropic Factor (BDNF) in the blood. This data joins accumulating evidence that exercise increases BDNF gene expression in the hippocampus[78] which contributes to the effects of physical exercise on cognition[79,80]. A study of healthy adults revealed increased levels of BDNF in the blood after two 3 minute sprints[81]. When compared to sedentary or moderate exercise conditions, participants showed a 20% increase in the speed of recall for words they learnt immediately following their intense exercise.

Educational application

Can exercise improve academic achievement?

- Almost entirely, exercise interventions have had either no effect or positive effects (in equal proportion) on learning, suggesting substantial likelihood of its academic value
- The most important factors influencing the academic outcomes of exercise are still the subject of research

Several studies of school-age children reveal positive effects of exercise on cognitive functions crucial for learning, and some have linked these to improvements in brain function. For example, Kubesch and colleagues showed on-task attention in the face of distraction was improved amongst 13-14 year olds after a single 30-minute physical education program in contrast to a 5-minute movement break[82]. Kindergarten children show improved attention and improved efficiency in associated neural function after two 35-minute sessions per week for 8 weeks[83]. On a longer time-scale, a 9-month randomised control physical activity intervention involving 7 to9 year olds provided improvements in working memory[3] function and its associated event-related brain potential[4] measurements, as well as fitness [84]. Brain-related improvements in function were also found in a study of 8 to 9 year-old children participating in 60 minutes of physical activity for 5 days a week over a 9 month period[85]. This

[3] *Abilty to hold information in consciousness*

[4] *Electrical brain response to an event*

intervention improved efficiency in prefrontal[5] networks and performance on measures of cognitive control.

A recent systematic analysis of studies examining the effect of exercise on academic achievement revealed findings were almost exactly split between no effect and positive effects[86] with a distinct lack of negative effects. It has been suggested the variation in outcomes may arise from differences in research methods [73], but Rasberry et al. found the quality of studies did not appear to influence this basic finding. The authors conclude that substantial evidence exists that physical activity can help improve academic achievement. Rasberry et al. point out the lack of theoretical foundation for most studies, suggesting further interventions should be informed by research across disciplines, including neurobiology.

What about Brain Gym?

- a review of the theoretical foundations of Brain Gym and the associated peer-reviewed research studies fails to support the contentions of its promoters

Reports of increased reaction times following Educational kinesiology exercises (or Edu-K, sometimes sold under the brand name of Brain Gym) are suggestive of some positive effect on cognition [87]. However, according to the science discussed above, greater benefits might be expected from more aerobic exercise.

Brain Gym is proposed to 'balance' the hemispheres of the brain so they work in an integrated fashion and so improve learning [88]. Brain Gym draws on theories of neurological repatterning and, more specifically, the Doman-Delacato theory of development [89] which recommends the acquisition of specific motor skills in the correct order [90]. This reflects the notion that ontogeny (individual development) recapitulates phylogeny (the development of the species), a theory now abandoned by modern science. According to this view, if a particular developmental stage is skipped, such as when a child learns to walk before crawling, then this may have a detrimental effect on later development of more complex processes such as language. Treatment in this case might be to encourage the child to rehearse crawling movements, in order to *repattern* their neural connections and improve their academic progress. It is difficult to test such a theory directly, but several reviews have concluded the theory is unsupported, contradicted or without merit [91-94], and practical approaches based upon such ideas have been revealed as ineffective [95].

Brain Gym also draws on ideas about perceptual-motor training, i.e. that learning problems arise from inefficient integration of visual, auditory and motor skills. This notion has spawned training programs seeking to ameliorate learning difficulties through exercises rehearsing integration of these perceptual and motor skills. Such approaches have been revealed as ineffective by numerous studies in the 1970s and 1980s [96-101], and yet these ideas continue to circulate. As recently 2003 and 2007, papers was published in the respected journal Dyslexia promoting the value of such exercises[102,103]. These articles provoked considerable critical attention from well-established researchers in the field of dyslexia, who highlighted serious methodological flaws such as the absence of standardised reading tests, inappropriate statistical analysis, lack of control for placebo effects and smaller student-teacher ratios in the experimental group, using unbalanced control and experimental groups, using an experimental group with few of the difficulties that the programme was intended to ameliorate and inadequate reporting of essential details on the basis of 'commercial sensitivity' [104-109] .

In addition to flaws in its theoretical basis, there is a lack of published research in high quality journals to make claims about the practical effectiveness of programmes such as Brain Gym, at least in terms of raising achievement. In those studies published elsewhere, it has been pointed out that the lack of information about the exercises undertaken and/or the insufficient or inappropriate analysis of the results undermine their credibility [110]. Given the deficiencies in both its theoretical validity and evidence of practical value, the apparently enduring popularity of Brain Gym continues to raise concerns amongst educators[111,112].

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[5] *The frontal regions of the frontal lobes – see Appendix 1*

Sleep, nutrition and hydration

Neurocognitive processes

- Sleep is important for rest and for consolidating the day's learning in long-term memory
- Technology, caffeine, psychosocial factors and biological changes are known to disrupt sleep patterns, particularly in adolescents
- Habitual ingestion of caffeine reduces cognitive function

Sleep and learning

Sleep does not merely provide rest that enables us to begin the next day more wakeful, attentive and alert. It helps us "lay down" and consolidate the day's experiences in long-term memory, so that our recollection of them becomes more robust and accessible to us in the future. While the waking brain appears optimized for first encoding memories in a biological form, neuroscientists characterize sleep as the brain state that best consolidates them[113]. This consolidation process starts by reactivating neuronal memory representations during slow-wave sleep, before these are transformed for integration into long-term memory. This is illustrated most strikingly by neuroimaging studies. One of these reveals how the sleeping brain reproduces the neural activities characterising whatever we experienced in our preceding hours of wakefulness[114]. The ensuing rapid-eye-movement sleep may be important for stabilizing these transformed memories. Sleep, through providing rest and better access to long-term memory, also helps us access remotely associated ideas more efficiently, improving our ability to generate insights the next day[115] . Regular and sufficient sleep is thus essential for the brain to learn and create efficiently. An important component in the processes that help us maintain regular sleep patterns (or so-called "circadian rhythms") is the melatonin secreted by the brain's pineal gland.

Adolescent sleep issues

Teenagers suffer a shortened sleep period due mainly to late onset (i.e. falling asleep late). This is due partly to biological reasons, with puberty disrupting melatonin secretion, and psychosocial reasons (such as increased freedom) further exacerbated by forced awakenings on school days[116]. The result is widespread daytime teenage sleepiness and associated reductions in cognitive function. Late night use of electronic media is also commonly perceived as a cause of poor sleep[117-119], with a study in the U.S. of teenagers' technology use after 9 pm indicating an average dose of 55 minutes online computer use plus 24 minutes of video games[120].

Sleep and technology

Excessive use of video games is partly identified by the disruption it causes in other important areas of life such as sleeping and eating. Indeed, excessive use of video games is detrimental to broad range of health measures and also influences educational achievement[121,122]. A 2-year longitudinal study[123] of children (aged 8-14 years) linked pathological gaming to increased aggression, likelihood of being a victim of aggression, and poorer academic grades. Such evidence, together with the data on attentional problems discussed above, tends to support current guidelines from the American Academy of Pediatrics (AAP) for a maximum of 2 hours total screen time per day for children[124,125]. However, even when use is not excessive, the use of the arousing effect of video game play on a school evening may also influence sleep. In a small experimental study [126], 10 school children (average age 13.5 yrs) played a computer game for 60 minutes on one night of the week, watched television for the same time on another evening and also experienced one evening with no technology (as a control). Game playing resulted in significantly disrupted sleep patterns (including an approximately 20 minute further delay in sleep onset). Significantly, there was also reduced memory for the material students were exposed to after the game play. Television viewing expends the same

energy as sitting quietly, while playing video games results in a higher arousal state of the central nervous system[127] and viewing TV did not produce such large negative effects on sleep and memory.

Small screens may also be particularly problematic due to bright display terminals suppressing nocturnal melatonin secretion[128]. In a Belgian study of 13-16 year olds, Van den Bulck[129] found that mobile phone use after "lights out" was very prevalent (most participants using their phones several times a month in this way) and significantly related to increased tiredness both concurrently and a year later.

There are many anxieties expressed in headlines about children's use of technology. However, there is presently little advice offered to students, teachers and parents in the UK about using it healthily, beyond online safety and minimising the risks of being abused by others. It has been recently suggested that digital hygiene might usefully be included in sleep intervention programmes aimed at schoolchildren and their parents[130].

Caffeine

Like technology, caffeine also disrupts sleep, with one study estimating children who drink caffeinated beverages sleep 15 minutes less every night [119]. Apart from the effects of reduced sleep, caffeine can contribute to poor cognitive functioning in other ways. Rather than making us more alert, habitually using caffeine tends to suppress cognitive function, which only returns to baseline levels after ingestion of caffeine and then, of course, only temporarily [131]. It is the only psychoactive drug legally available to children, and their consumption of it is very widespread. A small 500 ml bottle of cola dispensed by a vending machine possesses the same amount of caffeine as a cup of coffee. Many children commonly experience caffeine withdrawal [132]. A study of children aged 9-10 years old who habitually drunk no more than 2 cans a day showed decreased alertness relative to low users [133]. As with adult studies of caffeine, alertness of these children only rose to baseline levels after receiving more caffeine. It would appear that, rather than making children fizzy for their lessons, the cola "caffeine fix" provides only a momentary return to the state of alertness offered by a caffeine-free lifestyle. A clinical review of the evidence confirmed clear links between caffeine and day time sleepiness, for both adults and children, and concluded that these effects are greatly underestimated by the general population and physicians[134]. Caffeine may influence student achievement directly via its suppression of cognitive function, but caffeine's disruption of night-time sleep can also induce tiredness and, as described above, disrupt memory consolidation.

Water

It is also true that even small amounts of dehydration can reduce our cognitive ability. There are very few studies investigating the effects of dehydration on children, but these few, together with adult studies [135], confirm the deleterious effect of even mild dehydration on the ability to think. However, a recent adult study has shown that drinking water when not thirsty can also diminish cognitive ability[136] and, as with extreme dehydration, drinking too much water can also be dangerous, resulting in water intoxication and even death [137]. There are studies showing children do not always drink recommended levels of fluid[138] but, apart from circumstances involving unusual heat or exercise, there is little evidence to suggest that normally functioning children are generally prone to voluntary dehydration. The two studies available relate to classrooms in the Dead Sea area[139] (the lowest point on the planet and notoriously hot) and in Sicily, where researchers describe the children as "living in a hot climate"[140]. Evidence for improvements in cognitive function after providing supplementary water to students is reported in some studies, although the design of these studies detracts from their findings. For example, a report from the UK claims that an hour after 6 to7 year old children were provided with a 500 ml bottle of water, effects were observed in terms of thirst and happiness ratings, visual attention and visual search[141], but the sample was small (N=11 in the test group) and did not control for the effects on cognitive function of positive affect [142] which can be induced by researchers through the giving of small gifts. Another study claims similar effects but does not appear to correct for multiple testing of the same data set[143]. Against such claims must be balanced results showing some reduced cognitive function after supplementary water [136] even when participants are mildly dehydrated[140]. The drinking of water is often promoted as a way to improve learning, with some schools enthusiastic in their promotion of water as a means to raise attainment. In a BBC report headed "Water improves test results", the headteacher of a school in Edinburgh explains "the human brain uses water in its

transmission of neural messages ……if children are regularly hydrated their brains are better physically equipped to learn."[144]. Of course, all children require easy access to good quality water. However, studies assessing the effects of providing supplementary water provide a weak basis for hypothesising educational benefits for UK schools.

Educational application

Would teenagers achieve more if they were allowed to sleep later?

- Later starts in schools that begin the day early have been shown to improve attendance and engagement in lessons

In some countries, there is evidence that a double-shift school schedule seems to benefit the fulfilment of teenage sleep needs. There is a lack of reported interventions of the effects of school starting late in the UK, although two notable studies report improvements in the US. In one study, shifting the start of school from 7.15 am to 8.40 am improved attendance and reduced numbers falling asleep in a cohort of primary and secondary school students[145]. In a more recent study, moving start times from 8.00 am to 8.30 am for 14-18 year olds improved self-reported motivation and attendance[146]. However, it should be noted that the new start times trialled in these studies are similar to, and frequently earlier, than many UK schools begin their day.

Can academic achievement benefit from lifestyle education about neurobiological processes?

- Simply providing information to teenagers about sleep, including its chronobiology, raises awareness but fails to change habits.
- Great involvement of such interventions with homelife and culture has shown, tentatively, more promise

Rather than change the school day, an alternative type of intervention involves educating adolescent students about the chronobiology of their sleep, in the hope this will empower and encourage students to make wiser decisions about night-time sleep habits. Such interventions can successfully impart knowledge about sleep with good retention of the knowledge, but they appear unsuccessful in changing sleep habits[147-152]. This has brought about calls for improved research efforts that focus upon, amongst other potential factors, how to create a cultural change in the importance assigned to sleep by adolescents[153]. A more intense intervention involving a wall poster, fridge magnets, progress chart and fortnightly telephone calls has, with some caution, reported more positive results[154].

It has also been suggested that interventions concerned with sleep might benefit from considering the interrelation of sleep circadian rhythms with those more closely associated with nutritional issues. Specifically, receiving breakfast at school might delay the timing of nutritional intake to a later circadian phase when both appetite and the intestinal systems are activated, making it possible to ingest larger and perhaps more nutritional meals. This may contribute to the improved school functioning that is sometimes observed when students are enrolled on school breakfast programs[155]. The factors and processes behind such improvements, where they are observed, are themselves the subject of nascent research[156].

While the eating (or not) of breakfast remains the chief nutritional issue influencing children's cognitive function[157,158], it has been suggested that there are specific food products that may improve brain function and, thereby, academic achievement. Omega-3 supplements (e.g. fish oils) are possibly the best known of these products. However, there have now been several studies undertaken on the cognitive effects of taking of such supplements amongst typically developing children and these show disappointing results[159-163].

Genetics

Neurocognitive processes

- Genes have a major influence on educational achievement, suggesting genetics can play an important role in the understanding of individual differences

Generalist genes

It has been argued that DNA has a unique causal status in educational outcomes since, while causal direction between brain function and environment can flow in either direction, variation in DNA sequence is not changed by behaviour, brain biology or our environment[164]. Furthermore, according to Plomin's generalist genes hypothesis, the same genes are responsible for learning abilities and disabilities, and a gene influencing outcomes in one educational subject is likely to influence outcomes in another[165]. Such a hypothesis is supported by the fact that those genes of greatest cognitive influence have very basic neural functions. This suggests their effects in the brain should be widespread both in terms of structure and function. Such genes include the BDNF and COMT(catechol- *O* –methyltransferase) genes, that code proteins influencing nerve growth and the activation of a range of neurotransmitters.

Educational application

Can genetics be usefully applied in educational interventions?

- Some genetic markers already have current practical value in deepening our understanding of the effects of educational interventions

Although we are some years from providing tailored instruction in response to an individual's genetic profile, there are already some genetic markers that might inform interpretations of intervention outcomes. One example of such a marker is the dopamine D4 receptor gene (DRD4 7-repeat). A computer-based early literacy intervention involving 2 to 5 year olds provided evidence that, irrespective of cognitive level, children who carry this variant may be more receptive to the same parental, educational, or environmental influences than those who do not[166]. In other words, behind non-significant or modest overall educational intervention effects, there may be significant and strong effects on a subgroup of susceptible children. This provides quite a different perspective than the present "horses for courses" approach for understanding why children vary in their response to an educational programme. Rather, we may have only susceptible children ('orchids') who are strongly dependent on quality of instruction, and less susceptible children ('dandelions'[167]), who will adapt to most learning environments with less dramatic influence. The influence of this gene as a general environmental mediator is supported further by teenage carriers being disproportionally affected by both the negative and positive effects of parents monitoring their cannabis use[168].

Embodied cognition

Neurocognitive processes

- Neuroscience has helped us understand that our body plays a crucial role in our cognitive processes (embodied cognition)
- Embodied cognition provides a theoretical basis for understanding how actions influence our learning (e.g., the enactment effect)
- Some of our neurons mirror the actions made by others (so-called mirror neurons) and these processes may inform an embodied cognition approach to understanding, for example, how a teacher's actions influence a student's learning

Enactment effect

Theories of embodied (or "grounded" or "situated") cognition suggest we cannot consider those neurocognitive systems involved with educational learning as separate from those involved with action. In addition to behavioural evidence, supporters of embodied cognition increasingly draw on neuroscientific studies when promoting its educational implications [169,170]. Embodied cognition provides a theoretical basis for the well-established enactment effect. This effect is illustrated by better memory of action verbs when they are performed than after they are simply read[171].

Mirror neurons

Brain imaging is beginning to provide unexpected insights into vicarious learning as another example of embodied cognition. When we observe others carrying out actions, some of the same cortical areas are activated as if we are carrying out the actions ourselves[172]. This so-called mirror neuron system (MNS) is thought to mediate imitation-based learning and this capacity of the brain may have evolved as a type of 'mind reading'. Our MNS may not be "innate" but derive, instead, from sensorimotor learning we acquire when observing ourselves and others [173]. Nevertheless, the functioning of the MNS provides evidence that our neural representation of others' actions is influenced by our own embodied experience of those actions [174,175].

Educational application

Can an embodied cognition perspective predict and theorise effects that are useful for education?

- Embodied cognition helps explains the well-established enactment effect but may also provide insight into how students learn from the actions of their teachers

The enactment effect has been successfully applied in studies of foreign language learning[176,177]. For example, a within-subjects experimental study of 20 adult German speakers learning abstract Italian words showed better memory for words encoded with gestures and improved frequency of use in transfer tasks, suggesting enhanced accessibility in memory[178]. Increased memory for observing a teacher using gesture cannot be explained by the enactment effect, but such effects have been shown for adults and children[179] and could be predicted by an embodied cognition perspective. Embodied concepts may have further applications. For example, when a teacher imitated students' behaviour during interactions, students later reported significantly higher perceptions of rapport, more confidence and satisfaction about learning outcomes and scored significantly higher in a subsequent quiz [180]. A range of different ways in which gestures can embody mathematical concepts has been theorised[181],

although experimental work exploring testable hypotheses remains sparse in this area. The interrelationship between fingers and mathematics has already been cited (see Mathematics) and this is one example of embodied cognition that has given rise to interventions. An extension of this approach has led to the use of dance-mats for children to explore number lines with their whole body. In a small study (N=22), kindergarten children were asked to compare magnitudes using a full-body spatial movement on a digital dance mat[182]. Spatial training was demonstrated as more effective than non-spatial training in enhancing children's performance on a number line estimation task and on a subtest of a standardized mathematical assessment.

“Brain training” of executive function

Neurocognitive processes

- Many studies exist demonstrating that the executive functions of adults and children can be trained, and there is clear potential for such training to contribute to education
- However, there have been difficulties in replicating successful outcomes and there is debate regarding how far transfer can be achieved to tasks dissimilar to those used in training.

The origins and meaning of “brain training”

Brain training has been broadly defined in a recent review as “the engagement in a specific programme or activity that aims to enhance a cognitive skill or general cognitive ability as a result of repetition over a circumscribed timeframe”[183]. Given the extent to which they predict educational outcomes, there is particular interest in the training of executive functions (EF), i.e. those control functions required to concentrate, think, and control initial impulses that might be ill-advised. These include functions such as reasoning, working memory and inhibition control.

Brain training has its roots in neuropsychological attention training of those suffering brain damage. Some success in rehabilitating the cognitive functions of this population resulted in efforts to apply similar techniques for children with impaired control of their impulses. There is, for example, evidence that attention training can improve attentional capacity amongst autistic children[184] and the attentive abilities and academic efficiency of children with ADHD[185]. In turn, this led to research efforts focused on the supplementation of normally-developing cognitive function with training, often accompanied by neuroimaging studies of associated changes in brain function.

Transfer – a critical test for brain training

At the present time, there is intense activity in attempts to develop and evaluate computer-based brain training, but claims are highly contested. While few commercial brain-training games have been convincingly evaluated, many research studies exist that suggest reasoning skills and working memory are amenable to computer-based training. For example, “Cogmed” computerized training studies have shown transfer of improved working memory to untrained tasks [186,187]. Some evidence suggests working memory training can result in long term (6 month) retention of skills and transfer to gains in maths amongst 10 to 11 year-olds[188,189]. This test of transfer is critical for brain training enthusiasts, since the ultimate goal is to generate improvements not just on the task used to train the cognitive function, but benefits which transfer generally to untrained tasks that should rely on the cognitive function. However, a recent meta-analysis joins other voices[190] in pointing out methodological flaws, concluding there is a lack of convincing evidence for anything other than short-term, specific training effects that do not generalise[191]. Sceptics have also pointed to the failure of studies [192] attempting to use improved and extended experimental design to replicate the results of other researchers[193]. Although transfer often extends beyond the training task, it appears restricted to types of task that are similar to the training task (i.e. “near” transfer effects). For example, training on reasoning improves performance on untrained reasoning tasks but does not improve processing speed [194]. In short, there is an increasing number of published positive results in high-quality peer-reviewed journals - yet all have found themselves vulnerable, to greater or lesser extent, to critical review. Studies of cognitive inhibition or self-regulation training tasks are far fewer, focusing chiefly on young children and limited to near transfer, for example the study by Dowsett and Livesey looking at inhibitory controle.g. [195], although far transfer to other executive tasks and fluid intelligence are reported for 9 year-olds, younger and older adults from rehearsing a task-switching challenge[196,197]. An understanding of the factors mediating laboratory-based outcomes is still emergent, and particular scrutiny of methodological issues may be required in future studies aimed at developing such understanding.

Non-technological brain training

Training of EF using more physical activities that do not require technology, such as games with resources found in typical pre-school settings, have also reported some promising results[198]. Two school curricula have also been reported as having positive effects on EF in the early years: Montessouri[199] and Tools of the Mind[200]. These share a number of features in common, including an emphasis on rehearsing EF and reducing stress[201]. A meticulously executed randomisedcontrolled trial of "Tools of the Mind" is currently being carried out by the Peabody Research Institute. The evaluation has not yet been published, but a recent presentation by the PRI suggests disappointing results[202].

Educational application

Can cognitive training be used to enhance academic outcomes?

- There is a dearth of good quality investigations of the effects of training executive function on academic achievement.

Computer-based cognitive training that transfers to academic achievement remains a strong possibility but, there is little evidence for academic impact at the moment. A commercial game called "Dr Kawashima's Brain Training Game" has recently been reported as improving executive functions, working memory, and processing speed in young adults[203]. In a classroom-based study, positive effects on mathematics were reported after 10-11 year olds played this game for 20 minutes a day for 10 weeks. However, this classroom study was roundly criticised for its flaws in design and statistical analysis/reporting[204] and it should be noted that the game itself rehearses the player's numerical skills directly.

It has been suggested that, while exercise has itself been linked to improvements in EF (see Exercise above), activities combining exercise with mental development may be a more effective alternative to computer-based training[205]. It has been reported that a 3 month programme of Tae Kwon Do with primary school children preceded improvements in cognitive self-regulation, affective self-regulation, prosocial behavior, classroom conduct, and performance on a mental math test, all relative to a control group enrolled on a different exercise programme[206].

Spaced learning

Neurocognitive processes

- The spacing of learning sessions improves outcomes relative to massing sessions together
- A neuroimaging study suggests the effect is due to enhanced maintenance rehearsal in spaced, relative to massed, presentations of learning material

Evidence for the effect - and its candidate processes

Since the spacing effect was first discovered by Ebinghaus in 1885, research has consistently shown that learning performance improves if multiple study sessions are separated in time (or "spaced") rather than massed together. The effect occurs for adults[207], pre-schoolers and infants[208-210], and primary[210,211] and secondary school children [212]. A brain imaging study suggests the spacing effect in verbal learning is due to enhanced maintenance rehearsal (i.e. additional thinking about the material) in spaced, relative to massed presentations[213].

Educational application

How should the spacing effect be applied in education?

- The spacing effect on memorisation is well-established, and the benefits of spacing may extend to deeper types of learning
- Educational application of spaced learning has suffered from approaches that are not informed by current research

Although the vast majority of studies have focused on memory, the spacing effect may extend to other types of learning. In a study of undergraduates learning second language syntax, a 14-day spacing gap was shown to produce superior scores to a 3-day gap on a test given 60 days later[214]. An early study with secondary school biology students showed improved ability to describe and illustrate the biological process of mitosis[215]. Spaced learning effects have also been found in a classroom-based study of 5 year-olds' reading skills[216] and in a randomised controlled trial of surgery training amongst medical students (on measures such as time, number of hand movements, and expert global ratings)[217]. The spacing of learning sessions has also been found to advantage the learning of a mathematical procedure by undergraduates. Here, students were asked to calculate the number of unique orderings (or permutations) of a letter sequence with at least one repeated letter (e.g. sequence abbbcc has 60 permutations, including abbcbc, abcbcb, bbacbc, etc.) [218,219]. Like most mathematics, there was an element of memory, since the problem requires recall of a series of steps. Otherwise, however, the task was moderately abstract and students saw each problem no more than once, ensuring solutions could not simply be memorised.

Although generally overlooked in schools[220], spaced learning has received UK media attention in the last decade though its adoption as a key teaching concept at Monkseaton school[221-223]. Here, the headteacher adopted it after reading the work of Fields[224] about "discoveries in the chemical and genetic processes of creating memory" in Scientific American[221] and drew on this work to settle on 10 minutes as the recommended optimum duration of the space between learning sessions. However, rather than converging on one optimal amount of time for the spacing, recent work shows the optimal gap increases as the time to test also increases. This study indicates the penalty for a too-short gap is far greater than the penalty for a too-long gap[225,226].

A brain imaging study[227] suggested spaced learning operates via enhanced maintenance rehearsal and this, raises the issue of how different activities undertaken in the spacing period might influence outcomes by interacting with this rehearsal process. In the practices at Monkseaton school, students sometimes undertook exercise between learning sessions, which is known to increases the efficiency of neural networks and can improve memory and cognitive functions important for learning. Undertaking other learning experiences in the spacing period might interfere positively or negatively with ongoing maintenance rehearsal of the previous learning. Indeed, as reviewed below, there is evidence that *interleaving* learning in certain ways can improve efficient encoding. Understanding of the underlying neural and cognitive processes may help predict, and so identify, optimal configurations of the various spacing/interleaving options available.

Interleaving

Neurocognitive processes

- Interleaving topics can increase the efficiency with which learned material is remembered and also the effectiveness of some other learning processes
- Interleaving may operate by reducing the suppression of neural activity in memory regions that occurs when similar stimuli are repeatedly presented

Evidence for the effect - and its candidate processes

A typical interleaving strategy might involve each lesson being followed by practice problems drawn from many previous lessons, such that that no two problems of the same kind appear consecutively. So, at the end of a lesson about electricity, a teacher might alternate electricity questions with questions about heat, light and motion (if these were taught in the previous lessons).The resulting improvement in the efficiency with which learning is achieved is called the interleaving effect. Knowledge of the effect has its roots in observations of motor learning[228-231], but the underlying processes remain poorly understood.

Some psychological research has suggested a “discriminative-contrast” hypothesis to explain interleaving. That is, it can help highlight category differences and so enhance inductive learning [232,233]. This would suggest interleaving would be more suitable for inductive learning than a spacing strategy. Neuroimaging studies, however, suggest an automaticity in the processes involved (i.e. that they are not within conscious control) and that interleaving reduces the suppression of neural activity in memory regions that occurs when similar stimuli are repeatedly presented[234,235]. This predicts advantage at a perceptual level and such hypotheses require further testing in order to fully unravel the underlying processes and help guide efforts towards an optimal pedagogic approach.

Educational application

Can the interleaving effect be applied in education?

- Though considerably less established than the spacing effect, a small number of studies reveal educational potential

There are fewer studies of interleaving in education and they have arisen relatively recently, compared with spaced learning. One example involves a study of 10-12 year olds learning fractions[236]. Here, results showed an advantage of learning effectiveness and efficiency for interleaving task types (with representations blocked together) over blocking representations (with task types blocked together). In another study involving adults, numerous paintings by each of 12 artists with similar styles were viewed, with either the paintings blocked by artist or interleaved. Interleaving was shown to improve the ability of learners to identify the creator of previously unseen paintings, and also improved their ability to discriminate between the different kinds of styles[237].

Further evidence for a difference in the processes underlying spacing and interleaving comes from a recent study involving 10 to11 year old children learning to solve mathematical problems[238]. Here, interleaving impaired performance during the practice session but boosted test performance on a subsequent test, prompting the suggestion that interleaving encourages the pairing of each kind of task with its appropriate procedure.

Testing

Neurocognitive processes

- It has been established, in a range of contexts, that testing can improve memory for learned material and may also improve some other types of learning
- Currently, there are several candidate neural processes for the testing effect – all of which may contribute to outcomes

Evidence for the effect - and its candidate processes

Many laboratory studies have established that being tested on studied material improves remembering it on a final test, and more so than simply rereading the material for reviews, see [239,240],there is also evidence that it slows the rate of forgetting in the longer term[241]. The effect has been confirmed as robust for a wide range of material and contexts[242], including computer-mediated scientific explanations with adults[243], multiple choice questions during undergraduate lectures[244], science quizzes with 13-14 year olds[245] and shown as superior to concept mapping for undergraduate scientists[246]. Rather than simply being due to heightened attention, behavioural studies have suggested it may arise from rehearsing retrieval[247], yet testing can also improve memory for associated material that is not tested [248,249]. It can improve performance on applying the learned information to make inferences[246,250] and promotes meaningful conceptual links[251], although some evidence suggests it may not apply to the retention of problem-solving skills [252]. Ongoing neuroimaging studies are now identifying candidate processes that may underpin the testing effect, and these insights may contribute to its optimal application. Suggested explanations include: testing increases attention during restudy, which may lead to enhanced encoding, and subsequently better performance[253], the possible role of reward in testing (see also Learning Games), different processes of semantic processing being involved during retrieval and restudying[254] and a decreased need for executive processing along with a strengthening of semantic representations[255].

Educational application

Can our understanding of the testing effect be applied in new ways?

- Insight from neuroscience and psychology, particularly when combined with technology, may help improve application of the testing effect in today's classroom.

The digital mediation of students' and teachers' communication in the "connected" classroom raises new opportunities for applying a scientific understanding of learning in education. For example, systems originally designed for audience response can allow all students to respond to a teacher's questions, and view the analysed outcome of their responses on the whiteboard. In studies of undergraduates, use of the so-called "clicker technique" has been shown to reduce teaching time [256] and improve learning outcomes [244,257-259]. Recent work appropriately links the potential benefits of using clickers with the "test effect"[260]. The case of the clicker technique is one example where a more scientific understanding may help develop improved practice and outcomes in the school classroom, by combining behavioural evidence for its effectiveness[261] with neural evidence of how the brain's response to reward influences learning (see Learning Games below) and the influence of contextual factors such as peer presence [262] on this response.

Learning games

Neurocognitive processes

- Popular games provide rapid schedules of uncertain reward that stimulate the brain's reward system
- The brain's reward response can positively influence the rate at which we learn
- Beyond just the magnitude of the reward, a range of contextual factors influence this reward response

Dopamine, reward and engagement for learning

A lack of established understanding about how games engage their players, and how these processes relate to learning, has hampered attempts to combine learning and gaming. These difficulties have led some commentators to write the ''only consensus in this whirlwind of activity seems to be that educational games are something of a failure'' [263]. This activity may be aided by findings from cognitive neuroscience which provide insight into the motivating role of uncertain reward in games, including educational games. Uptake of dopamine in the midbrain regions is closely related to many of our motivations and chance-mediated uncertainty of outcome causing dopamine to "ramp up" until the outcome is known. This is thought to be why uncertain rewards are more stimulating than either wholly predictable or unexpected rewards, providing an explanation for the attractiveness of games. While reward response peaks at 50% certainty in games, students prefer much higher levels of certainty in school tasks[264], presumably due to social- and self-esteem factors. Research in cognitive neuroscience has established that declarative memory formation is strongly related to this response of the brain to reward[265]. That implies that the neural response to reward should be of educational interest, not simply in terms of motivating us and making lessons more rewarding, but because reward appear to have more direct effects on the rate at which we learn. An array of neuroimaging studies provides insight into this neural response and how team-based competitive learning games can support our learning. In brief, our reward response is i) egocentric so that we respond to our competitor's loss as our gain[266] ii) can become heightened in the presence of peers[262] and iii) increases with reward size but it is also depends on context, such that it is scaled with respect to the maximum reward available in a particular context[267] (suggesting, for example, that the absolute value of the winner's prize may not be an issue in terms of engagement). However, these neural processes are still the subject of scientific research. For example, the exact mechanism by which reward response enhances declarative memory formation is still to be determined. Additionally, while it is known that response is mediated by the many factors above and more besides, their relative significance for education and their interaction remains the subject of neuroscientific, psychological and educational research.

Educational application

Can insights help design and implement more engaging and effective learning games?

- Efforts to develop and implement learning games are already drawing on concepts about brain and mind, although there have been no rigidly-controlled comparisons of their effectiveness compared with other teaching approaches

As well as providing insight into scientific curiosity[268], understanding about neural concepts such as reward uncertainty can provide a scientific basis for designing learning games[269]. In short, such findings suggest a games-based approach to learning that increases emotional/motivational response by disrupting the learning-reward relationship with chance, in order to encourage greater reward activity without endangering self- and social esteem. This approach, relative consistent reward, was preferred by children in a study of 10 to11 year olds and has been shown to increase the emotional

response to learning in a study of adults [270]. A recent laboratory study of IT undergraduates learning about database concepts has confirmed that reward uncertainty can improve motivation and learning. Importantly, the study demonstrated the potential of the approach with what the authors call “deep learning” (in terms of meaningful understanding), rather than just factual recall [271].

Such concepts have formed the basis of a freely available app for teachers that allows all students to simultaneously respond via their mobile phones (this is a cheaper and more flexible option to using the clickers discussed previously)[272]. Here, researchers have worked to develop and combine the scientific understanding with practitioner expertise. They have developed a pedagogy for using uncertain reward in response to measurements of classroom learning outcomes[273], but no large-scale classroom trials of this pedagogy have been initiated. No data exists regarding the long-term use of this teaching-through-games strategy.

Creativity

Neurocognitive processes

- There is a burgeoning field of creative neurocognition that has provided insights into individual differences in creativity and creativity-fostering strategies.

Creativity is an important quality of thought that is greatly prized by many types of enterprise, from science, to business and the arts. Advances in the expanding field of creative neurocognition confirm that creativity involves a daunting range of complex processes[274]. These advances support a model of creativity based on moving between a generative process facilitating the production of novel ideas and an evaluative process enabling the assessment of their appropriateness[275]. While evaluation is considered to require narrowly-focused critical attention, the generation of ideas appears to benefit from a broader focus of attention. A study using EEG has shown how individual differences can be explained in terms of an individual's resting state of attention (i.e. whether they are more broadly or narrowly focused)[276]. fMRI techniques have also been used to validate and explore strategies considered to foster creativity. One of these suggests that sharing ideas with others can boost our creative output by reducing our need to suppress our own automatic associations[277]. A study investigating the effect of incorporating unrelated stimulus into a product suggests this strategy boosts creativity by automatically increasing neural function in regions related to creative effort and the making of meaningful connections[278].

Educational application

Can an understanding of creative cognition support the fostering of creativity in the classroom?

- Neuroscience is providing insights into strategies found to foster creativity in the classroom, but no attempt has been made to evaluate such strategies when their design and/or implementation have been informed by these insights.

An attempt has been made to develop strategies for drama teaching that are informed by the neuroscience of creativity. However, there have been few attempts to subject neuroscientifically-informed strategies to classroom-based trials (although see Neurofeedback below). For example, classroom studies exist that report positive results on creativity for strategies that broaden the attention of young children[279], and a similar type of strategy for broadening attention has been investigated with adults using fMRI[278]. However, no field trials have taken place of such strategies when their design and/or implementation has been influenced by current neuroscientific understanding.

Personalisation

Neurocognitive processes

- Responding to learner preference does not automatically lead to improved learning
- Cognitive neuroscience is providing insight into individual differences likely to influence learning outcomes

Neural perspectives on individual differences

Insights from neuroscience regarding individual differences may help select teaching approaches for different students. Examples of neuroimaging studies that might contribute in this way include examinations of gender difference in response to games[280] and age-related difference in response to different types of feedback[281]. At the recent EARLI SIG conference on neuroscience and education, Lee et al. [282] reported adult neural activites related to choice suggesting that choice induces high levels of cognitive engagement and the impact of choice becomes stronger as the interest for topics increases.

Educational application

Is there evidence of personalisation improving outcomes in the classroom?

- It is known that providing choice can improve motivation, but little attempt has been made to inform such personalisation with insights from authentic neuroscience.

The identification of learner preference does not always guarantee a learning advantage. There is, for example, a distinct lack of evidence for teaching to learning styles (e.g. see lack of evidence for teaching to learning styles[283]). However, it is established that providing the freedom to make some choices can, in itself, provide motivation [284]. There is a dearth of evaluated attempts to apply authentic neurocognitive understanding of individual differences (in terms of gender, age group, etc) to the personalisation of teaching and learning approaches or resources.

Neurofeedback

Neurocognitive processes

- Neurofeedback enables individuals to alter their mind state by monitoring their own brain activity

Neurofeedback using EEG

Neurofeedback is the monitoring of one's own brain activity with a view to influencing it. Recent work has involved participants increasing the ratio of theta to alpha waves using auditory feedback with their eyes closed[285]. This protocol was originally designed to induce hypnogogia, a state historically associated with creativity.

Educational application

How can neurofeedback be applied in the classroom and to improve which outcomes?

- EEG feedback has been demonstrated as beneficial in studies of creative performance
- The technology to provide neurofeedback in classrooms is becoming more portable and cheaper, but its value in these contexts remains unexplored.

A study investigating EEG neurofeedback concluded that it produced improvements in the performance ability of music students not found with other neurofeedback training protocols or in alternative interventions. In this study, conservatoire students received training using neurofeedback and improvements in their musical performance were highly correlated with their ability to progressively influence neural signals associated with attention and relaxation[286,287]. Similar results have been found for dancers[288]. The underlying neural mechanisms are the subject of active research, with evidence that self-induced changes in neural rhythms can produce detectable changes in neural function that last 20 minutes or more[289]. This supports the potential effectiveness of neurofeedback as tool for mediating the plasticity of the brain, but many questions remain about the processes involved and how these are best exploited for educational benefit. However, recently an initial study with 11 year-olds showed improved musical performance, creative improvisation and measures of attention after 10 sessions of neurofeedback of 30 minutes duration[290]. A study with adults has also shown improvements in mental rotation skills[291], which are thought to contribute to mathematical and scientific ability (see Mathematics above).

Neurofeedback may also be shared with the teacher. Alongside an understanding of technology use by children, Battro's review of the teaching brain identifies the use of wearable brain image technologies in classrooms as the second biggest new challenge for the field of Mind, Brain, and Education [292]. Whereas studies such as above used high quality multiple electrode EEG apparatus, simple EEG devices retail for around £50. Manufacturers of such a device claim it "safely measures brainwave signals and monitors the attention levels of students as they interact with math, memory and pattern recognition applications"[293]. Although these devices are primitive relative to those more often used in research environments, there are a number of ways in which even a noisy indicator of attention level might impact positively on learning. Such impacts might arise from the learner's self-monitoring of their cognitive state, or by passing information to the teacher regarding individual or global levels of attention in a classroom. A recent study used such a device to inform an adaptive artificial agent designed to recapture diminished attention using verbal and nonverbal cues, significantly improving student recall of the learning content[294].

Transcranial electrical stimulation (TES)

Neurocognitive processes

- Although a full scientific understanding of the effect remains elusive, applying small electric currents or signals to the scalp TES can benefit some cognitive functions and learning processes

History and recent evidence

Experiments with the effects of small currents to the scalp have a history extending back to beginning of the 19th century[295]. Recently, however, this approach has gained considerable more credibility as scientists have begun identifying the size, type and location of current that is optimal for demonstrating different effects. These effects are attributed to a shift in the resting potential of cortical neurons by the weak direct currents that are applied[296]. In a recent study, the military potential of TES was assessed using a virtual reality training game used to familiarise military personnel with a middle-eastern threat environment before deployment. Adult volunteers who received 2 milliamps to the scalp showed twice as much improvement in learning and performance as those receiving one-twentieth the amount of current[297].

Educational application

Is TES ready to be applied in classroom interventions?

- Positive effects are now being reported for learning tasks relevant to education, but remaining questions regarding risk and ethics makes TES classroom interventions unlikely in the near future

A few other studies of TES have recently emerged that are focused on more conventional educational aims. In one of these, three times as many adult participants achieved success in an insight problem solving task using TES[298]. In another adult study, a 6-day course of training adults with TES produced improvement in numerical abilities that were present 6 months later[299], and a similar study also showed lasting improvements 6 months later coupled with more efficient neurovascular coupling at the treated region. The simplicity of the treatment for the size and duration of the effects appears remarkable, but the risks[300] and ethical implications[301] are still to be fully explored.

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Appendix 1: Basic Neuroanatomy and Terms

Neurons

The adult brain contains about 90 billion brain cells – or *neurons*. Each neuron, such as shown in Figure A1, consists of a *cell body*, from which are connected *dendrites* and an *axon.*

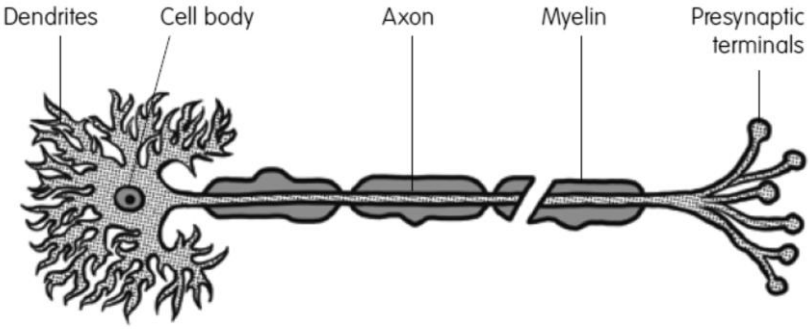


Figure A1 Each neuron in the brain consists of a cell body, from which are connected dendrites and an axon. The axon ends in presynaptic terminals that form connections (synapses) with the dendrites of other neurons (see Figure A2).

The *presynaptic terminals* at the end of the axon make contact with the dendrites of other neurons and allow connections, or *synapses*, to form between neurons. In this way, complex neural networks can be created. A simple network is shown in Figure A2.

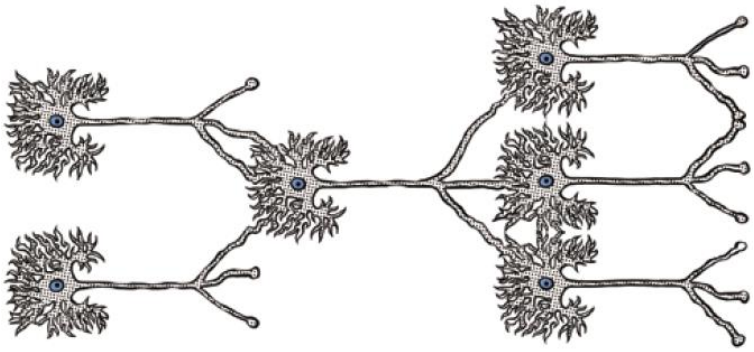


Figure A2 Neurons connect together to form networks.

Within such networks, signals can flow down the axons of one neuron and cross the synapse to other neurons, allowing neurons to communicate with each other. The signal passing down the axon is electric, and its progress is hastened by insulation around the axon known as *myelin.* However, the

process that allows the signal to pass through from the synaptic terminals to the dendrites of the next neuron is more chemical than electrical. This process involves transmission across the synapse of special substances known as *neurotransmitters* (e.g. dopamine) that pass across the gap to be received by *receptors* on the other side.

Forebrain, midbrain and hindbrain

Our brains, like those of other vertebrates, consist of the three main parts (*forebrain, midbrain* and *hindbrain*) shown in Figure A3. The hindbrain includes structures regulating bodily functions such as sleep and blood flow. It also contains a cauliflower-like structure at the back of the brain called the *cerebellum*, and this is involved in many cognitive processes that require careful timing such as language, music and movement. The midbrain includes structures that relay sensory and movement information. There are also important structures in the midbrain that help us respond to reward. In humans, the forebrain has evolved to be largest part of the human brain and this includes the *cortex.* The regions most associated with higher-level thought processes exist close to the wrinkly surface of the cortex. This part of the brain is often described in terms of two (so-called cortical) hemispheres, left and right, joined together by a mass of fibers known as the *corpus callosum.*

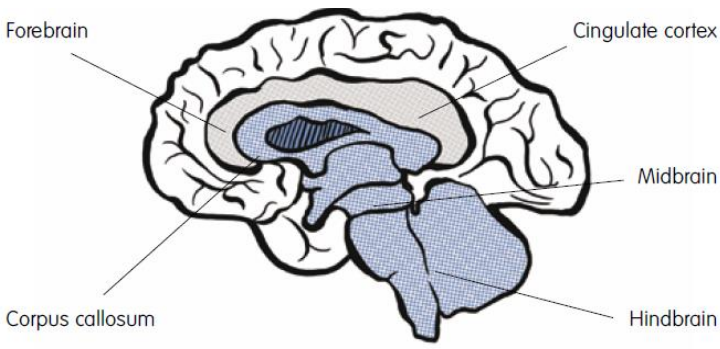


Figure A3: Section through the brain showing division into forebrain, midbrain and hindbrain regions. This diagram also shows the position of the corpus callosum which connects hemispheres, and the cingulate cortex.

The lobes of the brain

The cortex can be further divided into four *lobes:* the *frontal, parietal, occipital* and *temporal* shown in Figure A4. The cortical surface (sometimes referred to as the neocortex) is more wrinkled in humans than any other species, a characteristic thought to reflect our greater reliance upon complex social behavior. Each type of lobe has been associated with a different set of cognitive functions. The frontal

lobes (left and right) may, perhaps, be of particular interest to teachers because, as well as movement, they support many different aspects of reasoning. This is also the home of the dorsolateral prefrontal cortex (DLPFC), which is an important region for working memory – our ability to hold several pieces of information in our attention in the same instant. The temporal lobe has much to do with memory, as well as auditory skills. The parietal lobes are heavily involved in integrating information from different sources, and they include regions linked to some types of mathematical skill. The occipital lobes are critical regions for visual processing. However, no one part of the brain (or hemisphere) is dedicated to, or solely responsible for, any one type of thinking process. The fact that some types of cognitive function, more than others, can be associated with particular regions in the brain is sometimes misinterpreted as implying that the different things we do in a day can be neatly mapped onto different parts of the brain – with a bit for creativity, math, music etc. Any everyday task recruits a large and broadly distributed set of neural networks that communicate with each other in a complex fashion. So, different brain regions do support different cognitive functions, but 'real world' thinking and actions recruit processes distributed across the brain.

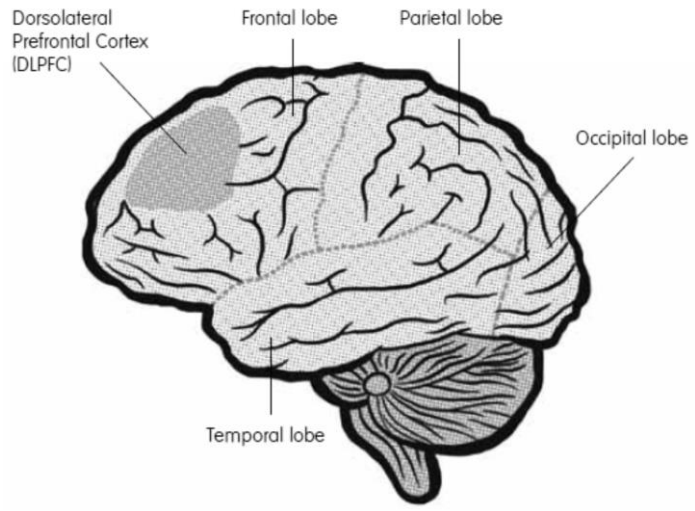


Figure A4: Each cortical hemisphere is divided into four lobes. Also indicated is the region referred to as the dorsolateral prefrontal cortex (DLPFC).

The evolutionary pressure to maximise cortical area has resulted in some of our cortex existing well below the outer surface. One notable example of this is the *cingulate cortex* (see Figure A3). The *anterior* (or forward) part of the cingulate cortex becomes active when we engage with a wide variety of tasks, and appears to have a significant role in how and where we allocate our attention.

Subcortical structures

Journeying deeper inside each of the temporal lobes, we encounter the *hippocampus* – a part of the brain critical to consolidating new memories, and the *amygdala* which plays an important role in our emotional responses (See Figure A5). The closeness of these two structures (each represented twice, ie in both left and right hemispheres) is no coincidence, with the connectivity between them supporting

the formation of emotional memories. These also belong to a set of structures collectively called the **mesolimbic** pathway, which is of particular interest in understanding our response to reward, and that can influence our attention and learning. This is one of the dopaminergic pathways in the brain, involving movement of the neurotransmitter dopamine from one region to another. In the mesolimbic system, dopamine flows from the midbrain region to parts of the frontal cortex, the hippocampus, amygdala and also into a region called the **ventral striatum** (ventral meaning lower) to a small pea-sized dense collection of neurons called the **nucleus accumbens** (again, one in the left and one in the right hemisphere). Dopamine activity in the nucleus accumbens appears central to our motivation to approach many different types of reward.

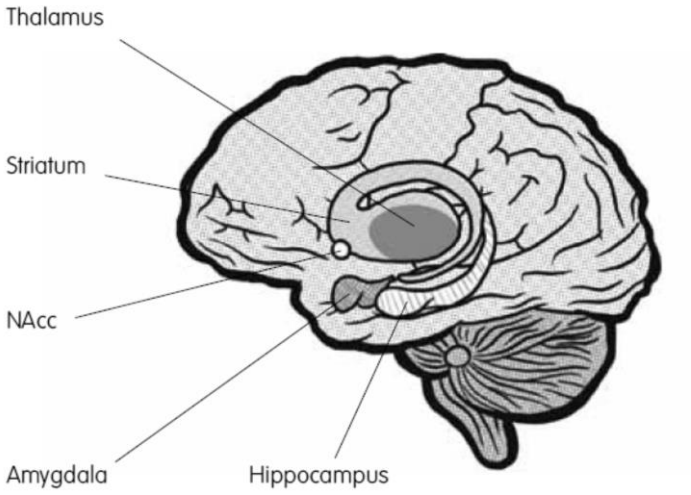


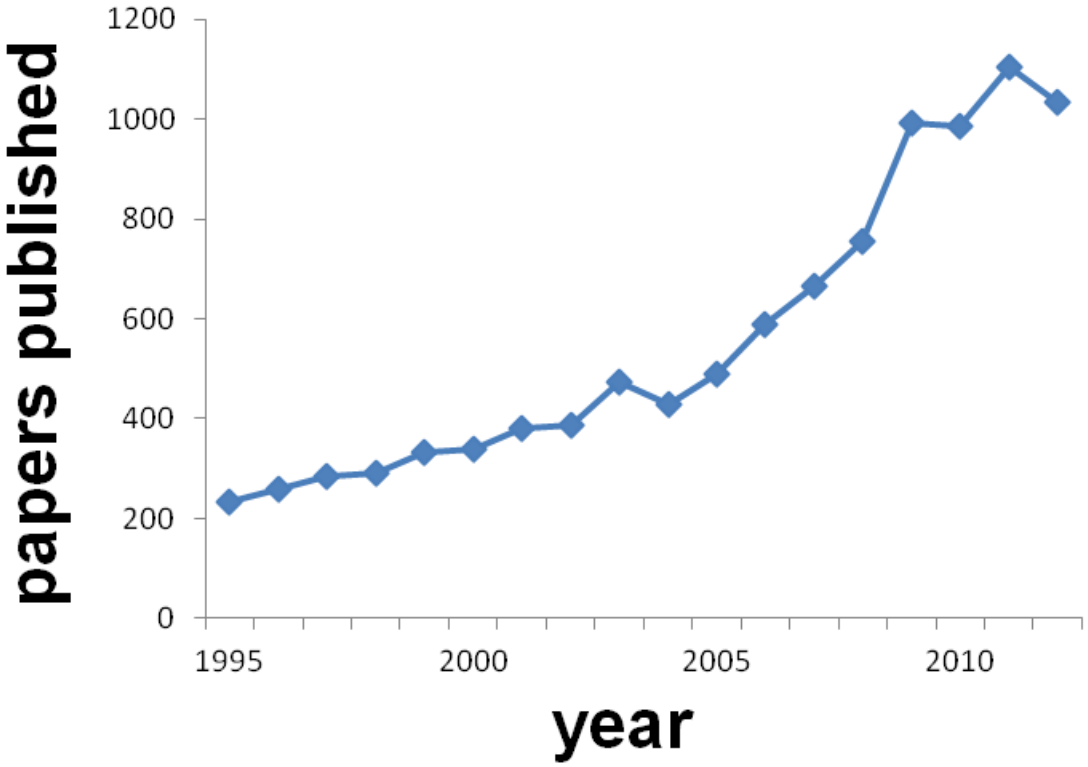
Figure A5: Some important sub-cortical (below the cortex) structures include the thalamus, and also showing the left hemisphere structures of the hippocampus, amygdala and nucleus accumbens (or NAcc, in the ventral striatum).

Appendix 2: Acronyms

ADHD	Attention Deficit Hyperactivity disorder
BDNF	Brain-Derived Neurotrophic Factor
EARLI SIG	European Association for Research on Learning and Instruction Special Interest Group (dedicated to neuroscience and education)
EEG	ElectroEncephaloGraphy
EF	Executive Function
fMRI	functional Magnetic Resonance Imaging
MNS	Mirror Neuron System
STEM	science technology engineering and mathematics
tDCS	transcranial Direct Current Stimulation

Appendix 3: Increase in Academic Publications linking Neuroscience and Education

Numbers of papers per year identified by Web of Knowledge in response to the search term: "(neuroscience OR brain) and education". It should be noted that many of these articles s are beyond the scope of the present document (including, for example, rehabilitation programmes for brain trauma). However, the graph illustrates a trend in appreciating the links between neuroscience and education, in the broadest sense, that appears to accelerate around 2005.



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