STELLAR

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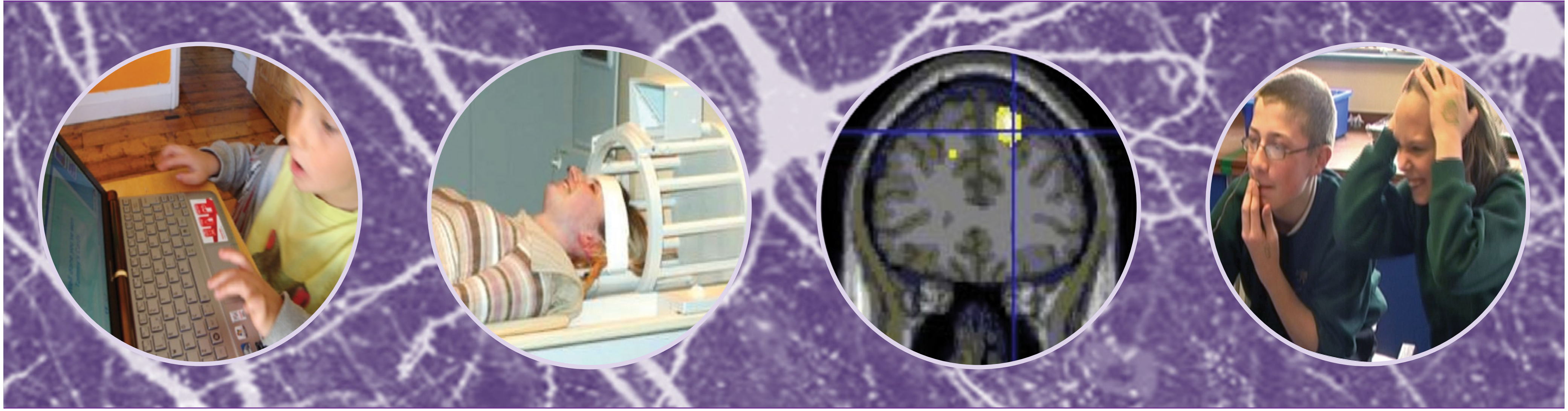
innovation in education

Neuroscience and technology enhanced learning



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Summary

Burgeoning insights from the sciences of mind and brain are generating fresh perspectives on education. Their impact may be greatest where another force for change, technology, is already transforming how we learn. However, to date, little work has focused specifically on the potential of the neurosciences to inform the design and use of technology enhanced learning (TEL). This document reviews some of the insights of relevance to TEL, and discusses how neurobiological concepts might be included in TEL theory and practice.

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Acknowledgements

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About the brain: Function, anatomy and methods

No expert knowledge of neuroanatomy is required to understand this review, but some basic facts are helpful for two reasons:

- they will help you visualize some of the brain regions you will encounter later, and help you understand and remember the principles discussed
- they are a good first defence against neuromyth in TEL.

If you already know some basic neuroscience, you may wish to skip this section and go straight to page 11.

The adult brain contains about 100 billion brain cells – or **neurons**. Each neuron, such as shown in Figure 1.1, consists of a **cell body**, from which are connected **dendrites** and an **axon**.

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 1.2.

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**. It is this electrical nature of neural activity that creates minute changes in the electrical field around our heads, that can be measured using Electroencephalography (EEG – see Box 1).

However, the process that allows the signal to pass through from the synaptic terminals to the dendrites of the next neuron is chemical. The electrical signal travelling in the transmitting neuron causes chemicals called **neurotransmitters** to be released from its presynaptic terminals and bind to **receptors** on the dendrites of the receiving neuron, influencing the electrical signal that this neuron now generates.

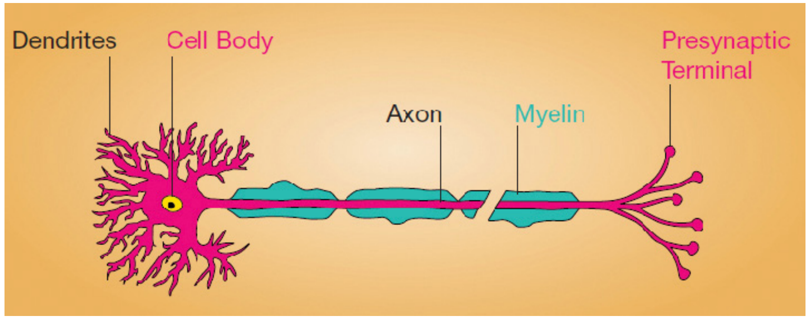

Figure 1.1 Each neuron in the brain consists of cell body, from which are connected dendrites and an axon. The axon ends in presynaptic terminals that form connections (synapses) with the dendrites of other neurons (see Figure 1.2).

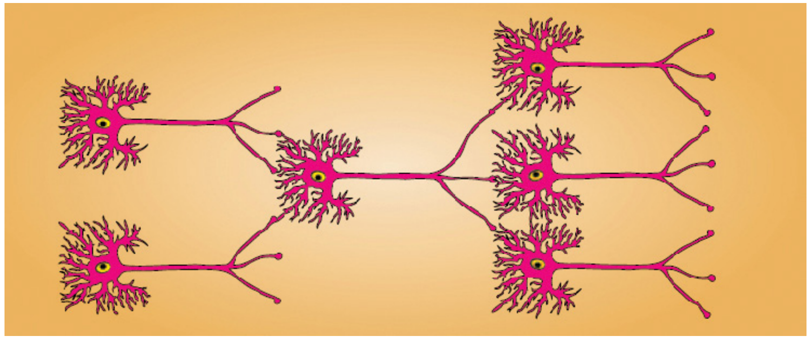

Figure 1.2 Neurons connect together to form networks.

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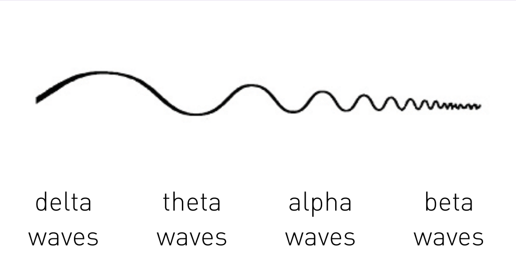
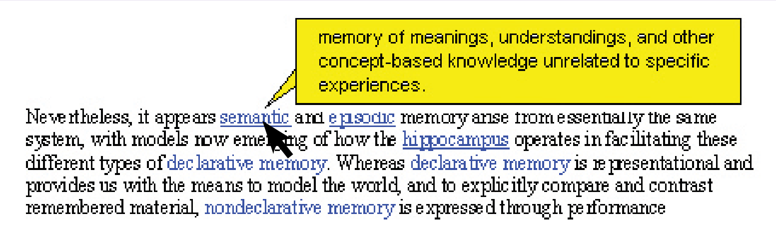
Box 1 Electroencephalography (EEG)

EEG measures the electrical field near the scalp generated by neural processing, which generates at least four distinct rhythms (delta, theta, alpha, beta in order of diminishing wavelength). Alpha and theta activity is related to task difficulty or cognitive load, allowing EEG to be used to detect changes in instantaneous cognitive load when a learner is interacting with technology, even if he/she is unaware or unable to report this change [2].

A recent study showed EEG was more effective than self-report measures in an investigation of leads (or hypertext node previews) [4]. The study revealed how these links influence **cognitive** load, so reducing mental burden associated with creating coherence between two linked nodes.

EEG has excellent temporal resolution (in the order of milliseconds) which allows it to accurately detect when the brain responds in relation to a stimulus. It can help us describe the rapid sequencing of neural processes that underlie a behavioural response. It is non-invasive which makes it suitable for use with children of all ages, and its portable nature makes mobile use possible. The output of EEG can be processed in real-time, supporting applications that require online measurement of neural response (eg as part of an adaptive system). It does, however, have poor spatial resolution, although special source localisation techniques have improved its ability to identify the activity in different cortical regions.





memory of meanings, understandings, and other concept-based knowledge unrelated to specific experiences.

Nevertheless, it appears 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. 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

Example of a hypertext node

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Our brains, like those of other vertebrates, consist of the three main parts (**forebrain**, **midbrain** and **hindbrain**) shown in Figure 1.3. The hindbrain includes structures regulating bodily functions such as sleep and blood flow. It also contains a cauliflower-like structure at the back of 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 appreciate reward and enjoy games. 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 fibres known as the **corpus callosum**.

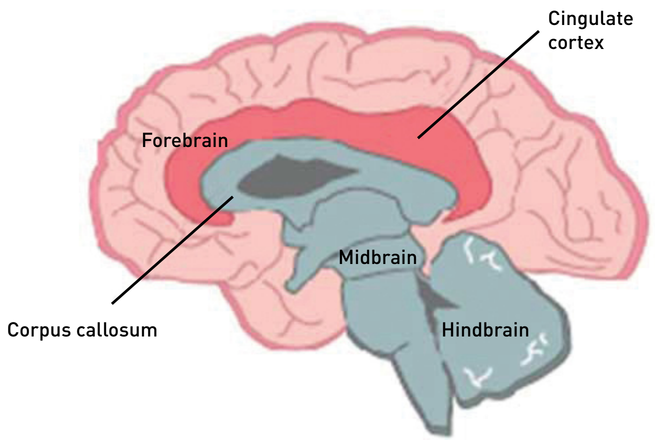


Figure 1.3 Section through the brain showing division into forebrain, midbrain and hindbrain regions. This diagram also shows the position of the corpus callosum which connects hemispheres, and the cingulate cortex.

The cortex can be further divided into four **lobes**: the **frontal**, **parietal**, **occipital** and **temporal** as in Figure 1.4. Note that these names are sometimes joined together such that the term 'occipitotemporal' (used below) refers to a region intersecting across both lobes. 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 behaviour. 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. The temporal lobes have 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 significance of some types of cognitive function, more than others, being associated with particular regions in the brain is often misinterpreted. It does not mean that our different daily activities can be neatly mapped onto different parts of the brain – with a bit for creativity, maths, 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' thoughts and actions recruit processes distributed across the brain.

The functionality of different brain regions is sometimes used to support learning style theory. For example, some have suggested categorising learners as 'left-brained' or 'right-brained', or as 'visual', 'auditory' or 'kinaesthetic'. Neuroimaging techniques such as functional Magnetic Resonance Imaging (fMRI – see Box 2) generate static pictures of well-defined islands of activity that can mislead in this respect. They appear to show just a few parts of the brain as being active. In reality, however, these 'hot spots' usually correspond to where the difference in activity between two conditions compared by the experimenter has exceeded an arbitrary threshold. No part of the brain is ever normally inactive in the sense that no blood is flowing. Furthermore, performance in most everyday tasks, including learning, requires many regions in both hemispheres to work together (helped by the corpus callosum) in parallel. In reality, brain activity at any moment is occurring, to greater or lesser extent, throughout the brain.

Static brain images belie the rapidly changing nature of real brain activity. If the technology was better, scientists could show shimmering changes of activity all over the brain, fluctuating on time scales of milliseconds. The idea we use the left side of our brain in one task and the other side of our brain in another is very far from the mark. The division of people into left-brained and right-brained takes this misunderstanding one stage further. At the end of their extensive review, Coffield et al. [5] concluded there were no clear implications for pedagogy arising from any existing models of learning styles, and psychological research has labelled learning styles as 'wasted effort' [6].

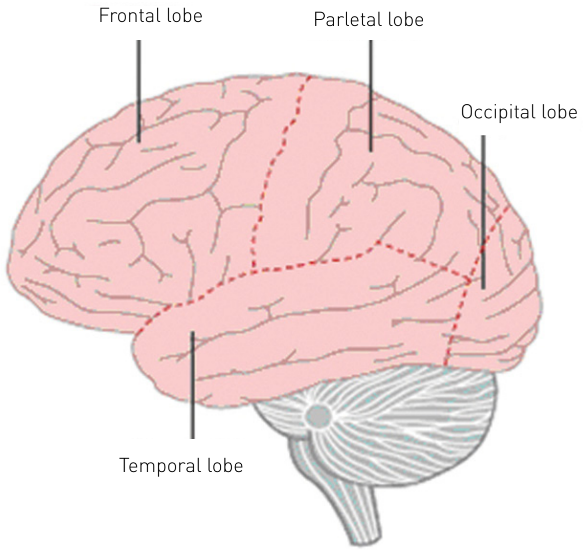


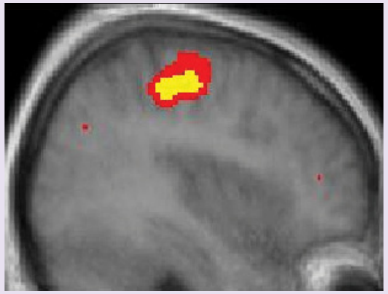
Figure 1.4 Each cortical hemisphere is divided into four lobes.

Box 2 Functional Magnetic Resonance Imaging (fMRI)

In this method, the participant is placed with a strong magnetic field (about 10,000 times the strength of the Earth's magnetic field). The hydrogen nuclei (or protons) in the participant's body respond to this field by aligning themselves with it. A secondary magnetic field produced by a coil around the head is then pulsed at radio frequency, and this causes the protons to temporarily change their alignment again. It is the way in which the protons relax back that produces the important signal, which can be picked up by the coil. Haemoglobin has different magnetic properties depending on whether it is oxygenated or not and, in the brain, this depends on the activity of local neurons. Thus, by computerised analysis of the relaxation signal, it is possible to determine a Blood-Oxygen-Level Dependent (or BOLD) signal corresponding to activity in different parts of the brain. The chief advantage of fMRI, compared with other brain imaging techniques, is a spatial resolution that allows identification of activity within 3mm. However, due to the time taken for the blood to respond, its temporal resolution is a few seconds.

fMRI recently revealed how we learn when playing a computer-based game against an artificial competitor, suggesting our brains can represent technology as having a mind.

In this study, Howard-Jones et al. (2010) found that players' neural circuits mirrored their competitor's virtual actions as if they were their own, and then inhibited these actions if they resulted in unexpected failure. The image on the right shows where the player's mirror neuron system increased its activity both when they made left-handed moves (compared with right-handed) and when they observed their computer opponent making the same 'virtual' moves – even though they knew it was a computer (without left and right hands).



Brain image © 2010 from Howard-Jones, P. A., Bogacz, R., Yoo, J. H., Leonards, U., & Demetriou, S. (2010). The neural mechanisms of learning from competitors. Neuroimage, 53(2), 790-799. Reproduced by kind permission of Elsevier Inc.

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 1.5). 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 how and where we allocate our attention. Journeying deeper inside each of the temporal lobes, you 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. Emotional and memory processes are not situated in a single place in the brain but are distributed in many different regions. However, 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 its effects on our attention and memory. This is one of the dopaminergic pathways in the brain, involving movement of the neurotransmitter **dopamine** from one to 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 strongly related to our motivation towards many different types of rewarding activity (food, money, sex, etc).

Below the thalamus (in Figure 1.5) is a small structure known as the **hypothalamus** (not shown), that helps control a range of internal body processes that can occur without conscious awareness (including body temperature, hunger, thirst and circadian cycles). The hypothalamus and regions within the brainstem can generate changes in a range of measurable physiological signals. These indicators of bodily arousal, which are much simpler to measure and analyse than the neural signals detected by fMRI and EEG, can also be used to investigate mental processing. For example, electrodermal activity (EDA) can be used to index attention, with findings suggesting commonality in the neuroanatomy supporting both attention and the bodily arousal related to EDA change [7]. Early effects of emotional arousal on cerebral activity are also significantly correlated with later increases in EDA magnitude [8]. For an example of the use of heart-rate, see Box 3.

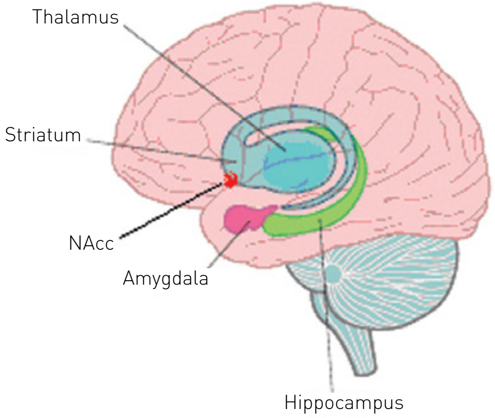
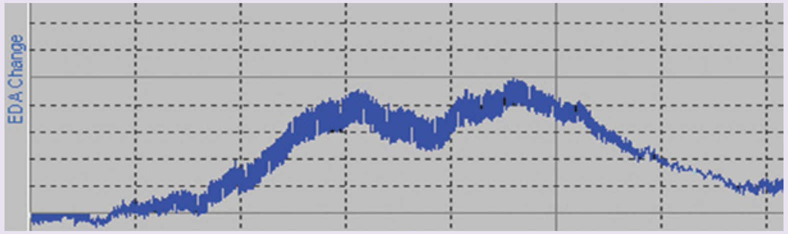


Figure 1.5 Some important sub-cortical (below the cortex) structures include the thalamus, hippocampus, amygdala and nucleus accumbens (or NAcc)

Box 3 Simple Physiological Measurements - Electrodermal activity (EDA)

Lim and Reeves used EDA, heart-rate and self-report to study influence on physiological arousal of being able to choose avatar and visual point of view (POV) when playing 'World of Warcraft'[3]. Their study demonstrated that being able to pick the character that will represent the player in the game led to greater arousal, especially for males.

Different POVs did not appear, on their own, to affect the game player's arousal, but moderated the effect of avatar choice on the game player's heart rates. Importantly, these effects were not observable in self-reports provided by participants, which suggests that simple physiological measures can capture aspects of user-interaction that the user is not consciously aware of.



Neuroscience with potential relevance for TEL

Developmental disorders

Neuroscience is shedding light on a range of developmental disorders including dyslexia and dyscalculia. Some neuroscientists have already been actively involved in developing technology-based educational interventions that seek to apply this knowledge. For example, Butterworth and Laurillard suggest several attractions of applying our emerging knowledge of dyscalculia in educational digital technology [9]. They point out that digital implementation can be:

- practice-oriented (providing easily-accessed and unsupervised repeated practice)
- age-independent
- needs-oriented (eg providing alternative input/output modes for learner also suffering from slight dyspraxia or reading difficulties)
- meaningful (eg they can link the physical to the abstract in ways not possible in the physical world, such as when a learner 'zooms into' a 1–10 number line to discover decimal numbers)
- used to offer private, unthreatening interaction and feedback in an endlessly patient fashion.

These potential advantages of integrating our scientific understanding with technology are relevant when remediating a broader range of developmental disorders. Although claims about the general effectiveness of commercial programmes must be carefully scrutinised [10], neuroimaging can also provide insights in cases where successful results are reported. For example, a dyslexia intervention using commercially available language training software reported partial remediation and improved reading, with remediation of previously disrupted function in brain regions associated with phonological processing [11]. Similarly, a recent study used an educational game based on neuroscientific understanding to demonstrate remediation of dyscalculia in terms of numerical performance and brain function [12]. When the cognitive and neural data converge in this way, we can be more confident in the underlying theoretical models and the effectiveness of the intervention, and such imaging studies can also inform the future design of interventions.

Individual differences beyond abnormal development

Historically, neuroscientists have focused more upon abnormal than normal development and this helps explain why the first examples of neuroscience in TEL have been aimed at ameliorating developmental disorders. However, understanding from neuroscience has increasingly wider implications for TEL, with relevance to a range of mainstream TEL concepts.

Although a preference for a particular learning style does not appear helpful in educational terms, we have seen (in Box 3) how some types of digital **personalization** can influence emotional engagement. Neuroscientific techniques may also provide insights into **individual differences** on a range of factors that can inform how technology might be tailored to suit particular types of learner. These factors may include ability, but also gender and age. One study has highlighted gender differences in how individuals respond to video games [13], which have been cited as an informative and engaging context that educators may wish to understand and learn from [14]. In another example, the type of feedback which is optimal for our brain to learn appears dependent upon our maturity. Here, in a study of a computer-based rule search and application task, brain imaging data suggested a qualitative difference in how children and adults use performance feedback, with a transition around 11-13 years-old towards an increased influence of negative feedback on performance adjustment [15]. Understanding how our ability to self-regulate develops through to adulthood may also provide insights and reasoned expectations (rather than constraints) about the **self-regulated learning** of children at different ages. Recent research shows how a range of factors that are critical to successful self-regulated learning (processing speed, voluntary response suppression, and working memory) mature across different age groups [16], and this development is linked to an understanding of structural changes that occur in the brain until early adulthood [17].

Adaptive systems

Technology can adapt dynamically to the changing needs of the learner based on an automatic assessment of their responses. This assessment can be informed by neuroscience and the potential of combining TEL and neuroscience in **adaptive educational systems** has been highlighted in the UK as an area of research deserving future investment [18]. An example of where scientific research has been integrated with an adaptive educational system 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 [19]. In this game, online algorithms analyze a child's performance and rewrite the lesson plans 'on the fly' depending on which specific confusions the learner shows [20]. The difficulty of the content is adjusted so that the challenge matches the learner's ability. Using brain imaging, it has been shown that practice with the game could initiate print-sensitive activation in a critical component of the mature reading network located in the left occipitotemporal cortex, termed the 'visual word-form system' [21]. The establishment of this occipitotemporal print sensitivity during the earliest phase of reading acquisition in childhood suggests a crucial part of the later reading network first adopts a role in mapping print and sound. Such results provide insight into how the software succeeds in supporting literacy, how/when it should be implemented and how neuroscience can be used to inform TEL design. McCandliss [20], reflecting on this and other studies, suggests:

> "Given that adaptive educational computer programs are being developed in tandem with imaging studies of how such innovations drive changes in brain activity, new possibilities may emerge for educational and neuroscience research efforts to inform one another in increasingly rapid cycles."

Multimodality

It has been known for some time that illustrating text can enhance memory [22], with pictures of objects appearing more memorable than their names. This effect provides an important justification for the type of **multimodality** that technology can provide. Use of multimodality might be further informed by a study showing it can produce additional brain activity over and above that produced by experiencing each mode separately [23]. In this study, participants were scanned while exposed to auditory and visual characteristics of tools (hair-dryer, hammer etc) and the additional activities from multimodal exposure arose from making links between visual and auditory features. This automatic recruitment of additional processing might suggest we should necessarily observe improved memory for stimuli presented multimodally. However, this is not always the case. Simply presenting cues in two modes does not guarantee improved long-term memory (although it can decrease the load on working memory). The effectiveness of multimodal presentation as a memory/learning strategy appears to rely on whether it encourages processing related to educational objectives [24].

Andreano et al. recently studied the effects of increasing the immersive nature of a virtual reality environment, with the hypothesis that this should increase brain activity associated with learning [25]. The study showed that adding auditory cues to a virtual reality environment (comparing unimodal with multimodal) increased activation in the hippocampus, a region strongly associated with memory formation, thus supporting the hypothesis. The educational use of **tangibles** may also be informed by fresh understanding from neuroscience. For example, topics involving shape have been principally taught through the medium of vision, but there is increasing evidence for shape information being easily transferable between vision and haptics. A recent imaging study suggests that the relationship between audio and visual processes, which may be considered complimentary in their differences, may not resemble the relationship between haptic and visual processes, which may be considered more similar. Indeed, object recognition by touch and vision activate several overlapping and closely-related brain regions (see Figure 2.1). In this study, the researchers observed 'enhanced effectiveness', in neural terms, of combining haptic and visual stimulus [26]. That is, the multisensory gain with a combination stimulus was greater when its unisensory components were themselves associated with greater neural activity.

Neurocomputational models of behaviour (models based on our understanding of neural systems) can help inform us about how visual cues engage our primary visual processes. These processes have been shown to account for a significant portion of human gaze behaviour in a naturalistic, interactive setting [27]. It has been suggested that these algorithms may be useful in the implementation of interactive virtual environments, both to predict the cognitive state of human operators, as well as to effectively endow virtual agents in the system with human-like visual behaviour.

Neurocomputational bottom-up models of visual processing [28] can also be used to predict salience and memory for locations of objects on a screen, with memory effects strengthening with task difficulty [29]. This could be of immediate value in TEL design, since such algorithms can support the designer when seeking to assign what parts of the screen they wish to be salient and remembered.

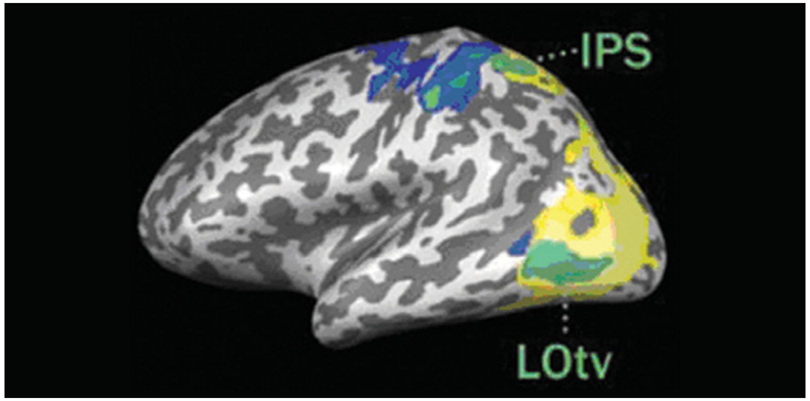


Figure 2.1 Regions of the brain that activate for visual and haptic object recognition overlap. Tangibles activate both types of information about shapes and these appear to enhance each other's neural effectiveness

YELLOW = activation due to visual object recognition

BLUE = activation due to haptic object recognition

GREEN = overlapping activation regions

Image © 2010 from Kim, S. and T.W. James, **Enhanced Effectiveness in Visuo-Haptic Object-Selective Brain Regions with Increasing Stimulus Salience.** Human Brain Mapping, 2010. **31**(5): p. 678-693. Reproduced by kind permission of Wiley-Liss.

Engaging with others - human and artificial

Advances in fMRI techniques are now allowing the neural substrates of social processes to be imaged. This is providing insights into the subtleties of how we engage with others in simple co-operative tasks, which can contribute to our understanding of **collaborative learning**. A recent study identified a key brain region for both social interaction and joint attention in the right temporal lobe. By considering activations of this region in this and other studies [30, 31], the authors suggest that full joint attention requires more than just simultaneously gazing at the same object. Instead, two people must deliberately coordinate attention on the object, usually with the expectation that the object will be rewarding (for cooperative exchanges) and/or relevant (for communicative exchanging), and it is this behaviour that activates this region of the brain. In other research, it has been found that several aspects of social interaction that may support collaborative learning, such as interactional synchrony, anticipation of other's actions and co-regulation of turn-taking, are associated with neural synchronisation between collaborators' brains as measured by EEG [32]. Brain research has also helped establish a better understanding of how trust between potential collaborators develops through reciprocity [33, 34] and how different contexts engender different types of trust [35].

Technology is providing new opportunities to share ideas and neuroscience is helping us understand how this can improve our individual and collective **creativity**. A recent brain imaging study suggests that accessing the ideas of others may enhance creativity by reducing the need to deactivate automatic bottom-up processes (associated with fixation on one's own ideas) [36]. That is, when we are trying to think of new ideas on our own, we must suppress those within our immediate attention in order to find original and novel associations (Figure 2.2). However, another study has shown that creativity can also be boosted by incorporating unrelated ideas, and this recruits brain regions supporting higher level conscious control, because of the increased need to evaluate and reject unsuitable outcomes. That can help explain why more time is sometimes required to make the types of remote associations that support creative thinking [37].

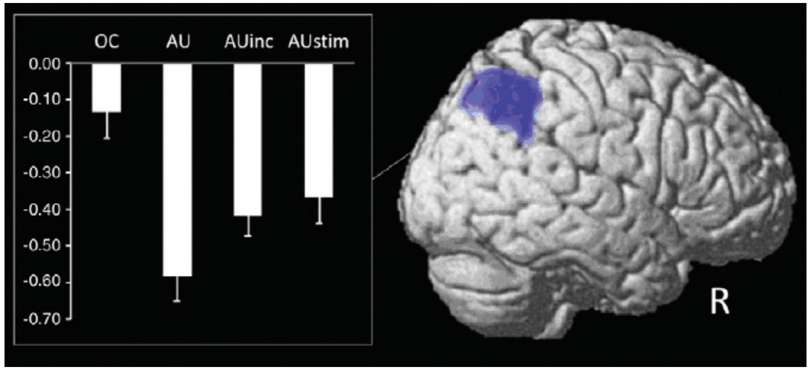


Figure 2.2 In a recent neuroimaging study by Fink and colleagues (2010) [36], participants were asked to produce typical characteristics (OC) or unusual uses (AU) to a given stimulus word. In the AUinc condition, participants were allowed to 'incubate' their ideas before responding and, in the AUstim condition, they were encouraged to reflect on the ideas of others before responding. The AUstim condition provided the most original responses, and was associated with greater deactivation of the angular gurus – which is involved with automatic bottom-up, or low level, processing. Accessing the ideas of others may enhance creative efficiency by reducing the need to deactivate such processes.

Image © 2010 from Fink, A., et al., **Enhancing creativity by means of cognitive stimulation: Evidence from an fMRI study.** Neuroimage, 2010. **52**(4): p. 1687-1695. Reproduced by kind permission of Elsevier Inc.

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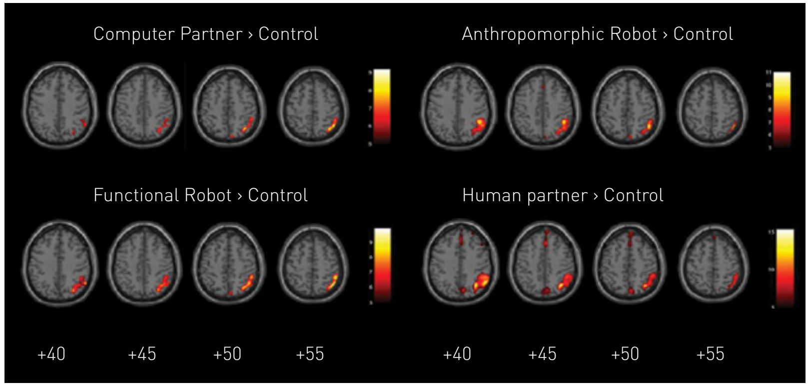
Other work suggests individual differences in creative ability may be related to differences in focus of attention [38], suggesting personalisation might include support which is differentiated according to users. For example, support might be provided for helping more-focused individuals make remote associations, and to help less-focused individuals evaluate their ideas more thoroughly. Taken together, this work may provide a means to understand the creative benefits of sharing ideas, that greater conscious effort is required when connecting remotely associated ideas, and a basis for understanding individual needs in respect of creativity.

Understanding how our brain responds to other humans can also shed light on our response to **artificial agents** (tutors, competitors, collaborators). New learning technologies that simulate individual human-like tutoring can benefit from what we understand about human processes of imitation, shared attention and empathy [1]. Although we have already seen that visual appearance is not a prerequisite (see Box 3) for activating some of these processes, it does seem that it can play an important role. When we 'communicate' with non-human technology we may recruit brain regions usually involved with communicating face-to-face with each other, but more so 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, ie a theory of mind. In a recent fMRI study, participants were asked to play a game against different types of opponent who, unbeknown to them, were all playing randomly [39]. 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 cosmetic attempts to make technology more human-like may significantly influence how we engage with it (Figure 2.3).



Interaction partner				
Condition	Computer partner (CP)	Funtional robot (FR)	Anthropomorphic robot (AR)	Human partner (HP)
Human-likeness	No human shape; no perceivable button pressing	No human shape; button pressing with artificial hands	Humanlide shape; button pressing with humanlike hands	Human shape; button pressing with human hands

Figure 2.3 Regions associated with 'theory of mind' grow more active as the appearance of a technological opponent becomes more human-like, even when it is clearly not human. [39]

From Krach, S., Hegel, F., Wrede, B., Sagerer, G., Binkofski, F., & Kircher, T. (2008). Can machines think? Interaction and perspective taking with robots investigated via fMRI. [; Research Support, Non-U.S. Gov't]. PLoS ONE, 3(7), e2597. Reproduced by kind permission of PLoS ONE. © 2008.

Through technology, we are now able to experience 24/7 **mobile, ubiquitous and pervasive learning**, but understanding its effectiveness may require attention to biological contexts. Sleep plays an important role in memory, so 'when' we learn influences 'how well' we learn, with better recall following a period asleep than after the same period awake. Since technology now makes it easier for us search out, learn, communicate and apply knowledge all day and all night, this access can impact negatively on our sleep. For example, hormonal developmental influences produce a phase delay in the circadian timing mechanism of teenagers, but the use of mobile technology has also been shown to contribute to their sleep loss [40].

A recent study in the US showed the average teenager indulging in around four activities involving technology after 9.00pm, spending over an hour on each [41]. When we sleep after learning, the hippocampus in our brain rapidly integrates this information within distributed regions of the cortex [42]. Successive sleep-dependent reactivation of this hippocampal-cortical network leads to progressive strengthening of connections across the cortex which, over time, allows these memories to become independent of the hippocampus and gradually integrated with other, pre-existing cortical memories. Therefore, not only does sleep support our recall of these memories but it also supports our ability to make links between these memories and older ones, which is important for our creative functioning. So, when access to technology impacts on our sleep habits, it can be detrimental to both our learning and our creativity. Disruption of sleep and associated impairment of memory consolidation has been demonstrated for playing video games in the evening [43]. Moreover, activities involving close bright screens are able to delay the brain's production of the hormone melatonin and so interrupt sleep-cycles in ways that a TV screen does not [44, 45].

Video games – a case of special interest for neuroscience

Although often characterised in the popular press as mindless activities, it seems that computer games can influence the development of abilities that psychologists call 'skills' [46-54]. These skills include very basic perceptual, cognitive and motor (movement) abilities rather than higher-order reasoning skills or the 'thinking skills' taught in schools. They can, however, contribute to the efficiency with which many everyday tasks are carried out, including, tasks that are critical to some professions and fields of learning. An early study by Gopher [55] showed 10 hours of video game experience using Space Fortress (designed specifically to study cognitive training [56]) improved the subsequent flight performance of cadets, resulting in its incorporation into the regular training programme of the Israeli Air Force. (An echo of this finding can be found in recent informal reports that gamers make better drone pilots [57].) In a study of laporoscopic surgery, Rosser et al. [58]found that surgeons who had played video games in the past and were playing video games currently made 37% and 32% less errors (respectively) during examination of their surgical skills. These results join several other studies showing individuals with previous regular engagement with video games have better videoendoscopic surgical skills [59, 60]. Recent developments in video game technology may strengthen this relationship. For example, skill on a Nintendo Wii, with its motion sensing interface, has been shown to be a good predictor of laporoscopic skill [61].

This significance of the ability of video games to enhance transferable cognitive skills is emphasised by the many failed efforts by scientists to do this the past [62-64]. It should also be noted that the training periods used by experimenters with video games are relatively modest compared with the several thousands of hours per year spent gaming by many regular players. This makes video games a special case of scientific interest and efforts are underway to understand why they have such influence on our cognitive abilities. For example, a study by Green et al. [65] implicates improved probabilistic inference as the causal mechanism. That is, action video games appear to train participants in making better decisions about the likelihood of outcomes based on previous history. Action video games rarely repeat exactly the same situation so, as pointed out by Green et al., learning requires an improvement in rapidly and accurately 'learning the statistics on the fly and how to accumulate this evidence more efficiently'. They speculate three possible candidate explanations for the general nature of this learning: it may be linked to development of neural regions that are shared across modalities, and/or the development of the frontoparietal circuits that control these regions, and/or the global release of neuromodulators such as noradrenalin that can improve such probabilistic inference across a wide range of circuits.

A simple observation about video games is their capacity to engage their players, to the point that the attraction of video games can become problematic for some children. Neuroscience research provides some insight into why games are so engaging and why this can become a problem. Along with many other rewarding pleasures such as food, drugs, gambling and music, studies have suggested midbrain dopamine is released when we play video games [66] (but see Egerton, A. **et al.** [67] for constraints on interpretation).

Efforts to understand how persistent drug use influences the brain have focused on mechanisms underlying long-term associative memories in the frontal lobes and striatum which receive input from dopamine neurons in the midbrain [68]. Video gaming provides many instances of reward per unit of time relative to most 'real world' experiences, and a recent study suggests it can release amounts of dopamine comparable to the effects of psycho-stimulant drugs on the brain [69]. Further studies have directly compared the neural responses to video games and drugs likely to induce dependency. For example, when regular video game players encounter images from their game, the response of their brain resembles that observed when drug addicts encounter cues reminding them of their drug [70, 71]. Changes in the brain over a 6 week period of playing video games are comparable to those observed in the early stages of addiction [72].

Problematic gaming may be a serious down side of the ability of video games to capture their players' attention, but there can be significant benefits as well. The ability of such technology to strongly stimulate their player's reward system may also contribute to their potential as teachers. Increases in midbrain dopamine are also associated with improved ability to store and to explicitly recall information (declarative memory) possibly due to the enhanced plasticity that dopamine can provide [73-75]. When models are used to estimate changes in midbrain dopamine during an educational game, these can predict when, during the game, a player can recall newly-learnt educational content [76]. A study of working memory training (see above) has also shown individual improvements in working memory are correlated with changes in cortical dopamine receptor density, supporting the notion that working memory training may help dopamine-based transmission of information in the brain [77]. Such results, and the ability of video games to teach visuo-motor skills (above), are encouraging some neuroscientists to suggest that video games may prove a promising method to 'take the brakes off adult plasticity' [78].

Cognitive training

Despite the accumulating evidence for video games enhancing some cognitive skills, more direct attempts to develop cognitive ability have been less successful. The many commercial products that claim to develop cognitive function have also failed to produce convincing evidence for their effectiveness. Computer-based cognitive training (or so called '**brain training**') has chiefly been found to improve performance on the training itself, rather than transferring to everyday application [64]. One important exception, however, is the training of working memory. Working memory describes our ability to hold information in our attention and it is a major constraint on our ability to learn new concepts. When young adults undertook a 19-day computer-based training program that focused on developing working memory for 30 minutes a day, it was found that not only their working memory, but also their fluid intelligence improved (ie their ability to solve problems in new situations) [79]. A convincing range of such results have led scientists to conclude that working memory can be trained [80], and changes to prefrontal activations associated with working memory training have been identified [81] (see Figure 2.4). This bodes well for those wishing to develop more effective 'brain training' games – but so far the commercial response to these exciting developments has been slow.

Although other types of training, beyond working memory, have been disappointing in their ability to enhance cognitive function, we know that cognitive stimulation (eg reading and socialising) is healthy and can help protect our mental faculties [82]. This can include computer-based training, which has been shown as an effective form of **technology enhanced lifelong learning** amongst the elderly [83] that slows the rates of cognitive decline in adults [84], including suffers of Alzheimers [85].

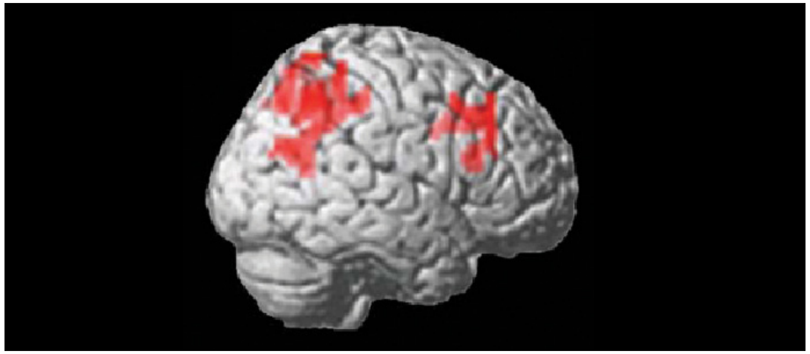


Figure 2.4 Increases in frontal and parietal regions after WM training [81]

Image © 2004 from Olesen, P.J., H. Westerberg, and T. Klingberg, **Increased prefrontal and parietal activity after training of working memory.** Nature Neuroscience, 2004. **7**(1): p. 75-79. Reproduced by kind permission of the Nature Publishing group, a division of Macmillan Publishers Ltd.

Research bridging TEL and neuroscience

The challenge of bridging TEL and neuroscience research is exemplified by their different interpretation of what is meant by 'learning'. The scientific term 'learning' is often synonymous with memory and, whether we need to learn a simple fact or gain a deep understanding, it is generally accepted that memory is important for learning. A particular memory is distributed throughout the brain and does not reside in any one place, although there are some regions linked to particular aspects of memory (such as spatial memory, which depends more on the right hemisphere than left hemisphere). But the fact that memory has to be coded in the brain somewhere appears indisputable. When neural networks were introduced at the beginning of this review, we saw how signals can flow down the axons of one neuron and cross the synapse to other neurons, allowing neurons to communicate with each other. This provides a basis for understanding how the brain is able to process or 'think about' incoming information, but how can this information cause the brain to change in the longer term and represent a new memory? Neuroscientists generally believe that human learning, as in the formation of memory, occurs by changes in these patterns of connectivity between neurons – or 'synaptic plasticity'. (However, note that forming connections between ideas is not the same as forming connections between neurons. We know most about making mental connections from our educational and psychological research rather than from neuroscience. In reality, we are still developing the technology needed to study educational learning at the level of the synapse.)

In education, of course, we think about learning in ways that extend well beyond the concept of memory. Indeed, learning is often considered as happening between people, rather than just inside their brains. This is a very sensible perspective that has underpinned teaching for decades, and it naturally emphasises the importance of social context and complexity. Neuroscientists are only just beginning to study these social aspects of learning. For that reason alone, neuroscience cannot offer anything like a complete story of learning in the classroom. So, what we do know about the learning brain must be combined with educational research and expertise, and also some common sense, if we are to develop TEL that draws on authentic science and is educationally valuable.

Although the task of introducing the brain into ideas about 'real world' learning may appear daunting to some, it seems increasingly unreasonable to exclude it. All learning can be assumed to have a biological substrate, and the rate at which we are coming to understand its underlying neural mechanisms is accelerating. Perhaps in recognition of the brain's central importance to learning, many references to it can be found in the TEL literature, although some of these reveal important misunderstandings. For example, in 2008, the new journal **IEEE Transactions on Learning Technologies** identified key visionaries in the field of TEL and invited these to contribute to a special 'vision' issue. The issue began with discussing the need to focus the design of learning technologies to support social learning in context, echoing the type of emphasis on situated social environments common within other areas of educational thinking. The paper leads off by making several references to neuroscience – and this provides insight into how some in the TEL community may view the relationship between brain and TEL. The second sentence begins

> 'Some authors claim that the internet actually changed the way the human brain is wired'.

This tends to imply a belief that the brain is hard-wired, and difficulty in believing the internet can change the brain's connectivity. From neuroscience, however, we know the brain is plastic and that experience (including educational experience) can change its connectivity, function and even structure [86, 87].

Later, the author suggests the chronic and intense multitasking experienced by 'digital-natives' may:

> 'also delay adequate development of the frontal cortex, the area of the brain that helps us see the big picture, delay gratification, reason abstractly, and plan ahead. Multitasking leads to a short attention span and errors in decisions and judgment'.

Despite lack of convincing scientific evidence for such ideas, the brain is again seen as something that can be potentially damaged by technology, rather than an important element in understanding how we experience technology. Other references indicate a construction of the brain as biologically determined, static and vulnerable to damage from technology. The author balances this rather negative biological concept with the fact that teenagers demonstrate good skills with technology and are very social online, with arguments presented that their skills and interest with technology can be exploited to their educational benefit, through pedagogically-grounded, learner-centered social learning environments. This emphasis on context and social interaction continues in other articles. For example, Pea and Lindgren [88] use words carrying an emphasis on both social and experiential (eg 'authentic') perspectives, indicating an abandonment of 'decontextualised' educational ideas:

> 'We view the Web 2.0 participatory media culture illustrated by media-sharing community sites as exemplifying how new forms of collaboration and communication have important transformative potentials for more deeply engaging the learner in authentic forms of learning and assessment that get closer to the experiences of worldly participation rather than more traditional decontextualized classroom practices.'

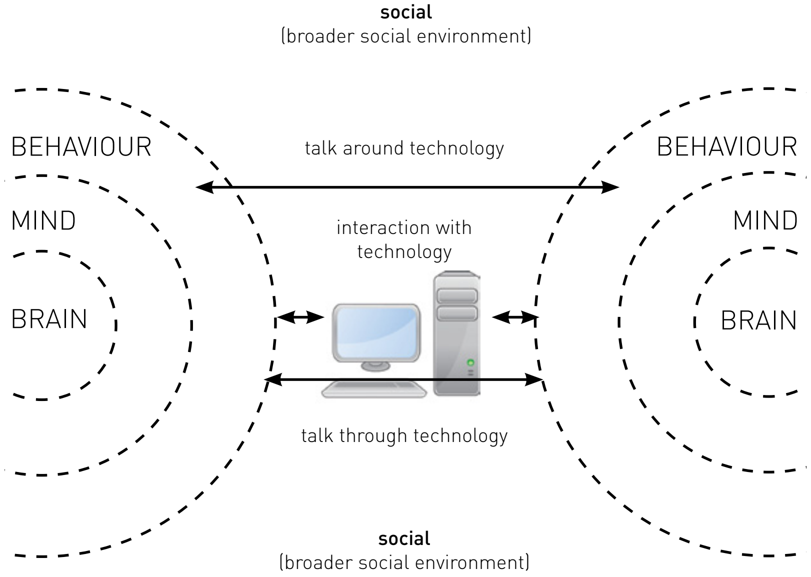


Figure 3.1 A 'levels-of-analysis' approach to understanding the potential interrelation of different perspectives on learning (see text)

We would argue that our neurobiology is an important part of every authentic learning context, and that its omission has served to reinforce the practice of developing decontextualised educational ideas. However, the difference between neuroscience and current TEL perspectives on learning is significant and their interrelation may, therefore, be challenging in terms of building bridges across the natural and social sciences. We propose that a 'levels-of-analysis' approach can help understand where a perspective may be particularly helpful, while also emphasising the need to remain mindful of the broader picture, and acknowledging that learning involves processes spanning brain, mind, behaviour and social context/environment (see Figure 3.1).

While cognitive neuroscience emphasises how neural processes give rise to mental processes, much educational research emphasises how social interaction influences our mind. More accurately, of course, there is a two-way interaction between our biology and our social environment, with mind as an essential concept for understanding the bidirectional influence between brain and behaviour, including learning behaviour. That makes cognitive psychology, as the study of mental models underlying behaviour, crucial to neuroeducational TEL research, as it is to all cognitive neuroscience. When we consider two brain-mind-behaviour models interacting within a social environment as shown in Figure 3.1, we can start reflecting on the complex interaction between cognitive/neural/social processes that can arise when behaviour becomes socially mediated. Social complexity remains chiefly the realm of social scientists, who often make meaning-based interpretations of human communication in order to understand the underlying behaviour. The dotted lines represent the bi-directional influence, emphasizing the extent to which the social/educational environment (as studied in the natural sciences) influences, via the mind, neural learning processes and brain development as well as vice-versa. In this diagram, we can see that technology may have at least three different roles (which are not mutually exclusive):

i) as a stimulus **with** which we can interact individually
ii) as a stimulus **around** which social interaction takes place (eg collaborating around computers)
iii) as a medium **through** which social interaction takes place.

The challenge faced by those wishing to integrate neuroscientific concepts into TEL research is to conceptualise these three types of interaction at the different levels of brain, mind and behaviour, including social behaviour.

The future

This report has highlighted a range of insights from neuroscience that may be of value to those researching and developing TEL. It has also briefly explored some of the issues involved with incorporating biological perspectives into TEL thinking, and the need to interrelate these insights with concepts from more traditional perspectives on learning.

Technology and neuroscience are two fast-moving fields of enterprise that, in some areas of important educational interest, are already becoming intertwined. However, there are at least three reasons why dialogue between the neuroscience and TEL communities is only likely to increase in the future:

1. Education will focus more on cognitive processes similar to those studied by neuroscience

Neuroscience is converging with other influences that are encouraging educators to move away from content towards thinking skills and, more specifically, the training of cognitive function. One of these other forces is the rapid advance of our access to information. Some commentators believe this leads automatically to a greater need for specialisation, as it places 'any human knowledge at the fingertips of any human' [89]. This places greater educational demand on our ability to manipulate information in a broader sense, rather than to practise only encoding and recalling it. The cognitive process, in this broader sense, is a central construct of cognitive neuroscience – and the neuroscience/education dialogue has already prompted a redefinition of education as an attempt to 'nurture' the brain and its processes [90].

2. Cognitive neuroscience already uses technology-based tasks to study learning

Neuroscience often derives knowledge about learning by using computer-based tasks in its experiments, which may make it easier to transfer its findings to technology-based learning contexts, rather than face-to-face classroom contexts. Due to the restrictions of the imaging environment and the need for experimental control, but also because the responsiveness of technology is particularly helpful in developing neurocognitive function, most published findings within cognitive neuroscience involve participants interacting with technology to carry out tasks. This can represent a difficulty for neuroeducational researchers wishing to apply findings to develop face-to-face conventional teaching in classrooms, since the differences between the two contexts are considerable. In contrast, this favours the transfer of neuroscientific knowledge to the development of technology-based learning. Indeed, the few attempts by neuroscientists to develop educational approaches based on their findings have usually included the production of computer-based resources [9, 91, 92].

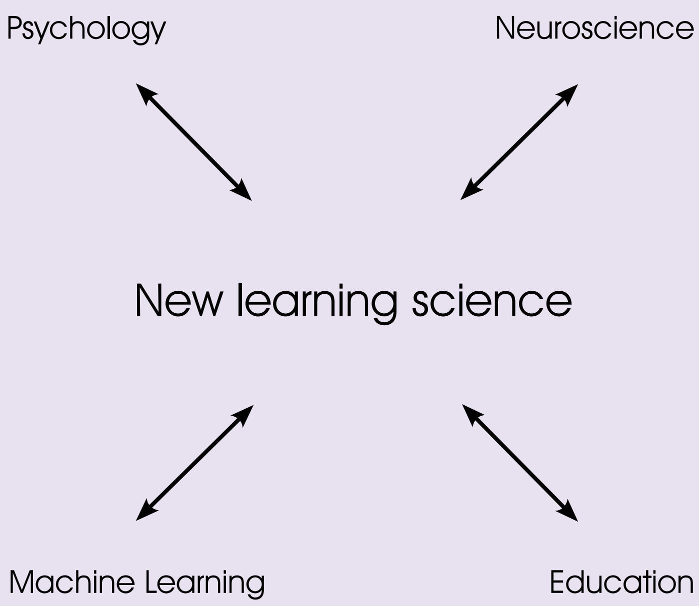
3. Aims of neuroscientists and TEL researchers may converge in terms of 'tool' development

We saw an example above of how a piece of learning technology [19] was used to investigate neurocognitive processes in a brain imaging study [21], whose results could be useful in further developing the technology. This suggests the potential to advance from merely using neuroscience techniques and concepts to inform the development of TEL, towards a cycle of iterative development involving both fields. Indeed, there are already increasing opportunities for closer collaboration that share some immediate professional aims. The examples of screen design and learning games (above) provide examples of how computational 'tools' might easily cross from one field to the other. In these areas, computational algorithms are being developed to support scientific research into human behaviour. These same algorithms can (and have) been used in research to understand how we interact with TEL. Perhaps more importantly, they might also be incorporated into future learning systems, and so enable these to arrange themselves to support optimal learning. That is, they can be used in adaptive learning systems to model the neural response of the learner based on their behaviour, and to optimally adapt to, and efficiently develop, the neurocognitive profile of each individual user. The development of neurocomputational models of learning behaviour are, therefore, an area of immediate benefit to both neuroscientists and TEL researchers.

Finally, dialogue between neuroscience and TEL may benefit TEL researchers by helping to dispel some of the common neuromyths that currently prevail, such as the notion of a hard-wired brain discussed above. Indeed, it may chiefly be misunderstanding, and the distrust that often accompanies it, that has led some commentators to dismiss neuroscience as an implausible 'silver bullet' for education [93]. However, rather than providing simple solutions, most experts see neuroscience as contributing, with other perspectives, to a richer and more sophisticated understanding of learning [1, 94, 95] (see also Box 4). The relevance of neuroscience to education is increasingly undisputed, and it may be within the field of TEL that its early impact will be greatest.

Box 4

Meltzoff [1] explains that a new science of learning is arising from several disciplines. Researchers in developmental psychology have identified social factors that are essential for learning. Powerful learning algorithms from machine learning have demonstrated that contingencies in the environment are a rich source of information about social cues. Neuroscientists have found brain systems involved in social interactions and mechanisms for synaptic plasticity that contribute to learning. Classrooms are laboratories for discovering effective teaching and tools that exploit these insights.



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About STELLAR

STELLAR, Sustaining Technology Enhanced Learning at a LARge scale, is an EU project represents the effort of the leading institutions and projects in European Technology-Enhanced Learning (TEL) to unify our diverse community.

This Network of Excellence is motivated by the need for European research on TEL to build upon, synergize and extend the valuable work we have started by significantly building capacity in TEL research within Europe, which is required to allow the European Union to achieve its goals via the Bologna Agreement and the execution of the Lisbon Agenda. The European TEL agenda has been set for the last four years by the Kaleidoscope network – with a huge strength in pedagogy and scientific excellence, and the Prolearn network – with a complimentary strength in technical and professional excellence. Integrating this excellence and moving on to the higher strategic formation of policy based in leading research is the key challenge for the next stage. The work of the stellarnet.eu community will move beyond the earlier networks by setting a new and critical foresight agenda for Technology Enhanced Learning. The Network will be executed via a series of integration instruments designed to increase the research capacity of European TEL at all levels.

About NEnet

NEnet **(www.neuroeducational.net)** is a group of scientists, educational researchers and educators who are interested in issues at the interface of neuroscience and education. The network is based at the Graduate School of Education, University of Bristol and coordinated by Paul Howard-Jones.

About Futurelab

Futurelab is an independent not-for-profit organisation that is dedicated to transforming teaching and learning, making it more relevant and engaging to 21st century learners through the use of innovative practice and technology.

We have a long track record of researching and demonstrating innovative uses of technology and aim to support systemic change in education — and we are uniquely placed to bring together those with an interest in improving education from the policy, industry, research and practice communities to do this. Futurelab cannot do this work on its own.

We rely on funding and partners from across the education community — policy, practice, local government, research and industry — to realise the full potential of our ideas, and so continue to create systemic change in education to benefit all learners.

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