Neuroscience, learning and technology (14-19)

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This review briefly summarises recent findings from cognitive neuroscience that may be relevant to discussions of learning among learners aged 14-19 years, in order to support the Deep Learning with Technology in 14- to 19-year-old Learners project. Three caveats should be noted:

1. The literature reviewed here is from studies with groups within or close to the age range covered by the project, or with individuals described as adolescent, whose pubertal state is often determined through self-report of physiological development.
2. The 'decade of the brain' in the 1990s generated a wave of unscientific ideas and programmes that are still popular in education. Interpretation of evidence (from the literature and/or the classroom) to support links between neuroscience and education should attend explicitly to the extent and limitations of that evidence. Weisberg et al (2008) recently showed that explanations involving neuroscience have a seductive quality, helping to explain why neuromyths propagate so easily. To help counter some of the neuromyths in circulation, an appendix is included that summarises them.
3. It would be easy to generate new myths in seeking to make links between what we know about the brain and concepts involving educational technology. As the author of Multiple Intelligences theory (see Appendix on Neuromyths) has commented: "I have come to realise that once one releases an idea– 'meme' – into the world, one cannot completely control its behaviour–anymore than one can control those products of our genes we call children." (Gardner 2003). It is worth remembering, then, that most of what we know about the brain comes from functional imaging experiments that average over many subjects, use technology that is still limited in capturing the rapid and detailed changes that characterise brain activity during even simplest tasks, and that involve environments very different from everyday contexts such as classrooms.

About the brain

To support discussion of the findings presented, it is helpful to acquire a few anatomical terms and phrases. Some of those you will encounter in this document are explained here.

The adult brain contains approximately 100 billion brain cells, or neurons. Each neuron (Fig. 1) consists of a cell body, from which are connected dendrites and an axon.

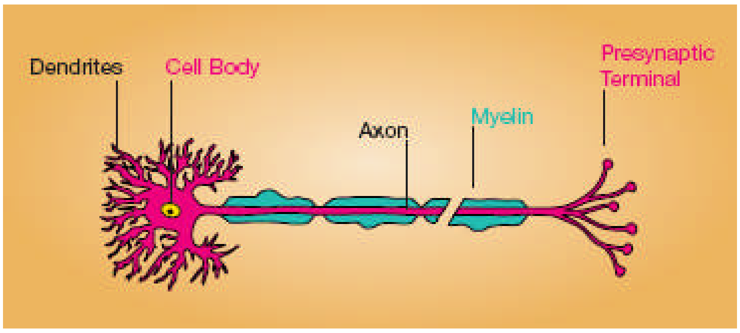

Fig. 1 Each neuron in the brain consists of cell body, from which are connected dendrites and an axon. The axon ends in presynaptic terminals that form connections (synapses) with the dendrites of other neurons.

The 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 (Fig. 2).

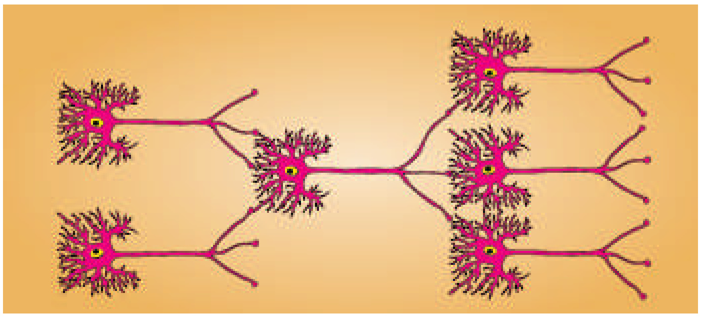

Fig. 2 Neurons connect to form complex networks that facilitate rapid, sophisticated and parallel movements of information.

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 chemical. This process involves transmission across the synaptic gap of special substances known as neurotransmitters.

The brain is often described in terms of two hemispheres, left and right, joined together by a mass of fibres known as the corpus callosum. It can be further divided into four lobes (Fig. 3*)*: the frontal, parietal, occipital and temporal. Each lobe is associated with a different set of cognitive functions. The frontal lobe may be of particular interest to educators due to its involvement with many different aspects of reasoning, as well as movement. The temporal lobe is associated with some aspects of memory, as well as auditory skills. The parietal lobes are heavily involved in integrating information from different sources and have also been associated with some types of mathematical skill. The occipital lobes are critical regions for visual processing.

As we shall see, however, it is not advisable to consider any one part of the brain as solely involved with any one task. Every task recruits a large and broadly distributed set of neural networks that communicate with each other in a complex fashion.

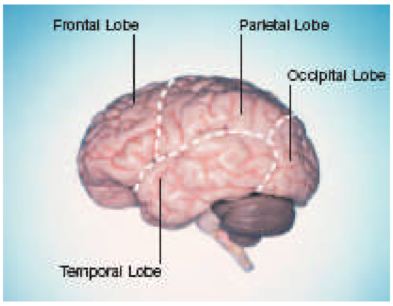

Fig. 3 Each hemisphere of the brain is divided into four lobes.

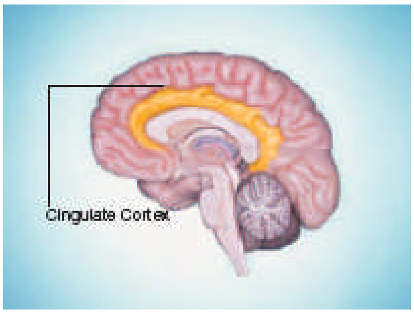

Fig. 4 This brain section shows the cingulate cortex.

The cortex of the brain refers to the wrinkled surface of these lobes. This surface is more wrinkled in humans than any other species, a characteristic believed to reflect our greater reliance upon higher level thought processes. 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 (Fig. 4). The anterior (or forward) part of the cingulate cortex becomes active when we engage with a wide variety tasks, and appears to have a significant role in the allocation of attention.

The brain, however, is not composed entirely of cortex. Many other structures are critical for learning. These include structures below the cortex such as the hippocampus, which is critical to consolidating new memories, and the amygdala (Fig. 5), which plays an important role in emotional response. Deeper within the forebrain lies the diencephalon, which houses the thalamus - another important structure for learning because this is where most sensory input arrives. Beneath this, lies the hypothalamus, which helps regulate the body's temperature and other basic functions. The diencephalon is also associated with declarative memory (see "What is learning", below).

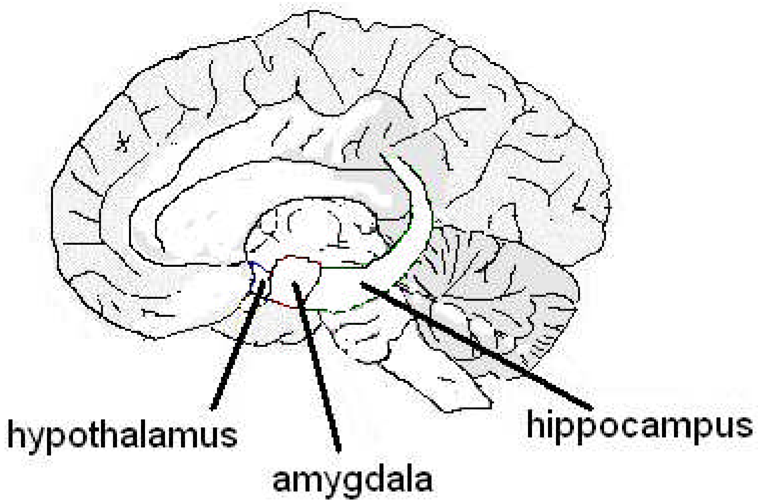

Fig. 5 Cross-section showing the hypothalamus, hippocampus and amygdala.

Brain development

Early development

Most of the neurons we possess throughout our lives are produced by the third month following our conception. Evidence suggests, however, that we continue to produce a small number of neurons in areas such as the hippocampus even in adult life. This birth of new neurons, or neurogenesis, has been linked to learning, but the key process by which learning occurs is thought to be through changes in the connectivity between neurons. The making of connections, or synapses, is called synaptogenesis and it occurs at a greater rate in children than in adults. Synaptic pruning, in which infrequently used connections are eliminated, also occurs at a greater rate in children than adults.

It is fair to consider that such overt changes in brain connectivity help make childhood a good time to learn and may explain the existence of sensitive periods, which are windows in time during which we learn better. What we know of these periods, however, is that they are not critical, but represent times when we are more sensitive to environmental influences, and that they chiefly involve visual, movement and memory functions that are learned naturally in a normal environment. Thus, research on sensitive periods is fascinating but it cannot yet contribute to meaningful discussions regarding formal curricula.

Brain development in adolescence

Neuroscience has shown the surprising extent to which the brain is still developing in adolescence, particularly in the frontal and parietal cortices, where synaptic pruning does not begin until after puberty (Huttenlocher 1979). A second type of change occurring in these brain regions during puberty involves myelination. This is the process by which the axons, carrying messages to and from neurons, become insulated by a fatty substance called myelin, thus improving the efficiency with which information is communicated in the brain. In the frontal and parietal lobes, myelination increases considerably throughout adolescence and, to a less dramatic extent, throughout adulthood, favouring an increase in the speed with which neural communication occurs in these areas (Sowell et al 2003).

In light of these findings, one might expect the teenage brain to be less ready than an adult brain to carry out a range of different processes. These processes include directing attention, planning future tasks and multi-tasking, as well as socially oriented tasks such as inhibiting inappropriate behaviour. For example, some evidence supports the existence of gaps in the abilities underlying social communication in adolescents, such as taking on the viewpoint of another person, or so-called ‘perspective-taking’ (Blakemore and Choudhury 2006; Choudhury et al 2006).

Just as linguistically sensitive periods have been linked to synaptic pruning in very young children, continuing synaptic pruning in adolescence suggests the possibility of sensitive periods in this age group as well. For example, research has shown that teenagers activate different areas of the brain than adults do when learning algebraic equations, and this difference has been associated with a more robust process of long-term storage than that used by adults (Luna 2004; Qin et al 2004).

However, an important point here is that, while young children’s development in areas such as language is advantaged by biological start-up mechanisms specific to these language skills, no such start-up mechanisms for adolescents are likely to exist that are specific to the KS3 curriculum. Thus, formal education, as well as social experience, may play a particularly important role in moulding the teenage brain. Such considerations have led a prominent expert on the adolescent brain to emphasise the importance of education at this age, and that the adolescent brain ‘is still developing ….it is thus presumably adaptable, and needs to be moulded and shaped.’ (Blakemore in Howard-Jones 2007).

Neuroimaging techniques have revealed enhanced activity in the brain’s reward system among teenagers. These findings have prompted the suggestion (Ernst et al 2005) that heightened risk-taking in adolescence may be due to unequal competition between increased activity in the reward system and top-down control from prefrontal cortex, a region of the brain known to be still developing during adolescence (Blakemore 2008). However, risk-taking (and, in a pilot study, reward activity) has been shown to increase in the presence of peers, demonstrating the high dependence of such mechanisms on social context (Steinberg 2008).

What is learning?

There are significant differences in the meaning of ‘learning’ in education and its meaning in neuroscience. Educational ideas are diverse and eclectic in their origins. They are the product of a variety of different processes and forces, including those arising from theoretical educational and psychological traditions and other culturally transmitted ideas from within and beyond the teaching profession.

It is difficult to generalise, but educators often consider learning to be distributed well beyond the level of the individual, as illustrated by Fig. 6, reproduced from *Principles into practice – a teacher’s guide to research evidence on teaching and learning* (TLRP 2007). The report from which these principles were drawn likens educational innovations to a pebble being thrown into a pond (TLRP 2006). The first ripple may be a change in classroom processes and outcomes, but this may have implications for teachers’ roles, values, knowledge and beliefs. This may require a change in professional development and training that may, in turn, influence school structure and even national policy. The key point is that changes at any one of these levels may have implications for other levels.

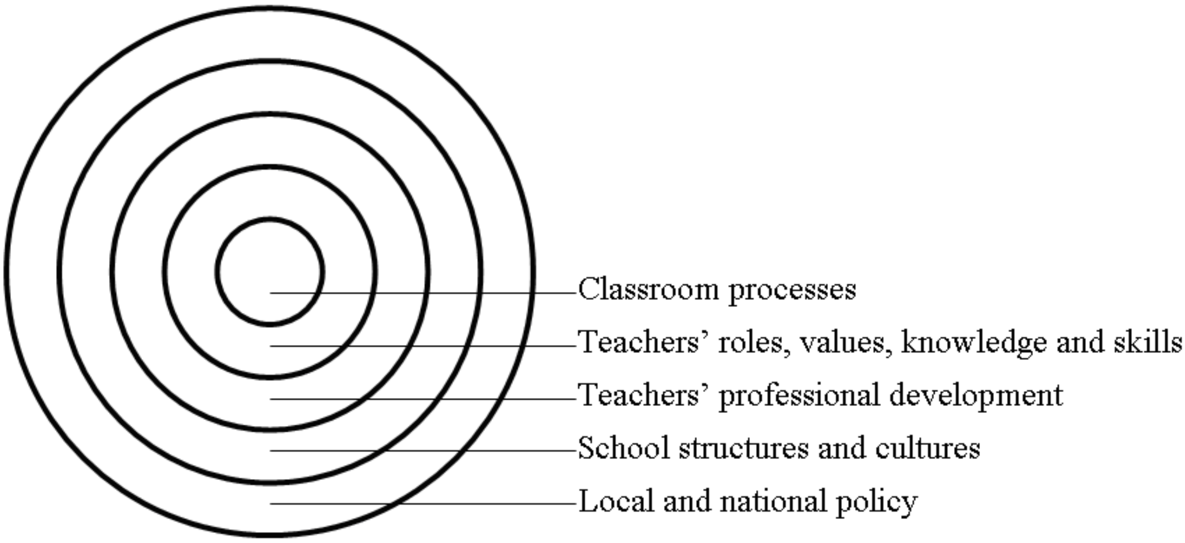

Fig. 6 Levels of educational change as proposed in a recent commentary by the Teaching and Learning Research Programme (TLRP 2006)

This UK report, like those surveying teachers in the US (Snider and Roehl 2007), suggest a strong emphasis on ideas about distributed learning, social construction, learning within groups and communities and the importance of context. Additionally, there are issues of meaning, the will to learn, values and the distributed nature of these and other aspects of learning beyond the level of the individual.

In contrast, the scientific term ‘learning’ is often synonymous with memory. Within cognitive neuroscience, there is now a general acceptance that we have multiple memory systems that can operate both independently and in parallel with each other. It is useful to classify these broadly in terms of declarative and nondeclarative systems (Fig. 7).

The declarative memory system is closest to the everyday meaning of ‘memory’ and perhaps most clearly related to educational concepts of learning. Defined as our capacity to consciously recall everyday facts and events, this system appears most dependent on structures in the medial temporal lobe (for instance, the hippocampus) and the diencephalon (Squire 2004). The forming and recalling of declarative memories activates a variety of additional areas in the cortex, whose location can appear influenced by other characteristics of these memories, such as whether these are episodic (the re-experiencing of events) or semantic (facts). Nevertheless, it appears that semantic and episodic memory arise from essentially the same system, with models now emerging of how the hippocampus operates in facilitating these different types of declarative memory (Shastri 2002).

Whereas declarative memory is representational and provides us with the means to model the world and to explicitly compare and contrast remembered material, nondeclarative memory is expressed through performance rather than recollection. Declarative memories can be judged as either true or false, whereas nondeclarative memories appear only as changes in behaviour and cannot be judged in terms of their accuracy.

Nondeclarative memory is actually an umbrella term for a range of memory abilities arising from a set of other systems. One type of nondeclarative memory supports the acquisition of skills and habits, and is related to changes in activity in the striatum, a compound brain structure involved in a variety of cognitive activities. Another type of nondeclarative memory supports conditioned emotional responses and is associated with activity in the amygdala. Nonassociative learning responses, such as when a response is diminished by repetitive exposure to a stimulus, appear linked to reflex pathways located chiefly in the spinal cord. Priming, a fourth type of nondeclarative memory, refers to our capacity to use part of a representation in our memory to retrieve the rest of it, such as when the first one or two letters of a word allow us to recall it in its entirety. This capacity appears dependent on a number of cortical areas but, again, is thought to arise from a system essentially different from the one serving declarative or other types of nondeclarative memory.

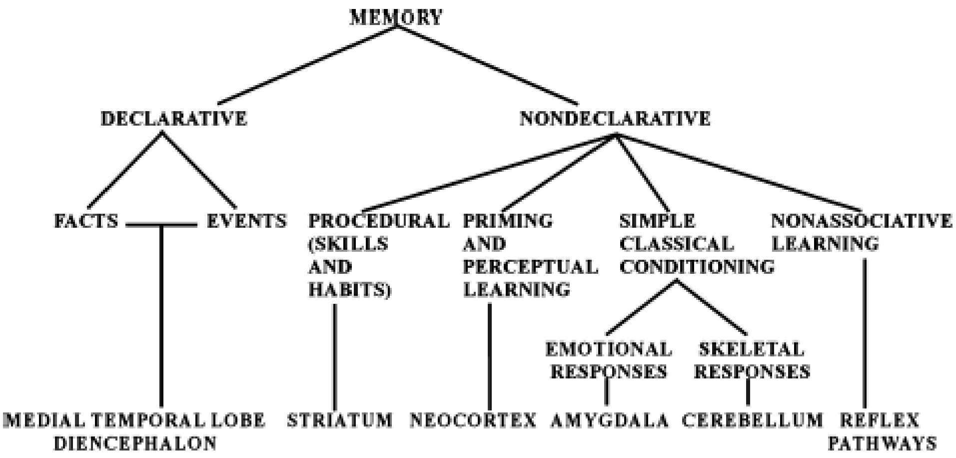

Fig. 7 A taxonomy of mammalian memory systems listing the brain structures thought to be especially important for each form of declarative and non-declarative memory (Squire 2004).

Learning as changes in connectivity

An appreciation of memory as distributed and involving multiple systems is important, but it tells us little about the process by which a memory is achieved. Within the neuroscience community, there is a common acceptance that human learning, in terms memory formation, occurs by changes in the patterns of connectivity between neurons, a phenomenon known as ‘synaptic plasticity’. There are two key ways in which synoptic plasticity can occur, known as long-term potentiation (LTP) and long-term depression (LTD).

LTP refers to an enduring increase (upwards of an hour) of the efficiency by which a neuron relays electrical information, as a result of a temporal pairing (coincidence in time) between the incoming and outgoing signal. Its role within the hippocampus, an area key to memory formation, has been the subject of particular focus. LTP refers to the ability of a neuron to adjust its connectivity in response to signals related in time, an ability noted in the expression ‘neurons that fire together, wire together’.

LTP may seem like a modest ability, but simulations with artificial neurons have shown that it affords even small networks the possibility of organising themselves to produce a type of ‘learning’ with human-like qualities and a range of cognitive functions (Arhib 2003; McClelland and Rogers 2003). Such networks can ‘learn’ to identify patterns and make useful guesses. These networks of artificial neurons also exhibit a graded decrease in functionality when connections are damaged, just as biological neural networks do in a process called ‘graceful degradation’.

Long-term depression (LTD) refers to an enduring decrease in synaptic efficiency. This is a mechanism thought to explain, for example, how neurons in the perirhinal cortex (a region in the temporal lobe) decrease their output as a stimulus is repeatedly presented. This process underlies our ability to recognise familiarity.

Since it is not presently possible to directly observe the role of synaptic plasticity, or the mechanisms thought to facilitate it, in human learning, researchers seek indirect evidence using experimental models. In one experiment, animals are given a protein-synthesis inhibitor, which diminishes memory retention. Animals in this study were shown to experience a slow (over a period of hours) onset of amnesia, which coincides with decreasing ability to maintain LTP.

Such studies provide compelling evidence, but not firm proof, of LTP's role in memory retention. Present data suggest we can be sure such mechanisms are necessary for learning, but we cannot be sure that the plasticity required for learning rests on these mechanisms alone (Martin et al 2000). Or, as Citri and Malenka (2008 p30) warned in a recent review, 'establishing a causal connection between a specific form of synaptic plasticity and the behavioural consequences of specific experiences remains a daunting task'.

Criticism of the synaptic plasticity hypothesis has increased in the neuroscience community in recent years. Critics question whether it is likely that stable declarative memory formation, lasting over decades, is founded on such an unstable phenomenon. This is one of the considerations underlying suggestions for a genomic hypothesis of memory, in which DNA modifications serve as carriers of elementary memory traces (Arshavsky 2006; Crick 1984; Davis and Squire 1984).

The role of working memory in learning

Working memory is essential to the type of learning promoted by education. It refers to our ability to temporarily hold information arriving via our senses, or from a longer-term memory store, in order to process it. Working memory is very limited in its capacity. For example, when we write down a telephone number, we prefer to receive it in chunks of three to four digits at a time because we can only hold a few unrelated digits in our working memory. The average upper limit of working memory is about seven chunks of information, but there are individual differences in this limit that are linked to differences in educational achievement (Pickering 2006).

Activity associated with working memory has been observed in many different parts of the brain, but particularly in an area of the frontal lobes known as the dorso-lateral prefrontal cortex (DLPFC). It appears that the DLPFC (Fig. 8) supports working memory by controlling a temporary activity increase within pre-existing networks inside this brain region or in other areas of the brain where the information is stored (Curtis and D'Esposito 2003).

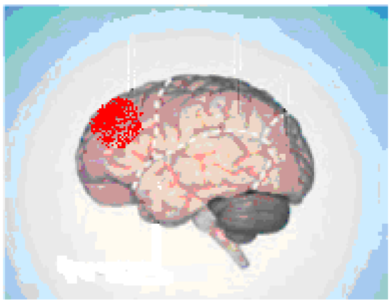

Fig. 8 Location of dorsolateral prefrontal cortex (DLPFC) (shown in red)

Learning and structural change

In addition to changes in connectivity at the cellular level, learning also has been linked to gross structural changes in the brain. For example, the type of declarative memory required for visuospatial tasks appears strongly dependent on regions of the hippocampus (Burgess and O'Keefe 1996). London taxi drivers are generally accomplished in their visuospatial learning, as demonstrated by their ability to rapidly and accurately recall complex street plans and routes. A well-known study demonstrated that the posterior part of the hippocampus in a sample of taxi drivers was larger than those of non-taxi drivers. Moreover, this growth was proportional to the number of years they had been driving a taxi (Maguire et al 2000). Since brain volume is constrained by the skull, such increases must be accompanied by decreases in other areas. In this case, there was an associated shrinking of the anterior part of the hippocampus.

More recently, research has shown that learning can produce detectable changes in brain structure over quite short time periods (Fig. 9). In a study of adults learning to juggle, the brain areas activated at the beginning of a three-month training period increased in size by the end of it. After three further months of rest, these areas had shrunk back closer to their original size (Draganski et al 2004).

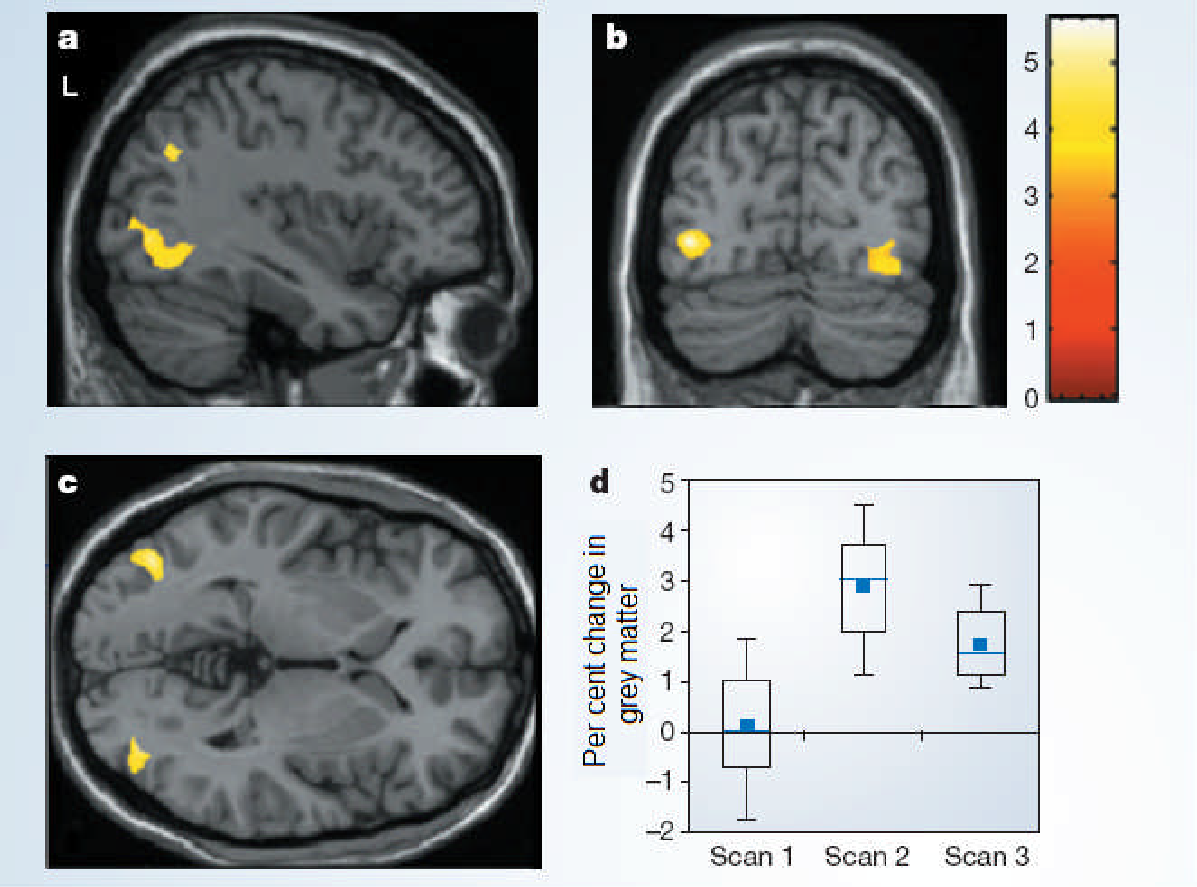

Fig. 9 Learning can produce changes in brain structure (see text).

Figure 9 shows that when adults spent three months learning to juggle, the size of some brain regions (shown in a, b and c in Fig. 9) changed relative to a non-juggling control group. Fig. 9 d) shows how the size of this grey matter changed:

Scan 1. before training.

Scan 2. after three months of practise.

Scan 3. three months since end of practise.

The graph in Fig. 9 d) shows the percentage difference in size of these regions for jugglers compared with non-jugglers, with a clear increase (from scan 1 to scan 2) after training. These regions shrank back closer to their original size (scan 3) after three months of not practising their skills (Draganski et al 2004).

Images showing a structural change associated with learning may promote a better sense of the learning being established and even, perhaps, evidence of 'deep' learning. Indeed, the learning has usually been achieved over a long period of rehearsal, so one may expect it to be well consolidated in memory and retrieval to be somewhat automatic. However, it is not presently clear how these structural changes come about and whether, for example, they are due to increased connectivity or the birth of new cells such as glial cells or even neurons. Moreover, the longer time period associated with structural change (compared to synaptic changes) may be a product of present limitations of technology. Smaller structural changes may be occurring over shorter time periods that we simply cannot detect.

Functional correlates of learning as shifts in dynamic networks of brain activity

When learning takes place, it is often possible to observe accompanying changes in biological function (Fig. 10). For example, in a functional MRI study (fMRI), a noninvasive technology that depicts active areas in the brain by measuring blood flow, Delazer et al (2003) found that adults attempting to perform long multiplication generated increased blood flow in the frontal areas associated with working memory load as they worked through new routines step-by-step. After practising 25 minutes per day for a week, however, their performance had improved and imaging showed increased activity in the posterior brain regions associated with more automatic processing demands. At the same time, frontal activity had decreased in a way indicative of reduced load on working memory.

This study provides a clear demonstration of how learning is often accompanied by a shift in activity patterns within brain networks, rather than an increase or decrease in a single region of the brain. Since we draw on different mental resources when we first attempt a task compared with when we are proficient, one may generally expect a changing relationship between regions of brain activity and learning over time. For more discussion of the importance of considering learning in terms of such changes in a dynamic networks, see Kaufmann (2008) and Varma and Schwartz (2008).

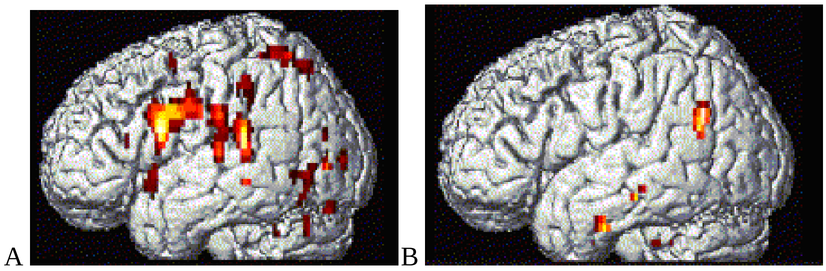

Fig. 10 Adult brain activity during complex maths, before and after training.

A: Hot spots show where brain activity decreased after participants undertook mathematical training, reflecting a decreased demand on working memory.

B: A different analysis of the same participants, this time with hot spots showing areas where brain activity increased after mathematical training, reflecting an increase in automatic processing (Delazer et al 2003).

The images of this shift in activity from frontal to posterior regions emphasises the significant difference between knowing how to solve a problem and having rehearsed that process so much that it becomes an automatic skill. Practicing may help perfect thinking processes, but it also helps develop them into skills, simultaneously liberating our working memory to help apply the learning in new contexts and, of course, to learn more. However, beyond monitoring and encouraging learners to rehearse what has been taught, whether we can 'teach to skills' is a moot point. Skills, by psychological definition at least, belong in the non-declarative class of memory. If we were asked how we do it, we might find it difficult to explain, or we might provide a rather incomplete set of instructions. These abilities have become automatic, non-declarative and unconscious. They are skills that have developed through rehearsal of what we once consciously had to learn and practise.

Working memory is closely linked to measures of intelligence (and thus to academic and professional performance), not least because it is particularly important when we are learning how to do something for the first time. If we are 'wasting' working memory when learning, due to simultaneously engaging with computer processes unrelated to the learning, then learning will be slower. On the other hand, repeating tasks, not dissimilar to remembering restaurant orders, have been shown to stretch working memory and improve intelligence (Jaeggi et al 2008). The impact of Jaeggi's computer-based task on intelligence provides some evidence for the potential of 'brain-training' games. However, it is important to note that commercial products (such as Nintendo Brain Training) still await scientific and educational evaluation.

Memory, understanding and multimodality

It has been known for some time that illustrating text can enhance memory (Paivio and Csapo 1973) because pictures of objects appear more memorable than their names. This effect has provided an important justification for the type of multimodality that technology can offer.

Such approaches might be further informed by evidence that multimodal stimulus produces additional brain activity over and above that produced by experiencing each mode separately (Beauchamp et al 2004). In this study, researchers used fMRI to scan participants' brains while they were exposed to auditory and visual characteristics of tools such as a hair-dryer, a hammer and other items. The additional brain activities related to simultaneous exposure to both types of sensory cue were associated with making links between visual and auditory features. This automatic recruitment of additional processing might suggest we should observe improved memory for multimodally presented stimuli, but this is not the case. Simply presenting cues in two modes is not likely to directly improve long-term memory, although it can improve working memory (see below). The effectiveness of multimodal presentation as a memory/learning strategy appears to rely more on whether it encourages in-depth processing of the type related to educational objectives (Dubois and Vial 2000).

Neuroimaging has also helped provide insights into individual learning strategies (Kirchhoff and Buckner 2006). In this investigation, researchers scanned the brains of adult participants while they tried to memorise images of pairs of objects for a test. They were then asked to complete a questionnaire about the strategies they used. There are many reasons to be sceptical about such self-report approaches, but the brain images confirmed that self-reported use of visual and verbal encoding strategies predicted activity in distinct regions of the brain associated with visual and verbal processing. These strategies had an additive effect on memory, such that participants who used multiple strategies showed improved memory performance. (NB: this is also evidence against using VAK. See Appendix on Neuromyths).

Stress and memory

Research into the effects of stress on memory has produced conflicting results. Most of us might feel we need a little stress to stay alert when learning, although too much stress can feel unhelpful. It is also true that many people are unable to forget some very stressful experiences (Olff et al 2005), yet the details of such events can be unreliable (Christianson 1992). Physical or psychological stress appears to facilitate the memory of an event when it occurs in the same context and at the same time as the event. Additionally, neuroscientific studies demonstrate that stress hormones and transmitters must also converge in time and space with the brain activity associated with the memory of the event if they are to enhance the memory (Joels et al 2006). Stress hormones appear to facilitate memory when they are present at the time of learning, but have the opposite effects when they are present before, or for a considerable time after, the learning event (de Quervain et al 2000; Kirschbaum 1996; Kuhlmann 2005). Physical stressors such as temperature and hunger activate lower regions in the brain than the psychological stress of receiving a stressful emotional message, which is more likely to activate limbic regions such as the amygdale (Herman and Cullinan 1997). Such an emotional stressor is also likely to produce stress hormone noradrenaline in these regions, and the coincidence in time and place promotes memory for the message, but not for any unrelated contextual information (McGaugh 2004).

Such models provide insights into, for example, the effects of examination stress on memory. If psychological (but not physical) stress occurs before the exam, and is associated with the learning, it may be beneficial. If it occurs during the exam, it can be detrimental. It seems possible, therefore, that the type of mild stress produced by a competitive computer-based learning game might support the encoding of new knowledge, whereas the type of technostress provided by challenging or dysfunctional computer processes may disrupt its recall later.

Rehearsal, working memory and technology

Many of the studies mentioned have examined learning in the context of memorising abstract material. From an educational point of view, repetitive factual recall of a list of steps required when carrying out a process may not appear as important as being able to carry out the process with understanding and efficiency. But rehearsing factual recall can support the 'deeper' learning required for skills acquisition, because it helps achieve automatic and effortless mental processing of the old material, freeing up the mental resources required to approach new material, or to apply the old material in new situations.

The math-learning study by Delazer et al (2003) described earlier in this review provided striking images of the educational importance of such rehearsal, as a means of liberating working memory. The images generated by this study illustrate how the types of mental resource required for solving a problem change with practice.

These images resonate well with classroom observations of the difficulties many learners face when engaging with new problems and the drain on working memory is high. In such situations, it can also be particularly helpful for pupils to show their working since, apart from allowing the teacher access to a learner's thinking, external representations can help offload some of these heavy initial demands on the learner's working memory.

Technology can sometimes contribute to releasing working memory capacity, or at least can be designed or used in a way that minimises unnecessary impingement upon it. Cognitive Load Theory (CLT), which is based on reducing load on working memory, has formed an important basis for much instructional design (Merrienboer and Sweller 2005). Multimodality is one way of achieving this by, for example, presenting auditory mathematical statements with their visual diagrams rather than both statements and diagrams in visual form. This approach has been shown to improve solution time by reducing working memory (Mousavi et al 1995).This type of presentation, in which the user controls the onset of the auditory statements, can easily be provided using technology.

However, it can also be argued that technology can increase the burden on working memory. For example, researchers have noted that when students write electronically rather than with a pen, they devote considerable time and effort to choosing fonts, layout and format. This activity can detract from the processing time required for constructing the language itself and increase the load on working memory. However, it has also been argued that learners' attention to these issues can support their development as 'multimodal makers of meaning' (Matthewman and Triggs 2004).

Meaning

The construction of meaning has also been identified as a key to understanding and remembering information. When we learn new information, the links that form between this new information and our existing knowledge serve to make it meaningful. An area of the left hemisphere, the left inferior (lower) prefrontal cortex, has been identified as a vital structure in this construction of meaning. When we learn something new, additional activity in this area occurs when we try to decide upon its meaning in relation to what we already know. The new information becomes more memorable once we have completed this process of ‘meaning making.’ How much more memorable the information becomes is linked to the amount of increased neural activity in the left inferior prefrontal cortex (Fletcher et al 2003).

Small et al (2009) reported that the left inferior prefrontal cortex was one of many regions activated in the brains of individuals as they used an internet search engine. Search engines such as Google tend to present a lot of information that may not be related to the users’ needs, and so the user must rapidly explore potential meaningful connections between search results and their topic of interest. Using search engines can, therefore, be seen as a ‘meaning making’ activity.

There are few studies that directly examine the neural correlates of engaging with modern technologies. Although study by Small et al was conducted with participants who are middle aged or older, it illustrates the potential of such technologies to engage higher order thinking skills. Small and his collaborators also found additional activity in regions associated with decision-making, complex reasoning and vision among participants who were more experienced at internet searching. The authors of the report suggest that prior experience with internet searching may alter the brain's responsiveness in neural circuits controlling decision-making and complex reasoning.

Sleep, the consolidation of memory and teenage circadian rhythms

Sleep helps us consolidate what we have learned during the day. The sleeping brain has even been shown to reproduce the neural activities that characterise whatever we experienced in our preceding hours of wakefulness (Maquet et al 2000). The neurotransmitter ACh (acetylcholine) has been identified as a ‘switch’ that changes our state of wakefulness and how we process information. High-levels of ACh help maintain a wakeful state that supports the encoding (laying down) of information, while low levels of ACh during sleep minimise the encoding of new memories but maximise consolidation (in long term memory) of what has already been experienced (Rasch et al 2006). As well as helping us remember what we learned yesterday, sleep also helps us prepare to learn more and use what we know to generate insights (Wagner et al 2004). Regular and sufficient sleep is essential for the brain to learn efficiently.

Circadian rhythms are natural cycles of approximately 24 hours (Fischer et al 2008). The need for sleep diminishes as children grow older. Between the ages of 14 and 21, sleep need is reduced to 7.75 hours (approximately 10 minutes per year). The onset of sleep for teenagers, however, is disrupted by biological and social factors. School timing is a major factor, and teenagers lose considerable amounts of sleep during term time compared to holidays.

Hormonal influences also produce a phase delay in the circadian timing mechanism, but the use of technology has also been shown to contribute (Van den Bulck 2004). A recent study in the US showed the average teenager engaging in approximately 4 activities involving technology after 9:00pm and spending over an hour on each activity (Calamaro et al 2009). As pointed out by this study, activities involving sitting close to bright screens are likely to delay production of melatonin and interrupt sleep-cycles (Higuchi et al 2003, 2005), in way that a TV on the opposite side of the bedroom would not.

Biology is not destiny

The existence of differences in brain structure or function between different groups of learners may inspire insights and contribute to more effective learning programmes and interventions. However, it can also lead to unhelpful notions of permanent deficits and performance ceilings that are biologically determined, despite the unpopularity of such ideas in modern neuroscience. ‘Cause is not an easy word,’ observes John Morton, an expert in developmental cognitive neuroscience. “Its popular use would be laughable if it was not so dangerous, informing, as it does, government policy on matters that affect us all. There is no single cause of anything and nothing is determined." (Morton in Howard-Jones 2007)

Put more simply, the brain is plastic and, as we have seen in studies cited earlier in this review, is changed by our experiences. This is a fact that is seldom fully appreciated. Indeed, it has been shown that adolescents’ own self-image and ability to academically achieve can be influenced positively by a greater awareness of brain plasticity (Blackwell et al 2007).

Music

Studies involving biological perspectives have provided educational insights into the role of experience over innate giftedness. For example, we appear born to appreciate a broad range different music. A sensitive window of music appreciation appears to be present in our development a few months following birth, during which we are eclectic in our appreciation of rhythms from diverse cultures, but after which are chiefly sensitive only to those we have already experienced (Hannon and Trehub 2005a; Hannon and Trehub 2005b).

When musicians were asked to search for bars of musical notation amidst musically meaningless ones, researchers reported that a period of training on the target bars set in motion a series of neural events related to learned music responses for those bars. Such automatic responses allude to the power of even brief periods of musical training to grant musical notes a significance that cannot be easily suppressed. Structural analysis of the brains of musicians have shown enlargement of the corpus callosum (Schlaug et al 1995), auditory (Schneider et al 2002) and motor region (Amunts et al 1997) but, again, such changes speak of the critical influence of experience. Structural alterations appear dependent on the age at which training began (Elbert et al 1995; Hutchinson et al 2003) and the intensity of training received (Gaser and Schlaug 2003; Hutchinson et al 2003; Schneider et al 2002).

Although neuroscience cannot promise that ‘practice makes perfect’, it does offer clear and observable evidence of how the brain adapts to the demands of extensive training. In contrast to notions of biology as destiny, findings from neuroscience place emphasis more effectively upon practice and experience, than giftedness (Stewart and Williamon 2008).

Creativity

Creativity is considered a key thinking skill, but the fostering of creative thinking in the classroom has been hampered by a lack of understanding of the thinking processes involved. Psychological research suggests that creativity requires switching between two very different types of mental process: generative and analytical thinking, each benefiting from a different attentional state. Analytical thinking, in which we research the background to a problem or evaluate a potential solution, requires the type of focused attention most often encouraged by a school environment. The generative thinking needed to produce ideas and potential solutions, however, requires more diffuse attention–the type supported by relaxed environments, changes in context and the absence of critical evaluation by self or others.

Kounios et al (2008) demonstrated the relationship between unfocused, diffuse attention and generative thinking at an individual level. The researchers recorded EEGs (electroencephalograms) of individuals with high and low insight problem solving ability when the subjects were at rest. Such measurements, when brain function is more spontaneous and less controlled by the experimenter than when an individual is performing a set task, can be helpful in identifying individual differences in brain function. Results confirmed psychological models by revealing that the brain activities of high insight problem solvers reflect greater attentional diffusion even at rest.

Other studies have shown how creative ability is not just about individual differences, but can be influenced by strategies used by teachers in the classroom. One such strategy requires the student to incorporate elements into their creative outcome which are not related to each other. A brain imaging study by Howard-Jones et al (2005) investigating the generation of stories from words that were unrelated showed that such strategies can increase the brain activity associated with creative effort (Fig. 11). These findings support the likely effectiveness of such strategies in fostering longer-term creative ability.

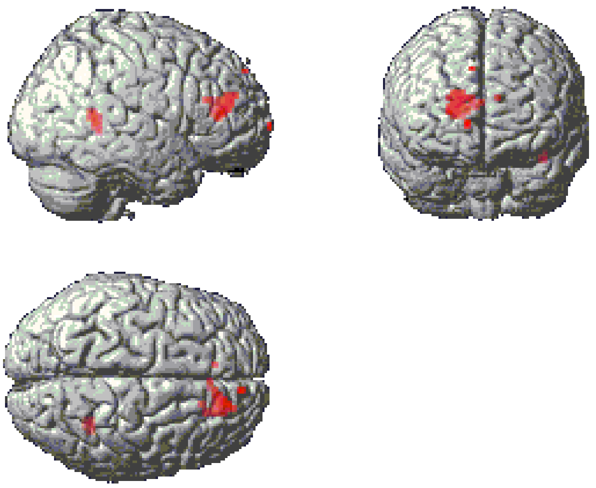

Fig. 11 Regions marked in red show where brain activity associated with creative effort in a story-telling task increased as a result of having to incorporate unrelated words (Howard-Jones et al 2005).

Technology also can challenge learners to make links between disparate elements. Proponents claim that Web 2.0 technology is supporting a new ‘internet-savvy youth’ to make these links on an entirely new scale, as they find themselves able to create and share original content or remix existing content into entirely new creations (Geyer 2007). The increasingly user-defined architecture of participation in Web 2.0 may effectively broaden the reservoir of associations available to an individual. Beyond increasing creative productivity, this technology may support longer term changes in the ability to think creatively if it is increasing the uptake of challenging opportunities to make remote associations.

Interaction with Technology

Computer-mediated communication

Although cognitive scientists have not directly investigated computer-mediated communication, the tasks they provide to participants are often computer-based, due to the environmental constraints of imaging and the need for experimental control. This was the case in a study of social exclusion using a virtual ball tossing game. Exclusion from social participation, even participation mediated by technology, produces activity in the same regions of the brain associated with physical pain (Eisenberger et al 2003).

Social participation appears particularly important during adolescence, and this is reflected in the high use of technology to communicate with peers. Young peoples’ prevalent use of technology to communicate through social networking sites such as Facebook, has been met with alarm by some commentators. Critics have claimed that this may damage or ‘infantilise’ young people’s brains and reduce their ability to communicate face-to-face (Wintour 2009). However, no evidence exists to support these claims. On the contrary, recent findings suggest using the internet to maintain, rather than create, relationships can improve social connectedness and well-being, with significantly positive relationships between online communication (mostly instant messaging) and adolescents’ social connectedness (Valkenburg and Peter 2009).

It is beyond the scope of this review to consider the complex relationship between cognition and emotion, but it is worth noting how neurobiological evidence suggest learning, attention, decision making and social functioning are profoundly affected by and subsumed within emotional processes. Evidence from brain-damaged patients has been used to emphasise the particular importance of emotion-related processes in transferring learning achieved within school to the outside world (Immordino-Yang and Damasio 2007).

The attraction of computer games: lessons for education?

Burgeoning research in neuroscience has supported some fresh educational thinking about motivation, which also has been prompted by researchers observing the intense engagement provided by computer gaming (Gee 2003).The proposed involvement of fantasy, challenge and curiosity seems inadequate to explain the attraction of traditional games such as Snakes and Ladders, Bingo, or simple (but very popular) computer games such as Tetris. This attraction may be due more to elements of chance-based uncertainty. The attraction of uncertainty is now gaining closer scrutiny, but it is a phenomenon well established by psychological experimentation (Atkinson 1957), which has shown moderate risk-taking (50 per cent chance) heightens motivation.

Recent understanding of reward1 involves consideration of ‘wanting’ and ‘liking’ as two dissociable components, with the wanting of a reward being coded by levels of dopamine release in mid-brain areas (Berridge and Robinson 2003). The predictability of an outcome has been shown to influence this activity. In primates, it has been shown that maximum dopamine is released when the likelihood of receiving reward for success is about half way between totally unexpected and completely predictable, that is, 50 per cent likely (Fiorillo et al 2003). Dopamine levels in this area of the human brain have been linked to our motivation to pursue a variety of pleasures, including sex, food, gambling (Elliot et al 2000) and computer gaming (Koepp et al 1988).

The link between the predictability of an outcome and mid-brain dopamine activity is, therefore, helpful in explaining why humans are so attracted to activities involving elements of chance (Shizgal and Arvanitogiannis 2003). Activity in this area has been studied non-invasively in humans during gaming using functional Magnetic Resonance Imaging. These fMRI studies have shown that patterns of dopamine activity are predicted less by reward in ‘real’ absolute terms and seem more to do with winning the game. Activity can increase with reward size (Knutson et al 2001) but, rather than being proportional to monetary reward, activation peaks at the same level for the best available outcome in different games (Nieuwenhuis et al 2005). The complex relationship between reward and motivation is thus strongly mediated by context.

When uncertainty is encountered in real life, the social environment can potentially create more complex effects. These effects are illustrated by the way our natural attraction to uncertainty falls off when the task is perceived as educational. Students generally prefer low levels of academic uncertainty and choose problems well below moderate (less than 50 per cent) challenge (Clifford 1988; Harter 1978). If these problems are presented as games, however, students will take greater risks (Clifford and Chou 1991). These findings may suggest that individuals can be deterred from

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[1] Note that reward is being used here in the psychological sense, i.e. as a process, or set of processes, by which behaviour is reinforced.

tackling academic tasks with higher levels of uncertainty due to the implications of failure for social status and esteem. This provides a means to understand how computer-based learning games with elements of pure chance can raise uncertainty without impacting negatively on self-esteem, thereby raising motivation (Howard-Jones and Demetriou in press).

The brains of male subjects show greater activation and functional connectivity compared to the brains of females in the reward system when playing computer games, which may be linked to an increased motivational state (Hoeft et al 2008). In addition to gender, there are likely to be other observable differences in how various age groups respond to computer games, since the reward system undergoes a dramatic remodelling around the time of puberty (Steinberg 2008). These are, of course, the same developmental changes mentioned earlier in relation to changes in risk-taking behaviour.

Learning by imitation and visualisation

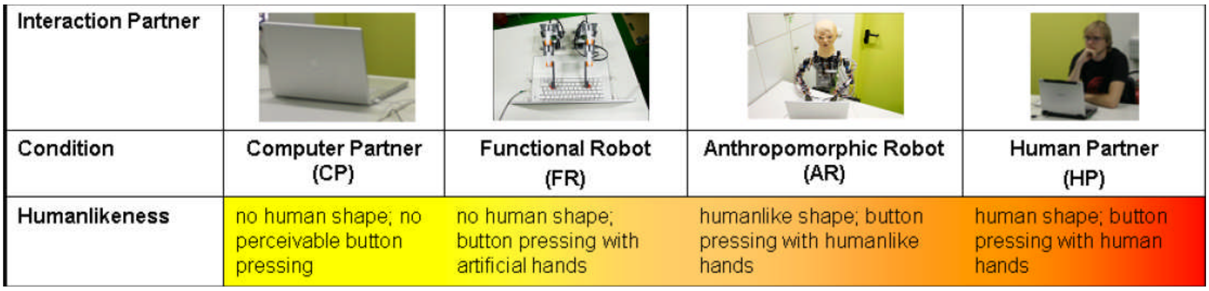
Many other psychological insights being explored by neuroimaging have broad implications for teaching and learning strategies. For example, it has been known for some time that visualisation is a useful strategy for learning. As well as producing strong physiological responses, visualising an object recruits most of the brain areas activated by actually seeing it (Kosslyn 2005).

The ability of mental imagery to engage so much of the brain circuitry involved with a real perceptual experience emphasises its potential power and usefulness as a learning tool. This raises questions about the extent to which modern educational software (such as the computer-aided-design packages with graphical qualities that are commonly used in secondary schools) tends to diminish and/or support learners' attempts to visualise. On the one hand, this technology may reduce the need for students to rehearse their own visualisation because the computer can, to some extent, do this for them. On the other hand, students are still required to visualise in order to monitor and check the computer's generation of imagery, and to anticipate a range of visual transformations in generating their design, which may be more interesting and complex than those possible without the software. It seems probable that technology may support or diminish students' rehearsal and development of their ability to visualise, depending on whether it is used to substitute for, or to challenge, visual imagination.

Brain imaging is also beginning to provide unexpected insights into vicarious learning. When we observe others carrying out actions, some of the same cortical areas are activated as if we were carrying out the actions ourselves (Rizzolatti and Craighero 2004). The so-called mirror neuron system is thought to mediate imitation-based learning, and is thought to have evolved as a type of 'mind reading'. The goal of the observed action is a key influence on mirror neuron activity, supporting the notion that it developed as a means to anticipate others' actions (Gazzola et al 2007). The mirror neuron system also activates when we merely hear of human actions being performed, suggesting ways in which the potential effectiveness of visualisation can be further realised (Tettamanti et al 2005). The restriction of mirror neuron activation to human movement may help explain apparent inconsistencies surrounding claims that animation can support learning (Tvesrky and Morrison 2002). The existence of mirror neuron systems suggest animation is most advantageous when the learning involves human movement.

In terms of the potential importance of multimodal communication technology, one of the ways in which the observation of facial movements appears to contribute to speech perception is through activating areas of the brain associated with speech production (that is, motor activity is produced as if the observer is speaking themselves) (Skipper et al 2005). This type of imaging evidence can be used to promote the importance of multimodal communication in empathetic communication, through supporting ‘an implicit, prereflexive form of understanding of other individuals’ (Gallese 2003). This suggests that some forms of digital communication, that is, those in which one cannot see facial movements, may never substitute for face-to-face contact, as also suggested by studies revealing the positive impact of face-to-face contact on online learning.

The neural processes we use to engage with other humans, however, can also become involved when we ‘communicate’ with non-human technology, particularly if this technology appears moderately human-like. A question tackled in a recent fMRI study was how human-like an artificial agent needs to be before we start attributing human intentions to them, i.e. a theory of mind. It seems that visual appearance plays an important role in this attribution. In a recent study, Krach et al (2008) asked participants to play a game against different type of opponent who, unbeknown to them, were all playing randomly. Brain regions associated with theory of mind were activated in order of increasing human-like features (computer<functional robot<anthropomorphic robot<human). This suggests that making technology more human-like in its appearance may seriously influence our tendency to attribute human intentions to it (Fig. 12). This study suggests that the cosmetic appearance of technology may influence how learners mentally engage with it.



Interaction Partner				
Condition	Computer Partner (CP)	Functional Robot (FR)	Anthropomorphic Robot (AR)	Human Partner (HP)
Humanlikeness	no human shape; no perceivable button pressing	no human shape; button pressing with artificial hands	humanlike shape; button pressing with humanlike hands	human shape; button pressing with human hands

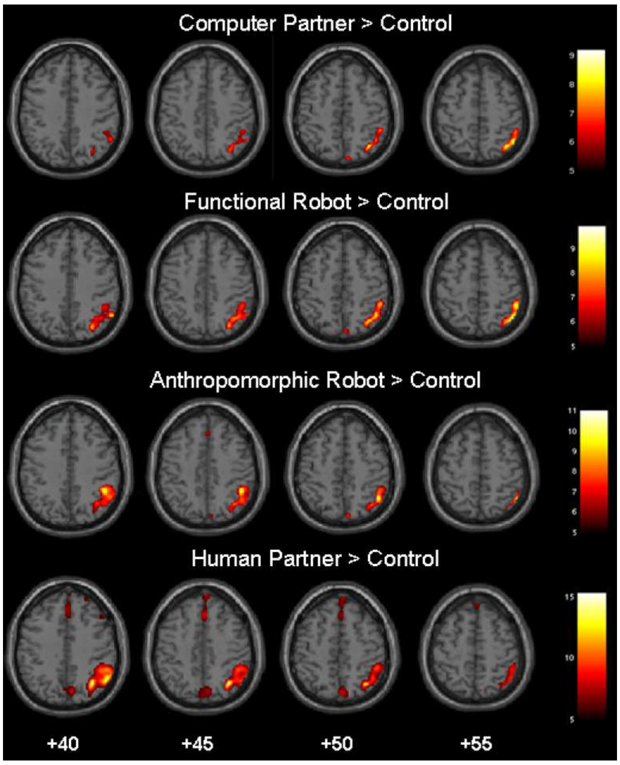


Fig. 12 Regions associated with ‘theory of mind’ grow more active as the appearance of a technological opponent beomes more human-like, even when it is clearly not human (Krach et al 2008).

Learning from feedback

The feedback provided by learning technologies can also be expected to influence learners in different ways. Development has been highlighted as an important factor in a recent neuroscientific study on how different age groups process feedback (van Duijvenvoorde et al 2008). Researchers have noted that it prefrontal activity suggestive of feedback-related learning starts to become greater for negative, as opposed to positive, feedback at the beginning of adolescence. This trend continued into the adult group and contrasted with the younger children, for whom positive feedback produced greater activity in these areas. This suggests that, from the beginning of adolescence, there is an increased influence of negative feedback on improving performance. That is, older children focus on adjustment in the light of negative feedback, while younger children focus on continuation in the light of positive feedback. This result was backed up by the behavioural evidence produced in the study.

Summary

This literature review has identified a number of areas in which our understanding of the brain may illuminate our understanding of 14-19 development and technology-based learning:

- The brain does not develop in linear fashion. Evidence suggests discontinuities in brain development, linked to discontinuities in the development of cognitive abilities such as perspective taking. Understanding also is emerging about particular characteristics of teenage behaviour, including risk-taking. Between the ages of 14 and 19, the brain is still developing, which highlights the importance of education for this age group. Around the beginning of puberty, learners become increasingly more influenced by negative, rather than positive, feedback. Throughout life, the brain is plastic and its connectivity, functionality and even structure are influenced by experience, including educational experience.
- The neuroscience perspective is contributing to a number of insights into how we use technology, such as how the appropriate use of the multimodality afforded by technology can reduce the burden on working memory, and how internet searching might be viewed as a meaning-making activity. Also, if Web 2.0 technologies are increasing the uptake of challenging opportunities to make remote associations, such advances have the potential to support creative development. Computer games are also highly popular amongst this age group, and new understanding about the brain’s reward system points to uncertainty as an important element in the motivation they provide, also suggesting potential insights into the enhancement of motivation in the classroom.
- Some concerns have been expressed about the use of technology in this age group. Home-use of technology by teenagers has been clearly implicated in sleep loss, with negative implications for academic performance. However, there is no evidence to suggest that the prevalent use of digital communications by the 14-19 age group is directly damaging brains, with recent evidence associating the use of social network sites with improved social connectedness.

Appendix: Neuromyths

Multiple Intelligences (MI) Theory

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

In a critical review, Waterhouse examined the empirical scientific for MI theory (Waterhouse 2006). MI theory claims to be drawn from a wide range of disciplines including neuroscience. Gardner has claimed, 'accumulating neurological evidence is amazingly supportive of the general thrust of MI theory'. In terms of an empirical basis for MI theory, one might point to neuroscientific evidence showing that achievement in different types of tasks is correlated with activity in different regions of the brain such that the behavioural influence of one region's efficiency may vary according to the task. Another argument supporting MI theory is the inadequacy of a single measure of intelligence to explain individual behavioral differences.

Both types of evidence might be used to argue against the likely usefulness of a single IQ measure as a strong general predictor of educational achievement[2]. This is not the same, however, as suggesting that the limits of our mental and/or neural performance arise from a small, distinct set of components, and that these limitations, in combination, account for the diversity of performance we observe across individuals tackling different tasks.

Gardner suggests that each intelligence operates from a separate area of the brain, although in response to Waterhouse he rephrased this claim more carefully. In his response, he refers to intelligences as being 'composites of fine-grained neurological subprocesses but not those subprocesses themselves' (Gardner and Moran 2006). Gardner refers to the type of test he believes would invalidate his MI concept, when he argues that if 'musical and spatial processing were identically represented' in the cortex, 'that fact would suggest the presence of one intelligence, and not two separate intelligences'. Yet, many shared and overlapping brain

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[2] However, general intelligence might also be distributed throughout the brain in terms of overall brain efficiency and, contrary to Gardner, some scientists point to the positive correlation between a measure of general intelligence 'g' , brain size and the level of brain activity to suggest that 'g' may be an important concept in understanding individual performance. These researchers include McDaniel, M.A. (2005) 'Big-Brained People Are Smarter: A Meta-Analysis of the Relationship between in Vivo Brain Volume and Intelligence,' *Intelligence*, 33, 337-46; Toga, A.W., and Thompson, P.M. (2005) 'Genetics of Brain Structure and Intelligence,' *Annual Review of Neuroscience*, 28, 1-23; and Geake, J.G., and Hansen, P.C. (2005) 'Neural Correlates of Intelligence as Revealed by Fmri of Fluid Analogies', *Neuroimage*, 26, 555-64.

processing pathways have been found between, for example, language and music skills (Koelsch et al 2004), music perception and nonverbal reasoning (Norton et al 2005) and distributed networks for emotion that are shared with reasoning, memory and action (Adolphs et al 2003; Morgane et al 2005; Phelps 2006).

Neither do two tasks recruiting the same shared region provide strong evidence for a single intelligence. The idea here is that if a single brain area is linked with two different activities, then performance in these two tasks might be affected only by the processing efficiency in this single brain region. This could contribute to the notion that these two tasks require a single type of intelligence. Functional isolation in the brain would be very unusual, with processes employing different pathways between the same areas and to different regions. In short, the general processing complexity of the brain makes it unlikely that a theory resembling MI theory will ever emerge from it.

Cognitive neuroscience is exploring the brain in terms of processes (vision, hearing, smell, etc) but not in terms of seeing intelligence, auditory intelligence or smelling intelligence. In the realm of neuroscience, it neither appears accurate or useful to reduce the vast range of complex individual differences at neural and cognitive levels to any limited number of capabilities.

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

Although Gardner is waiting chiefly for such behavioural evidence, and despite the absence of MI theory in the neuroscience literature, teachers heavily associate MI theory with neuroscience. To confirm this, the author returned to the data collected from the 150 UK teachers who were asked the question, 'Please list any ideas that you have heard of in which the brain is linked to education' (Pickering and Howard-Jones 2007). Of those teachers who responded to this question (121), most listed no more than two or three ideas. Of these, MI theory occurred 17 times (14 per cent).

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

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

Learning Styles

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

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

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

The implicit assumption appears to be that, since different modalities are processed independently in different parts of the brain, differences in the efficiency of these parts results in a clear modality-based method of classifying how learners are able to process information most efficiently. However, as pointed out by Geake and already discussed in terms of MI theory, this assumption flies in the face of what we know about interconnectivity of the brain (Geake 2008). Geake refers to a recent experiment that demonstrates the ineffectiveness of the VAK approach. In this piece of research, 5 year olds showed themselves able to distinguish between groups of dots even when the numbers were too large for counting (Gilmore et al 2007). They were then asked to repeat the task in auditory mode by counting clicks, and reproduced almost identical levels of accuracy. Geake suggests this is because input modalities in the brain are very interlinked.

As yet, no evidence arising from neuroscience, or any other science, supports the categorisation of learners in terms of their sensory modality or any other type of learning style. In the meantime, educators continue to be drawn to VAK as means to implement a new type of differentiation.

Another popular way to categorise learning style is in terms of ‘left-brain right-brain’ theory (Springer and Deutsch 1989). According to this theory, learners’ dispositions arise from the extent to which they are left- or right-brain dominant). It is true that some tasks can be associated with extra activity that is predominantly in one hemisphere or the other. For example, language is considered to be left lateralised. However, no part of the brain is ever normally inactive in the sense that no blood flow is occurring. Furthermore, performance in most every day tasks, including learning tasks, require both hemispheres to work together in a sophisticated parallel fashion. The division of people into left-brained and right-brained takes the misunderstanding one stage further. There is no reliable evidence that such categorisation is helpful for teaching and learning.

Educational kinesiology (Brain Gym)

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

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References

Amunts, K. , Schlaug, G. , Jancke, L. , Steinmetz, H. , Schleicher, A. , Dabringhaus, A. , and Zilles, K. (1997), 'Motor Cortex and Hand Motor Skills: Structural Compliance in the Human Brain', *Human Brain Mapping*, 5.3, 206-15.

Arhib, M.A. (2003), *The Handbook of Brain Theory and Neural Networks,* (Cambridge, MA, The MIT Press).

Arshavsky, Y. I. (2006), *Progress in Neurobiology*, *80*, 99-113.

Atkinson, J.W. (1957), 'Motivational Determinants of Risk Taking Behaviour', *Psychological Review*, 64, 359-72.

Beauchamp, M.S., Lee, K.E., Argall, B.D., and Martin, A. (2004), 'Integration of Auditory and Visual Information About Objects in Superior Temporal Sulcus', *Neuron*, 41.5, 809-23

Berridge, K.C., and Robinson, T.E. (2003), 'Parsing Reward', *Trends in Neurosciences*, 26.9, 507-13.

Blackwell, L.S., Trzesniewski, K.H., and Dweck, C.S. (2007), 'Implicit Theories of Intelligence Predict Achievment across an Adolescent Transition: A Longtitudinal Study and an Intervention', *Child Development*, 78.1, 246-63.

Blakemore, S.J. (2008), 'The Social Brain in Adolescence', *Nature Reviews Neuroscience*, 9, 267-77.

Blakemore, S.J., and Choudhury, S. (2006), 'Development of the Adolescent Brain: Implications for Executive Function and Social Cognition', *Journal of Child Psychology and Psychiatry*, 47.3, 296-312.

Burgess, N., and O'Keefe, J. (1996), 'Neural Computation Underlying the Firing Place Cells and Their Role in Navigation', *Hippocampus*, 6.6, 749-62.

Calamaro, C. J., Mason, T. B. A., and Ratcliffe, S. J. (2009), 'Adolescents Living the 24/7 Lifestyle: Effects of Caffeine and Technology on Sleep Duration and Daytime Functioning', *Pediatrics*, 123.6, E1005-E10.

Choudhury, S., Blakemore, S.J., and Charman, T. (2006), 'Social Cognitive Development During Adolescence', *Social Cognitive and Affective Neuroscience*, 1, 165-74.

Christianson, S.A. (1992), 'Emotional Stress and Eyewitness Memory - a Critical Review', *Psychological Bulletin*, 112.2, 284-309.

Citri, A., and Malenka, R.C. (2008), 'Synaptic Plasticity: Multiple Forms, Functions, and Mechanisms', *Neuropsychopharmacology*, 33, 18-41.

Clifford, M. M. (1988), 'Failure Tolerance and Academic Risk-Taking in Ten- to Twelve-Year-Old Students', *British Journal of Educational Psychology*, 58, 15-27.

Clifford, M. M., and Chou, F. C. (1991), 'Effects of Payoff and Task Context on Academic Risk Taking,' *Journal of Educational Psychology*, 83.4, 499-507.

Coffield, F., Moseley, D., Hall, E., and Ecclestone, K. (2004), 'Learning Styles and Pedagogy in Post-16 Learning: A Systematic and Critical Review', (Report No. 041543). (London, Learning and Skills Research Centre).

Crick, F. (1984), 'Memory and Molecular Turnover', *Nature*, 312, 101.

Curtis, C.E., and D'Esposito, M. (2003), 'Persistent Activity in the Prefrontal Cortex During Working Memory', *Trends in Cognitive Sciences*, 7.9.

Davis, H.P., and Squire, L.R. (1984), 'Protein Synthesis and Memory: A Review', *Psychological Bulletin*, 96, 518-59.

Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T., and Benke, T. (2003), 'Learning Complex Arithmetic - an Fmri Study', *Cognitive Brain Research*, 18, 76-88.

Dennison, P.E. (1981), '*Switching On: A Guide to Edu-Kinesthetics*', (Ventura, California Edu-Kinesthetics).

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., and May, A. (2004), 'Changes in Grey Matter Induced by Training', *Nature*, 427, 311-12.

Dubois, M., and Vial, I. (2000), 'Multimedia Design: The Effects of Relating Multimodal Information', *Journal of Computer Assisted Learning*, 16.2, 157-65.

Eisenberger, N.I., Lieberman, M.D., and Williams, K.D. (2003), 'Does Rejection Hurt? An Fmri Study of Social Exclusion', *Science*, 302, 290-92.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., and Taub, E. (1995), 'Increased Cortical Representation of the Fingers of the Left Hand in String Players', *Science*, 270, 305-07.

Elliot, R, Friston, K.J, and D., Raymond J. (2000), 'Dissociable Neural Responses in Human Reward Systems', *Journal of Neuroscience*, 20.16, 6159-65.

Ernst, M., Pine, D.S., and Hardin, M. (2005), 'Triadic Model of the Neurobiology of Motivated Behavior in Adolescence', *Psychological Medicine*, 36, 299-312.

Fiorillo, C.D., Tobler, P. N., and Schultz, W. (2003), 'Discrete Coding of Reward Probability and Uncertainty by Dopamine Neurons', *Science*, 299, 1898-902.

Fischer, F.M., Radosevic-Vidacek, B., Koscec, A., Teixeira, L.R., Moreno, C.R.C., and Lowden, A. (2008), 'Internal and External Time Conflicts in Adolescents: Sleep Characteristics and Interventions', *Mind, Brain and Education*, 2.1, 17-23.

Fletcher, P.C., Stephenson, C.M.E., Carpenter, T.A., Donovan, T., and Bullmore, E.T. (2003), 'Regional Brain Activations Predicting Subsequent Memory Success: An Event-Related Fmri Study of the Influence of Encoding Tasks', *Cortex*, 39, 4-5.

Gallese, V. (2003), 'The Roots of Empathy: The Shared Manifold Hypothesis and the Neural Basis of Intersubjectivity', *Psychopathology*, 36.4, 171-80.

Gardner, H. (1983), *Frames of the Mind: The Theory of Multiple Intelligences*, (New York, Basic Books).

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

Gardner, H. (2003), 'Multiple Intelligences after Twenty Years', *American Educational Research Association*.

Gardner, H., and Moran, S. (2006), 'The Science of Multiple Intelligences Theory: A Response to Lynn Waterhouse', *Educational Psychologist*, 41.4, 227-32.

Gazzola, V., Rizzolatti, G., Wicker, B., and Keysers, C. (2007), 'The Anthropomorphic Brain: The Mirror Neuron System Responds to Human and Robotic Actions', *Neuroimage*, 35.1674-1684.

Geake, J.G. (2008), 'Neuromythologies in Education', *Educational Research*, 50.2.

Gee, J.P. (2003), *What Video Games Have to Teach Us About Learning and Literacy*, (London, Palgrave Macmillan).

Geyer, R. (2007), New Kids on the Block: Internet Savvy Youth and Distributed Intelligence', in Remenyi, ed. *2nd International Conference on e-Learning (ICEL 2007)* (New York, NY, Academic Conferences Ltd) (167-72).

Gilmore, C.K., McCarthy, S.E., and Spike, E. (2007), 'Symbolic Arithmetic Without Instruction', *Nature*, 447, 589-91.

Hannon, E. E., and Trehub, S. E. (2005), 'Metrical Categories in Infancy and Adulthood', *Psychological Science*, 16, 48-55.

Hannon, E. E., and Trehub, S. E. (2005), 'Tuning in to Musical Rhythms: Infants Learn More Readily Than Adults', *Proceedings of the National Academy of Sciences (USA)*, 102, 12639-43.

Harter, S. (1978), 'Pleasure Derived from Cognitive Challenge and Mastery', *Child Development*, 45, 661-69.

Herman, J.P., and Cullinan, W.E. (1997), 'Neurocircuitry of Stress: Central Control of the Hypothalamo-Pituitary-Adrenocortical Axis', *Trends in Neurosciences*, 20, 78-84.

Higuchi, S., Motohashi, Y., Liu, Y., Ahara, M., and Kaneko, Y. (2003), 'Effects of Vdt Tasks with a Bright Display at Night on Melatonin, Core Temperature, Heart Rate, and Sleepiness', *Journal of Applied Physiology*, 94.5, 1773-76.

Higuchi, S., Motohashi, Y., Liu, Y., and Maeda, A. (2005), 'Effects of Playing a Computer Game Using a Bright Display on Presleep Physiological Variables, Sleep Latency, Slow Wave Sleep and Rem Sleep', *Journal of Sleep Research*, 14.3, 267-73.

Hillman, C.H., Erickson, K.I., and Framer, A.F. (2008), 'Be Smart, Exercise Your Heart: Exercise Effects on Brain and Cognition', *Nature Reviews Neuroscience*, 9, 58-65.

Hoeft, F., Watson, C.L., Kesler, S.R., Bettinger, K.E., and Reiss, A.L. (2008), 'Gender Differences in the Mesocorticolimbic System During Computer Game-Play', *Journal of Psychiatric Research*, 42, 253-58.

Howard-Jones, P.A., Blakemore, S.J., Samuel, E., Summers, I.R., and Claxton, G. (2005), 'Semantic Divergence and Creative Story Generation: An Fmri Investigation', *Cognitive Brain Research*, 25, 240-50.

Howard-Jones, P.A., and Demetriou, S. (in press), 'Uncertainty and Engagement with Learning Games', *Instructional Science*.

Hutchinson, S., Lee, L. H., Gaab, N., and Schlaug, G. (2003), 'Cerebellar Volume of Musicians', *Cerebral Cortex*, 13, 943-49.

Huttenlocher, P.R. (1979), 'Synaptic Density in Human Frontal Cortex – Developmental Changes and Effects of Aging', *Brain Research*, 163, 195-205.

Hyatt, K.J. (2007), 'Brain Gym: Building Stronger Brains or Wishful Thinking?', *Remedial and Special Education*, 28.2, 117-24.

Immordino-Yang, M.H., and Damasio, A.R. (2007), 'We Feel, Therefore We Learn: The Relevance of Affective and Social Neuroscience to Education', *Mind, Brain and Education*, 1.1, 3-10.

Jaeggi, S.M., Buschkuehl, M., Jonides, J., and Perrig, W. J. (2008), 'Improving Fluid Intelligence with Training on Working Memory', *Proceedings of the National Academy of Sciences (USA)*, 105.19, 6829-33.

Joels, M., Pu, Z.W., Wiegert, O., Oitzl, M.S., and Krugers, H.J. (2006), 'Learning under Stress: How Does It Work?' , *Trends in Cognitive Sciences*, 10.4, 152-58.

Kaufmann, L. (2008), 'Dyscalculia: Neuroscience and Education', *Educational Research*, 50.2.

Kirchhoff, B.A., and Buckner, R.L. (2006), 'Functional-Anatomic Correlates of Individual Differences in Memory', *Neuron*, 51.2, 263-74.

Knutson, B., Adams, C.M., Fong, G.W., and Hommer, D. (2001), 'Anticipation of Monetary Reward Selectively Recruits Nucleus Accumbens', *Journal of Neuroscience*, 21.RC159, 1-5.

Koelsch, S., Kasper, E., Sammler, D., Schulze, K., Gunter, T., and Friederici, A.T. . (2004), 'Music, Language and Meaning: Brain Signatures of Semantic Processing', *Nature Neuroscience*, 7, 302-07.

Koepp, M.J., Gunn, R.N., Lawrence, A.D., Cunningham, V.J., Dagher, A., Jones, T., Brooks, D.J., Bench, C.J., and Grasby, P.M. (1988), 'Evidence for Striatal Dopamine Release During a Video Game', *Nature*, 393, 266-68.

Kosslyn, S.M. (2005), 'Mental Images and the Brain', *Cognitive Neuropsychology*, 22.3-4, 333-47.

Kounios, J. , Fleck, J.I. , Green, D.L. , Payne, L. , Stevenson, J.L. , Bowden, E.M. , and Jung-Beeman, M. (2008), 'The Origins of Insight in Resting-State Brain Activity', *Neuropsychologia*, 46.1, 281-91.

Krach, Soren, Hegel, Frank, Wrede, Britta, Sagerer, Gerhard, Binkofski, Ferdinand, and Kircher, Tilo. (2008), Can Machines Think? Interaction and Perspective Taking with Robots Investigated Via Fmri', *PLoS ONE*, 3.7, e2597.

Kratzig, G.P., and Arbuthnott, K.D. (2006), 'Perceptual Learning Style and Learning Proficiency: A Test of the Hypothesis', *Journal of Educational Psychology*, 98.1, 238-46.

Luna, B. (2004), 'Algebra and the Adolescent Brain', *Trends in Cognitive Sciences*, 8.437-439.

Maguire, E.A., Gadian, D.S., Johnsrude, I.S., Good, C.D., Ashburner, J., Frackowiak, R.S., and Frith, C.D. (2000), 'Navigation Related Structural Change in the Hippocampi of Taxi Drivers', *Proceedings of the National Academy of Sciences (USA)*, 97.8, 4398-403.

Malone, T.W. (1981), 'Toward a Theory of Intrinsically Motivating Instruction', *Cognitive Science*, 4, 333-39.

Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., Aerts, J., Del Firoe, G., Degueldre, C., Meulmans, T., Luxen, A., Franck, G., Linden, Van Der, Smith, C., and Cleermans, A. (2000), 'Experience Dependent Changes in Cerebral Activation During Human Rem Sleep', *Nature Neuroscience*, 3.8, 831-6.

Martin, S.J., Grimwood, P.D., and Morris, R.G. (2000), 'Synaptic Plasticity and Memory: An Evaluation of the Hypothesis', *Annual Review of Neuroscience*, 23, 649-711.

Matthewman, S., and Triggs, P. (2004), 'Obsessive Compulsive Font Disorder: The Challenge of Supporting Pupils Writing with the Computer', *Computers & Education*, 43.1-2, 125-35.

McClelland, J.L., and Rogers, T.T. (2003), The Parallel Distributed Processing Approach to Semantic Cognition', *Nature Reviews Neuroscience*, 4, 310-22.

McGaugh, J.L. (2004), 'The Amygdala Modulates the Consolidation of Memories of Emotionally Arousing Experiences', *Annual Review of Neuroscience*, 27, 1-28.

Merrienboer, J.J.G, and Sweller, J. (2005), 'Cognitive Load Theory and Complex Learning: Recent Developments and Future Directions', *Educational Psychology Review*, 17.2, 147-77.

Mousavi, S. Y., Low, R., and Sweller, J. (1995), 'Reducing Cognitive Load by Mixing Auditory and Visual Presentation Modes', *Journal of Educational Psychology*, 87.2, 319-34.

Nieuwenhuis, S., Heslenfeld, D.J., von Geusau, N.J.A., Mars, R.B., Holroyd, C.B., and Yeung, N. (2005), 'Activity in Human Reward-Sensitive Brain Areas Is Strongly Context Dependent', *Neuroimage*, 25.4, 1302-09.

Norton, A., Winner, E., Cronin, K., Overy, L., Lee, D.J., and Schlaug, G. (2005), 'Are There Pre-Existing Neural, Cognitive, or Motoric Markers for Musical Ability?', *Brain and Cognition*, 59, 124-34.

Olff, M., Langeland, W., and Gersons, B.P.R. (2005), 'The Psychobiology of Ptsd: Coping with Trauma', *Psychoneuroendocrinology*, 30.10, 974-82

Paivio, A., and Csapo, K. (1973), 'Picture Superiority in Free Recall: Imagery or Dual Coding?', *Cognitive Psychology*, 5, 176-206.

Pickering, S.J. (2006), *Working Memory and Education*, (London, Elsevier Academic Press).

Pickering, S.J., and Howard-Jones, P. (2007), Educators' Views on the Role of Neuroscience in Education: Findings from a Study of Uk and International Perspectives', *Mind, Brain and Education*, 1.3, 109-13.

Qin, Y., Carter, C.S., Silk, E.M., Stenger, V.A., Fissell, K., Goode, A., and Andersen, J.R. (2004), 'The Change of the Brain Activation Patterns as Children Learn Algebra Equation Solving', *Proceedings of the National Academy of Sciences (USA)*, 101.5686-5691.

Rasch, B.H., Born, J., and Gais, S. (2006), 'Combined Blockade of Cholinergic Receptors Shifts the Brain from Stimulus Encoding to Memory Consolidation, , *Journal of Cognitive Neuroscience'*, 18.5, 793-802.

Rizzolatti, G., and Craighero, L. (2004), ,The Mirror Neuron System', *Annual Review of Neuroscience*, 27, 169-92.

Schlaug, G., Jancke, L., Huang, Y., Staiger, J.F, and Steinmetz, H. (1995), 'Increased Corpus Callosum Size in Musicians', *Neuropsychologia*, 33.8, 1047-55.

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., and Rupp, A. . (2002), Morphology of Heschl's Gyrus Reflects Enhanced Activation in the Auditory Cortex of Musicians', *Nature Neuroscience*, 5, 688-94.

Shastri, L. (2002), 'Episodic Memory and Cortico-Hippocampal Interactions', *Trends in Cognitive Sciences*, 6.4, 162-68.

Shizgal, P., and Arvanitogiannis, A. (2003), Gambling on Dopamine', *Science*, 299, 1856-58.

Skipper, J. I., Nusbaum, H. C., and Small, S. L. (2005), 'Listening to Talking Faces: Motor Cortical Activation During Speech Perception', *Neuroimage*, 25.1, 76-89.

Small, Gary W., Moody, Teena D., Siddarth, Prabha, and Bookheimer, Susan Y. (2009), 'Your Brain on Google: Patterns of Cerebral Activation During Internet Searching', *Am J Geriatr Psychiatry*, 17.2, 116-26.

Snider, V.E., and Roehl, R. (2007), 'Teachers' Beliefs About Pedagogy and Related Issues', *Psychology in the Schools*, 44.873-886.

Sowell, E.R., Peterson, B.S., Thompson, P.M., Welcome, S.E., Henkenius, A.L. , and Toga, A.W. (2003), 'Mapping Cortical Change across the Human Life Span', *Nature Neuroscience*, 6 3, 309-15.

Springer, S.P., and Deutsch, G. (1989), *Left Brain, Right Brain*. (New York, Freeman).

Squire, L.R. (2004), 'Memory Systems of the Brain: A Brief History and Current Perspective', *Neurobiology of Learning and Memory*, 82, 171-77.

Steinberg, L. (2008), 'A Social Neuroscience Perspective on Adolescent Risk Taking', *Developmental Review*, 28, 78-106.

Stewart, L., and Williamon, A. (2008), 'What Are the Implications of Neuroscience for Musical Education?', *Educational Research*, 50.2.

Tettamanti, M., Buccino, G., Saccuman, M.C., Gallese, V., Danna, M., Scifo, P., Fazio, F., Rizzolatti, G., Cappa, S.F., and Perani, D. (2005), 'Listening to Action-

Related Sentences Activates Fronto-Parietal Motor Circuits', *Journal of Cognitive Neuroscience*, 17.2, 273-81.

TLRP (2006), 'Improving Teaching and Learning in Schools: A Commentary by the Teaching and Learning Research Programme.' (London, TLRP).

TLRP (2007), 'Principles into Practice: A Teacher's Guide to Research Evidence on Teaching and Learning.'

Tvesrky, B., and Morrison, J.B. (2002) Animation: Can It Facilitate?, *International Journal of Human-Computer Studies*, 57, 247-62.

Valkenburg, P. M., and Peter, J. (2009), 'Social Consequences of the Internet for Adolescents: A Decade of Research', *Current Directions in Psychological Science*, 18.1, 1-5.

Van den Bulck, J. (2004), 'Television Viewing, Computer Game Playing, Internet Use and Self-Reported Time to Bed and Time out of Bed in Secondary-School Children', *Sleep*, 27 101-04.

van Duijvenvoorde, A. C. K., Zanolie, K., Rombouts, Sarb, Raijmakers, M. E. J., and Crone, E. A. (2008), 'Evaluating the Negative or Valuing the Positive? Neural Mechanisms Supporting Feedback-Based Learning across Development', *Journal of Neuroscience*, 28.38, 9495-503.

Varma, S., and Schwartz, D.L. (2008), 'How Should Educational Neuroscience Conceptualize the Relation between Cognition and Brain Function? Mathematical Reasoning as a Network Process', *Educational Research*, 50.2.

Wagner, U., Gais, S., Haider, H., Verleger, R , and Born, J. (2004), 'Sleep Inspires Insight', *Nature*, 427.6792, 352-5.

Waterhouse, L. (2006), 'Multiple Intelligences, the Mozart Effect, and Emotional Intelligence: A Critical Review', *Educational Psychologist*, 41.4, 207-25.

Weisberg, D.S., Keil, F.C., Goodstein, J., Rawson, E., and Gray, J. (2008), 'The Seductive Lure of Neuroscience Explanations', *Journal of Cognitive Neuroscience*, 20.3, 470-77.

Wintour, P. (2009), 'Facebook and Bebo Risk "Infantilising" The Human Mind,' *Guardian* (London).