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The potential relevance of cognitive neuroscience for the development and use of technology-enhanced learning

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There is increasing interest in the application of cognitive neuroscience in educational thinking and practice, and here we review findings from neuroscience that demonstrate its potential relevance to technology-enhanced learning (TEL). First, we identify some of the issues in integrating neuroscientific concepts into TEL research. We caution against seeking prescriptive neuroscience solutions for TEL and emphasize the need, instead, to conceptualize TEL at several different levels of analysis (brain, mind and behaviour, including social behaviour). Our review emphasizes the possibility of combining TEL and neuroscience concepts in adaptive educational systems, and we consider instances of interdisciplinary technology-based interventions drawing on neuroscience and aimed at remediating developmental disorders. We also consider the potential relevance of findings from neuroscience for the development of artificial agency, creativity, collaborative learning and neural insights into how different types of multimodality may influence learning, which may have implications for the future developments of tangibles. Finally, we identify a range of reasons why dialogue between neuroscience and the communities involved with technology and learning is likely to increase in the future.

Keywords: neuroscience; educational neuroscience; educational technology; game-based learning; multimedia; creativity; cognitive training

Introduction

Burgeoning insights from the sciences of mind and brain are generating fresh perspectives on education (Ansari and Coch 2006; Goswami 2006; Howard-Jones 2007; de Jong et al. 2009; OECD 2007; Royal Society 2011). The impact of these insights may be greatest where another force for change, technology, is already impacting the methods and means by which we learn. However, to date, little work has focused specifically on the potential of

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cognitive neuroscience to inform the design and use of technology-enhanced learning (TEL). Here, we provide a first review of the potential relationship between cognitive neuroscience and TEL. We began collecting evidence for this review in 2011, as part of STELLAR (Sustaining Technology Enhanced Learning at a LARge scale) – an EU project bringing together the leading institutions and projects in European Technology-Enhanced Learning. This project provided the opportunity to gain valuable feedback and suggestions from a range of researchers within European community and beyond. We now present a summary of our findings, beginning with a brief discussion of the challenges of integrating neuroscientific concepts into TEL. We then provide a short tour of some typical methods and techniques used in cognitive neuroscience, to illustrate the types of measurements they generate, and how these measurements can provide access to a new perspective on our interaction with technology. We then review a range of insights arising from cognitive neuroscience that have potential relevance to the development and implementation of TEL and attempt to consider how the involvement of cognitive neuroscience in TEL may develop in the future.

Bridging TEL and cognitive neuroscience

There are a number challenges in developing meaningful links between neuroscience and TEL. Even the meaning of the word ‘learning’ differs according to the domain it is used in. In neuroscience, ‘learning’ is often synonymous with memory. 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. Neuroscientists generally believe that human learning, as in the formation of memory, occurs by changes in patterns of connectivity between neurons, i.e., the building blocks of the nervous system. However, forming connections between ideas (which we all agree happens in the mind) is not the same as forming connections between neurons in the brain, although changes in neural connectivity are likely to be necessary. Our understanding of this process is still emerging, and although some proclaim neuroscience tells us to make mental connections in order to learn, we know this from our educational and psychological research rather than from neuroscience. In reality, we are still developing the technology needed to study human learning at the level of the connection between neurons (or ‘synapse’).

In education, of course, we think about learning in ways that extend well beyond the concept of memory. Here, 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 emphasizes the importance of social context and complexity. Cognitive 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 pedagogy 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, 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 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 a discussion of how the design of learning technologies should focus on supporting social learning in context, echoing the type of emphasis on situated social environments common within other areas of educational thinking (Vassileva 2008). 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 cognitive neuroscience, however, we know the brain is plastic and that experience (including educational experience) changes its connectivity, function and even structure (Draganski et al. 2004; Maguire et al. 2000). Later, the author suggests the chronic and intense multitasking experienced by 'digital-natives' may 'also delay adequate development of the frontal cortex. Multitasking leads to a short attention span and errors in decisions and judgment'. Despite lack of convincing (neuro)scientific evidence for such ideas, the brain is often referred to as if its structure and function is biologically determined, static and otherwise vulnerable to damage by technology. This is not true. Instead, our neurobiology makes a vital contribution to the contextual field in which learning should be considered, underpinning the transformative mechanisms by which learning occurs and meaning is constructed. On the other hand, the human brain can only develop through input from the environment and referred to as experience-dependent plasticity, a process that continues well beyond adolescence (Johnson and de Haan 2011).

However, the gap between cognitive neuroscience and current TEL perspectives on learning is significant and their interrelation may, therefore, be challenging in terms of building bridges. In considering the findings reviewed below, we would encourage readers to consider a 'levels-of-analysis' approach in which neural processes provide strong insight at a particular level of analysis. In this sense, and like cognitive, behavioural and social levels of understanding, it has a role in tethering our understanding to a reality that will always exceed the concepts we have access to (Bhaskar 1998). In practical terms, it is a new perspective which may be very helpful, but there is a need to remain mindful of the broader picture, and acknowledge that learning involves processes spanning brain, mind, behaviour and social context/environment when considering implications.

Cognitive neuroscience emphasizes how neural processes give rise to mental processes and how, in turn, these mental processes influence our behaviour. (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.) The central role of mind in the brain–mind–behaviour sandwich makes cognitive psychology crucial to all cognitive neuroscience and in turn to neuroeducational TEL research. Much of educational research, however, also emphasizes the importance of social interaction. For this reason, it seems appropriate that neuroeducational consideration of TEL should include two or more individuals represented as brain–mind–behaviour models interacting within a social environment. This is shown in Figure 1.

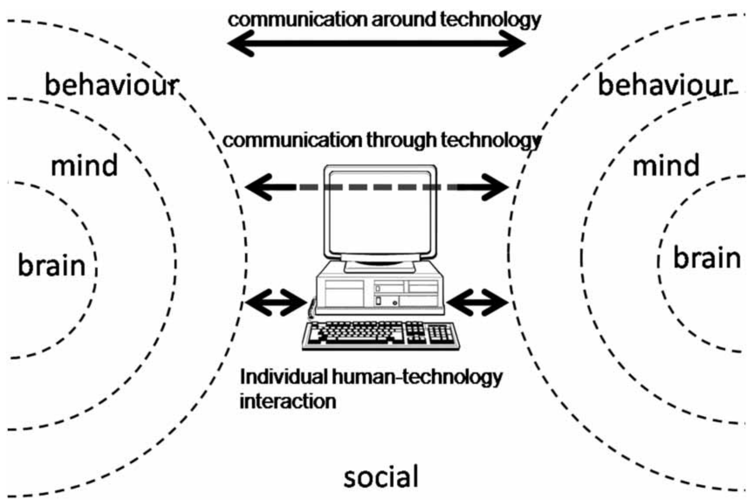

Figure 1. Integrating neuroscientific insights into TEL may benefit from a 'levels-of-analysis' approach to understand the role and potential interrelation of different perspectives on learning. Cognitive neuroscience has commonly used a three-level brain–mind–behaviour model to understand individual behaviour and learning, by interrelating measurable neural and behavioural data via the theoretical concept of mind. However, our real-world behaviour with technology inevitably involves our social behaviour, with technology able to mediate our social interactions in several different ways. Understanding at this level most often requires the interpretation of meaning using the types of interpretative methods favoured by the social sciences. Insights at all levels may crucially contribute to TEL understanding, and their interrelation represents a significant challenge for those wishing to enrich TEL with insights from neuroscience.

Using this levels-of-analysis approach, we can start reflecting on the complex interaction between cognitive/neural/social processes that can arise when behaviour becomes socially mediated. For example, in learning games informed by neuroscience, some of which are reviewed below, we might note that greater consideration could be given to the relation of gameplay with the social environment. This relation involves linking neural concepts with social complexities which are most often studied within the realm of social science, where meaning-based interpretations of human dialogue and reported personal experience provide insight into underlying processes. This type of insight might conceivably help develop the effectiveness of neurocognitive training software, which has traditionally drawn solely on principles derived using natural science methods and described in terms of brain–mind–behaviour interaction merely at the level of an individual. The dotted lines represent potential bidirectional influences at work, emphasizing the extent to which the social/educational environment 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 within this level of analysis (which are not mutually exclusive):

(1) as a stimulus *with* which we can interact individually
(2) as a stimulus *around* which social interaction takes place (e.g., collaborating around computers)
(3) as a medium *through* which social interaction takes place.

Space prevents more extended discussion of these broader considerations around situating neural insights into existing understanding about TEL, but we have presented this model here in order to discourage the reader from considering that the insights we present below provide any simple prescriptive solutions. Rather, effective integration of these insights will require conceptualizing TEL in terms of all levels (brain, mind and behaviour, including social behaviour) and considering the interrelation of concepts across levels.

Methods and techniques in cognitive neuroscience

We first consider a very modest selection of the many data collection techniques available to cognitive neuroscience, in order to demonstrate their potential in providing new insights into our interaction with technology.

Electroencephalography (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 (Antonenko et al. 2010). Such techniques have obvious application in exploring the design of TEL. For example, a recent study showed EEG was more effective than self-report measures in an investigation of *leads* (or hypertext node previews) (Antonenko and Niederhauser 2010). The study revealed how these links influence *germane* load (which is mediated by individual differences between learners), so reducing mental burden associated with creating coherence between two linked nodes. EEG has excellent temporal resolution (in the order of milliseconds) which can allow it to accurately detect when the brain responds in relation to a stimulus and can help us describe the rapid sequencing of neural processes that underlie a behavioural response. It is rather non-invasive, compared to other neuroscience methods, which makes it very 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 use online measurement of neural response (e.g., as part of an adaptive system). This technique, however, does have poor spatial resolution (i.e., poor information about where in the brain increases or decreases in activity take place), although special source localization techniques have improved its ability to identify the activity in different cortical regions.

There are several methods that can be used to achieve better spatial resolution, although these are all more expensive than EEG. These include functional magnetic resonance imaging (fMRI), in which the participant is placed in a scanner. This scanner has 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 computerized analysis of the relaxation signal, it is possible to determine a blood-oxygen-level dependent signal 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 3 mm. However, due to the time taken for the blood to respond, its temporal resolution is a few seconds. While the method is considered to be not invasive, as it does not involve the use of radioactive substances, the data are acquired in a specific and very noisy environment, the MRI scanner, which puts practical constraints on the type of tasks that participants can complete.

There are also simple indicators of bodily arousal which tap into the autonomic nervous system and these are much simpler to measure and analyse than the neural signals recorded by fMRI and EEG. These measures 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 (Critchley 2002). Early effects of emotional arousal on cerebral activity are also significantly correlated with later increases in EDA magnitude (D'Hondt et al. 2010). Another type of signal that is easy to measure is heart rate. Such technology can be useful in exploring the online engagement of individuals is response to different variations of technological design or affordance. For example, Lim and Reeves used EDA, heart rate and self-report to study the influence on physiological arousal of being able to choose avatar and visual point of view (POV) when playing 'World of Warcraft' (Lim and Reeves 2009). 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.

Cognitive neuroscience with potential relevance for TEL

Training of executive brain function

Technology can allow a learner easy access to unsupervised repeated practice that can adapt itself in order, for example, to keep pace with the learner's changing level of ability. Consequently, there have been many attempts to develop 'brain-training' programmes using technology, broadly defined in a recent review as 'the engagement in a specific programme or activity that aims to enhance a cognitive skill or general cognitive ability as a result of repetition over a circumscribed timeframe' (Rabipour and Raz 2012). In this sense, and like most TEL applications, it seeks to influence the mind, and through the mind the brain, by influencing our behaviour for short periods. Given the extent to which executive functions predict educational outcomes, there has been particular interest in training it.

At the present time, there is intense activity in attempts to develop and evaluate computer-based brain training, but claims are highly contested. While few commercial brain-training games have been convincingly evaluated, many research studies exist that suggest reasoning skills and working memory are amenable to computer-based training. For example, 'Cogmed' computerized training studies have shown transfer of improved working memory to untrained tasks (Klingberg et al. 2005; Thorell et al. 2009). Some evidence also suggests working memory training can result in long term (six months) retention of skills and transfer to gains in maths among 10–11-year-olds (Holmes, Gathercole, and Dunning 2009; Holmes et al. 2010). This issue of transfer is critical to those with educational aims, since the ultimate goal is to generate improvements not just on the task used to train the cognitive function, but on untrained tasks encountered in academic and professional contexts thought to rely on the cognitive function.

However, a recent meta-analysis joins other voices (Shipstead, Redick, and Engle 2012) in pointing out methodological flaws in much of the evidence supporting current brain-training claims, concluding that there is a lack of convincing evidence for anything other than short term, specific training effects that do not transfer in this way (Melby-Lervag and Hulme 2013). Sceptics have also pointed to the failure of studies (Chooi and Thompson 2012) attempting to use improved and extended experimental designs to replicate the results of other researchers (Jaeggi et al. 2008). Although transfer often extends beyond the training task, it appears restricted to types of task that are *similar* to the training task (i.e., 'near' rather than 'far' transfer effects). In short, there is an increasing number of published positive results in high-quality peer-reviewed journals – yet all have found themselves vulnerable, to greater or lesser extent, to critical review. Studies of cognitive inhibition or self-regulation training tasks are far fewer, focusing chiefly on young children and limited to near transfer (e.g., Dowsett and Livesey 2000), although far transfer to other executive tasks and fluid intelligence are reported for nine-year-olds, younger and older adults from rehearsing a task-switching challenge (Karbach 2012; Karbach and Kray 2009). There is presently a dearth of evidence for academic impact from off-the-shelf brain-training products, although a commercial game called 'Dr Kawashima's Brain Training Game' has recently been reported as improving executive functions, working memory and processing speed in young adults (Nouchi et al. 2013). In a classroom-based study, positive effects on mathematics were reported after 10–11-year-olds played this game for 20 minutes a day for 10 weeks. However, this classroom study was roundly criticized for its flaws in design and statistical analysis/reporting (Logie and Della Sala 2010) and it should be noted that the game itself rehearses the player's numerical skills directly.

Early years training of brain function for literacy and numeracy

Other attempts to train cognitive function using technology include the application of insights from cognitive neuroscience to ameliorate developmental disorders, such as dyscalculia – a significant and persistent difficulty with number. Cognitive neuroscience has helped to reveal how numerical abilities develop in young children, and it has pointed to the foundational role of non-symbolic (so-called number sense) and symbolic representation in this process. The design of a computer game called 'The Number Race' drew on these insights, with its creators (Wilson et al. 2006) suggesting their work provides evidence for how this type of software can help close the socioeconomic gap in mathematics achievement (Jordan and Levine 2009) but interpretation of results is not straightforward. A study of 30 low-numeracy kindergarten children playing this game for 10–15 minutes daily for three weeks revealed improvements in comparison of Arabic numbers but not in other areas of number skills (Rasanen et al. 2009). Evaluation with 53 young children (ages 4–6) with low socioeconomic status revealed improvements in tasks comparing digits and words but no improvement on non-symbolic measures of number sense (Wilson et al. 2009). Kucian and colleagues developed a game called ‘Rescue Calcularis’ which requires young children to land a spaceship on a number line, with the aim of helping them develop their own internal number line representation of number. In a 5-week intervention, 16 children diagnosed with dyscalculia (8–10 years old) and 16 matched controls played this specially designed computer game for 15 minutes a day at home (Kucian et al. 2011). The outcomes of the training were evaluated using behavioural tests and neuroimaging of brain function when children were performing a number line task. Both groups, with and without developmental dyscalculia, showed an improvement in various aspects of spatial number representation and mathematical reasoning five weeks after training. The intensive training led initially to a general activation decrease of relevant brain regions probably due to reorganization and fine-tuning processes (with greater changes for dyscalculics), and then to an increase in task-relevant regions after a period of consolidation. A further evaluation of this software was carried out with 40 children having difficulties in learning mathematics – as indicated simply by their below average performance in arithmetic (Käser et al. 2012). Playing 20 minutes per day, five days per week for six weeks improved arithmetic performance, especially subtractions (where performance is considered to represent a main indicator for development of spatial number representations and numerical understanding).

A vital first step in learning to read is mapping letters and letter strings on to the sounds of language (known as phonemes). Dyslexia is most commonly attributed to problems with this ‘phonological decoding’ process, and technology-based reading resources have been developed that combine cognitive neuroscience and educational understanding. One example is Graphogame – a non-commercial system developed at the University of Jyväskylä (Finland) which introduces the association of graphemes and phonemes to young children according to the frequency and consistency of a grapheme in a given language (Lyytinen et al. 2007). In Graphogame, online algorithms analyse a child’s performance and rewrite lesson plans ‘on the fly’ depending on the specific confusions shown by the learner (McCandliss 2010). The difficulty of the content is adjusted so that the challenge matches the learner’s ability. A neuroimaging study has shown that practice with the game can initiate print-sensitive activation in regions that later become critical for mature reading – the so-called visual word-form system (Brem et al. 2010). 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 (2010) points to this study as an example of how TEL and cognitive neuroscience work together, suggesting:

> 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 cognitive neuroscience research efforts to inform one another in increasingly rapid cycles. (p. 8050)

Multimodality

It has been known for some time that illustrating text can enhance memory (Paivio and Csapo 1973), with pictures of objects appearing more memorable than their names, and it can produce additional brain activity over and above that produced by experiencing each mode separately (Beauchamp et al. 2004). Andreano et al. (2009) studied the effects of increasing the immersive nature of a virtual reality environment, with the hypothesis that this should increase activity in regions associated with learning. The study involved the participant in moving through an icy environment looking for penguins or along a beach looking for shells. In both of these worlds, an auditory signal could be associated with locating the target type of object. The study showed that adding auditory cues to this virtual reality environment (i.e., comparing unimodal with multimodal) increased activation in the hippocampus, a region strongly associated with memory formation, thus supporting the notion that multimodality is an important aspect of virtual reality that can support learning.

The educational use of tangibles may also be informed by fresh understanding from cognitive 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 information from haptic and visual senses converges early in the brain compared with the convergence of audio and visual processes, with object recognition by touch and vision activating several overlapping and closely related brain regions. The type of 'enhanced effectiveness' that is achieved from combining haptic and visual stimulus (Kim and James 2010) suggests this type of multimodality may have advantages for communicating concepts such as 3D geometry.

Creativity

Technology is providing new opportunities to share ideas and cognitive 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 own ideas) (Fink et al. 2010). That is, when we are trying to think of new ideas, we must suppress those within our immediate attention in order to find original and novel associations. Other neuroscientific work has explored the existence of individual differences in creative ability and how these may be related to differences in focus of attention

(Kounios et al. 2008), while another has demonstrated how stimulus can influence this focus of attention and consequently the creativity of outcome (Howard-Jones et al. 2005). Taken together, this work may provide a means to understand how to construct online platforms for sharing ideas with others, and how such platforms can be adapted to the individual differences among contributors.

Neurofeedback

Neurofeedback is the monitoring of one's own brain activity with a view to influencing it. A study investigating EEG neurofeedback concluded that it produced improvements in the musical performance of conservatoire students not found using alternative interventions. In this study, the music students achieved improvements in their performance that were highly correlated with their ability to progressively influence neural signals associated with attention and relaxation (Egner and Gruzelier 2003; Gruzelier and Egner 2004). Similar results have been found for dancers (Raymond et al. 2005). The underlying neural mechanisms are the subject of active research, with evidence that self-induced changes in neural rhythms can produce detectable changes in neural function that last 20 minutes or more (Ros et al. 2010). This supports the potential effectiveness of neurofeedback as a tool for mediating the plasticity of the brain, but many questions remain about the processes involved and how these are best exploited for educational benefit. However, recently an initial study with 11-year-olds has shown improved musical performance, creative improvization and measures of attention after 10 sessions of neurofeedback of 30 minutes duration (Gruzelier et al. 2013).

Technology can also be used to share one's neural processes with the teacher. Indeed, Battro's review of the teaching brain identifies the use of wearable brain image technologies in classrooms as a major new challenge for the field of Mind, Brain and Education (Battro 2010). Whereas studies discussed above used high-quality multiple electrode EEG apparatus, simple EEG devices now retail from below $100. A recent study used such a device to inform an adaptive artificial agent designed to recapture diminished attention using verbal and nonverbal cues, significantly improving student recall of the learning content (Szafir and Mutlu 2012).

Engaging with others: human and artificial

Advances in fMRI techniques are now 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. It has, for example, 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 synchronization between collaborators' brains as measured by EEG (Dumas et al. 2010). Brain research has also helped establish a better understanding of how trust between potential collaborators develops through reciprocity (King-Casas et al. 2005; Miller 2005) and how different contexts engender different types of trust (Boudreau, McCubbins, and Coulson 2009).

New learning technologies that embody key elements of individual human tutoring are likely to exploit insights about human neurocognitive processes of imitation, shared attention and empathy. Although we have already seen that visual appearance is not a prerequisite for activating some of these circuits, 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. For example, Howard-Jones et al. (2010) found that players' neural circuits mirrored their artificial competitor's virtual actions as if they were their own, a type of neural response usually attributed to observing biological motion. However, effects may be greater if the 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., mentalizing or a theory of mind. Participants were asked to play a game against different types of opponent who, unbeknown to them, were all playing randomly (Krach et al. 2008). 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.

Games and learning

Although often characterized in the popular press as mindless activities, it seems that computer games can influence the development of abilities that psychologists call 'skills' (Caplovitz and Kastner 2009; Feng, Spence, and Pratt 2007; Green and Bavelier 2003, 2006a, 2006b, 2007, 2008, Green, Li, and Bavelier 2010; Li et al. 2009). In a study of laparoscopic surgery, Rosser et al. (2007) found that surgeons who had played video games in the past and were playing video games currently made 37% and 32% fewer 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 (Grantcharov et al. 2003; Tsai and Heinrichs 1994). 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 laparoscopic skill (Badurdeen et al. 2010).

The ability of videogames to influence the cognitive abilities of their players may be related to their capacity to intensely engage their players. Cognitive neuroscience research provides some insight into why such games are so attractive. Video games, along with many other rewarding pleasures such as food, drugs, gambling and music, appear to stimulate uptake of midbrain dopamine (Koepp et al. 1998) [but see (Egerton et al. (2009) for constraints on interpretation]. 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 (Weinstein 2010). These rewards are usually uncertain, in the sense that they are mediated by chance. Uncertain rewards are particularly stimulating to the reward system, and this ability of games 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 (Adcock 2006; Callan and Schweighofer 2008; Shohamy and Adcock 2010). 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 (Howard-Jones et al. 2011). 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'(Bavelier et al. 2010). Bridging studies have revealed the potential of 'gamifying' lessons with uncertain reward (Howard-Jones and Demetriou 2009), with laboratory-based data demonstrating that it can improve motivation and learning (Ozcelik, Cagiltay, and Ozcelik 2013) and providing the basis for a free web-based app that turns lessons into games (Zondle 2013).

The future

Technology and cognitive neuroscience are two fast-moving fields of enterprise that, in some areas of important educational interest, are already becoming intertwined. We believe dialogue between the neuroscience and TEL communities is only likely to increase in the future because:

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

Dialogue with cognitive neuroscience converges with other influences that are encouraging educators to move away from content towards thinking skills and, more specifically, the development of cognitive processes. 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 educational specialization, as it places 'any human knowledge at the fingertips of any human' (Stewart 2008). This places greater 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 (Koizumi 2004).

(2) Cognitive neuroscience and TEL already share an interest in the cognition of technology-based learning

Cognitive 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. Due to the restrictions of the neuroimaging environment and the need for experimental control, and 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 many types of face-to-face teaching in the classroom, since the differences between the two contexts are considerable. In contrast, this favours the transfer of neuroscientific knowledge to the development of TEL. Indeed, many of the attempts by neuroscientists to develop educational approaches based on their findings have focused on the production of computer-based resources (Butterworth and Laurillard 2010; Howard-Jones and Demetriou 2009; Wilson et al. 2009).

(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 (Lyytinen et al. 2007) was used to investigate neurocognitive processes in a brain imaging study (Brem et al. 2010), whose results could be useful in further developing the technology. This suggests we can advance from merely using cognitive neuroscience techniques and concepts to inform the development of TEL, towards a cycle of iterative development involving both fields (see also McCandliss 2010).

(4) TEL neuromyths need to be dispelled

A dialogue between cognitive neuroscience and TEL may benefit TEL researchers by helping to dispel some of the popular misconceptions about the brain prevailing in education (the so-called neuromyths; see Howard-Jones 2010), such as the notion of the hard-wired brain discussed above.

Although we feel confident that we will observe increasing dialogue between TEL and neuroscience, the quality of this exchange will depend on researchers bringing together the different levels of analysis discussed at the beginning of this paper to ensure their approach that is both valid in terms of underlying processes of mind and brain, and relevant in terms of TEL. A related challenge will be the negotiation of a common language to help facilitate the cautious, sceptical and critical co-construction of meaningful links between these levels.

As far as we aware, this is the first review of the neuroscience literature aimed at identifying insights that may be relevant for TEL. We have identified that neuroscience techniques can have practical value for TEL research, summarized a range of findings that provide cause for optimism regarding future interdisciplinary research between these areas, identified some of the forces driving the two areas together and pointed out some of the key challenges likely to arise from their interaction. As the first review of its type, it is perhaps unsurprising that we find few, if any, examples of replication. Furthermore, all cited studies have been situated within their own contexts, including laboratory and scanner-based environments and often involving adult participants. Additional caution is, therefore, required in relating such findings to real-world contexts involving other types of participant, including younger learners [see De Smedt et al. (2011) for critical consideration of such transfer issues]. Nevertheless, we have presented sufficient evidence to argue against portraying cognitive neuroscience as an implausible 'silver bullet' (Facer and Sandford 2010). In contrast, rather than providing a simple and prescriptive panacea, experts involved with neuroeducational research view cognitive neuroscience as contributing alongside other perspectives to a richer and more sophisticated understanding of learning and how it can be improved (Ansari and Coch 2006; Howard-Jones 2010; Meltzoff et al. 2009). The relevance of cognitive neuroscience to education is increasingly undisputed, and it may be within the field of TEL that its early impact will be greatest.

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References

Adcock, R. A. 2006. "Reward-Motivated Learning: Mesolimbic Activation Precedes Memory Formation." *Neuron* 50 (3): 507–517.

Andreano, J., K. Liang, L. J. Kong, D. Hubbard, B. K. Wiederhold, and M. D. Wiederhold. 2009. "Auditory Cues Increase the Hippocampal Response to Unimodal Virtual Reality." *Cyberpsychology & Behavior* 12 (3): 309–313.

Ansari, D., and D. Coch. 2006. "Bridges over Troubled Waters: Education and Cognitive Neuroscience." *Trends in Cognitive Sciences* 10 (4): 146–149.

Antonenko, P. D., and D. S. Niederhauser. 2010. "The Influence of Leads on Cognitive Load and Learning in a Hypertext Environment." *Computers in Human Behavior* 26 (2): 140–150.

Antonenko, P., F. Paas, R. Grabner, and T. van Gog. 2010. "Using Electroencephalography to Measure Cognitive Load." *Educational Psychology Review* 22 (4): 425–438.

Badurdeen, S., O. Abdul-Samad, G. Story, C. Wilson, S. Down, and A. Harris. 2010. "Nintendo Wii Video-Gaming Ability Predicts Laparoscopic Skill." *Surgical Endoscopy and Other Interventional Techniques* 24 (8): 1824–1828.

Battro, A. M. 2010. "The Teaching Brain." *Mind, Brain, and Education* 4 (1): 28–33.

Bavelier, D., D. M. Levi, R. W. Li, Y. Dan, and T. K. Hensch. 2010. "Removing Brakes on Adult Brain Plasticity: From Molecular to Behavioral Interventions." *Journal of Neuroscience* 30 (45): 14964–14971.

Beauchamp, M. S., K. E. Lee, B. D. Argall, and A. Martin. 2004. "Integration of Auditory and Visual Information about Objects in Superior Temporal Sulcus." *Neuron* 41 (5): 809–823.

Bhaskar, R. 1998. *The Possibility of Naturalism: A Philosophical Critique of the Contemporary Human Sciences*. London: Routledge.

Boudreau, C., M. D. McCubbins, and S. Coulson. 2009. "Knowing When to Trust Others: An ERP Study of Decision Making after Receiving Information from Unknown People." *Social Cognitive and Affective Neuroscience* 4 (1): 23–34.

Brem, S., S. Bach, K. Kucian, T. K. Guttorm, E. Martin, H. Lyytinen, D. Brandeis, and U. Richardson. 2010. "Brain Sensitivity to Print Emerges When Children Learn Letter-Speech Sound Correspondences." *Proceedings of the National Academy of Sciences of the United States of America* 107 (17): 7939–7944.

Butterworth, B., and D. Laurillard. 2010. "Low Numeracy and Dyscalculia: Identification and Intervention." *ZDM* 42 (6): 527–539.

Callan, D. E., and N. Schweighofer. 2008. "Positive and Negative Modulation of Word Learning by Reward Anticipation." *Human Brain Mapping* 29 (2): 237–249.

Caplovitz, G. P., and S. Kastner. 2009. "Carrot Sticks or Joysticks: Video Games Improve Vision." *Nature Neuroscience* 12 (5): 527–528.

Chooi, W. T., and L. A. Thompson. 2012. "Working Memory Training Does Not Improve Intelligence in Healthy Young Adults." *Intelligence* 40 (6): 531–542.

Critchley, H. D. 2002. "Electrodermal Responses: What Happens in the Brain." *Neuroscientist* 8 (2): 132–142.

De Smedt, B., D. Ansari, R. H. Grabner, M. Hannula-Sormunen, M. Schneider, and L. Verschaffel. 2011. "Cognitive Neuroscience Meets Mathematics Education: It Takes Two to Tango." *Educational Research Review* 6 (3): 232–237.

D'Hondt, F., M. Lassonde, O. Collignon, A. S. Dubarry, M. Robert, S. Rigoulot, J. Honore, F. Lepore, and H. Sequeira. 2010. "Early Brain-Body Impact of Emotional Arousal." *Frontiers in Human Neuroscience* 4: 33. doi:10.3389/fnhum.2010.00033

Dowsett, S. M., and D. J. Livesey. 2000. "The Development of Inhibitory Control in Preschool Children: Effects of 'Executive Skills' Training." *Developmental Psychobiology* 36 (2): 161–174.

Draganski, B., C. Gaser, V. Busch, G. Schuierer, U. Bogdahn, and A. May. 2004. "Changes in Grey Matter Induced by Training." *Nature* 427 (6972): 311–312.

Dumas, G., J. Nadel, R. Soussignan, J. Martinerie, and L. Garnero. 2010. "Inter-Brain Synchronization During Social Interaction." *PLoS ONE* 5 (8).

Egerton, A., M. A. Mehta, A. J. Montgomery, J. M. Lappin, O. D. Howes, S. J. Reeves, V. J. Cunningham, and P. M. Grasby. 2009. "The Dopaminergic Basis of Human Behaviors: A Review of Molecular Imaging Studies." *Neuroscience and Biobehavioral Reviews* 33 (7): 1109–1132.

Egner, T., and J. H. Gruzelier. 2003. "Ecological Validity of Neurofeedback: Modulation of Slow Wave EEG Enhances Musical Performance." *Neuroreport* 14 (9): 1221–1224.

Facer, K., and R. Sandford. 2010. "The Next 25 Years?: Future Scenarios and Future Directions for Education and Technology." *Journal of Computer Assisted Learning* 26 (1): 74–93.

Feng, J., I. Spence, and J. Pratt. 2007. "Playing an Action Video Game Reduces Gender Differences in Spatial Cognition." *Psychological Science* 18 (10): 850–855.

Fink, A., R. H. Grabner, D. Gebauer, G. Reishofer, K. Koschutnig, and F. Ebner. 2010. "Enhancing Creativity by Means of Cognitive Stimulation: Evidence from an fMRI Study." *Neuroimage* 52 (4): 1687–1695.

Goswami, U. 2006. "Neuroscience and Education: From Research to Practice?" *Nature Reviews Neuroscience* 7 (5): 406–413.

Grantcharov, T. P., L. Bardram, P. Funch-Jensen, and J. Rosenberg. 2003. "Impact of Hand Dominance, Gender, and Experience with Computer Games on Performance

in Virtual Reality Laparoscopy." *Surgical Endoscopy and Other Interventional Techniques* 17 (7): 1082–1085.
Green, C. S., and D. Bavelier. 2003. "Action Video Game Modifies Visual Selective Attention." *Nature* 423 (6939): 534–537.
Green, C. S., and D. Bavelier. 2006a. "Effect of Video Games on the Spatial Distribution of Visuospatial Attention." *Journal of Experimental Psychology* 32 (6): 1465–1478.
Green, C. S., and D. Bavelier. 2006b. "Enumeration Versus Multiple Object Tracking: The Case of Action Video Game Players." *Cognition* 101 (1): 217–245.
Green, C. S., and D. Bavelier. 2007. "Action Video Game Experience Alters the Spatial Resolution of Attention." *Psychological Science* 18 (1): 88–94.
Green, C. S., and D. Bavelier. 2008. "Exercising Your Brain: A Review of Human Brain Plasticity and Training-Induced Learning." *Psychology and Aging* 23 (4): 692–701.
Green, C. S., R. J. Li, and D. Bavelier. 2010. "Perceptual Learning During Action Video Game Playing." *Topics in Cognitive Science* 2 (2): 202–216.
Gruzelier, J. H., and T. Egner. 2004. "Physiological Self-regulation: Biofeedback and Neurofeedback." In *Musical Excellence*, edited by A. Williamon, 197–219. Oxford: Oxford University Press.
Gruzelier, J. H., M. Foks, T. Steffert, M. J. L. Chen, and T. Ros. 2013. "Beneficial Outcome from EEG-Neurofeedback on Creative Music Performance, Attention and Well-Being in School Children." *Biological Psychology* 95 (SI): 86–95.
Holmes, J., S. E. Gathercole, and D. L. Dunning. 2009. "Adaptive Training Leads to Sustained Enhancement of Poor Working Memory in Children." *Developmental Science* 12 (4): F9–F15.
Holmes, J., S. E. Gathercole, M. Place, D. L. Dunning, K. A. Hilton, and J. G. Elliott. 2010. "Working Memory Deficits Can Be Overcome: Impacts of Training and Medication on Working Memory in Children with ADHD." *Applied Cognitive Psychology* 24 (6): 827–836.
Howard-Jones, P. A. 2007. *Neuroscience and Education: Issues and Opportunities*. London: Teaching and Learning Research Programme.
Howard-Jones, P. A. 2010. *Introducing Neuroeducational Research: Neuroscience, Education and the Brain from Contexts to Practice*. Abingdon: Routledge.
Howard-Jones, P. A., S. J. Blakemore, E. Samuel, I. R. Summers, and G. Claxton. 2005. "Semantic Divergence and Creative Story Generation: An fMRI Investigation." *Cognitive Brain Research* 25 (1): 240–250.
Howard-Jones, P. A., R. Bogacz, J. H. Yoo, U. Leonards, and S. Demetriou. 2010. "The Neural Mechanisms of Learning from Competitors." *Neuroimage* 53 (2): 790–799.
Howard-Jones, P. A., and S. Demetriou. 2009. "Uncertainty and Engagement with Learning Games." *Instructional Science* 37 (6): 519–536.
Howard-Jones, P. A., S. Demetriou, R. Bogacz, J. H. Yoo, and U. Leonards. 2011. "Toward a Science of Learning Games." *Mind, Brain and Education* 5 (1): 33–41.
Jaeggi, S. M., M. Buschkuehl, J. Jonides, and W. J. Perrig. 2008. "Improving Fluid Intelligence with Training on Working Memory." *Proceedings of the National Academy of Sciences (USA)* 105 (19): 6829–6833.
Johnson, M. H., and M. de Haan. 2011. *Developmental Cognitive Neuroscience*. 3rd ed. Malden, MA: Wiley-Blackwell.
de Jong, T., T. van Gog, K. Jenks, S. Manlove, J. van Hell, J. Jolles, J. van Merrienboer, T. van Leeuwen, A. Boschloo. 2009. *Explorations in Learning and the Brain: On the Potential of Cognitive Neuroscience for Educational Science*. New York: Springer.

Jordan, N. C., and S. C. Levine. 2009. "Socioeconomic Variation, Number Competence, and Mathematics Learning Difficulties in Young Children." *Developmental Disabilities Research Reviews* 15 (1): 60–68.

Karbach, J. 2012. "Executive Control Training in Middle Childhood: Task-Switching Training Transfers to Inhibitory Control and Working Memory in Healthy Children and Children with ADHD." Paper presented at the EARLI meeting of the Special Interest Group on Neuroscience and Education, London.

Karbach, J., and J. Kray. 2009. "How Useful Is Executive Control Training? Age Differences in Near and Far Transfer of Task-Switching Training." *Developmental Science* 12 (6): 978–990.

Käser, T., K. Kucian, J. Kohn, U. Grond, V. Richtmann, M. von Aster, and M. Gross. 2012. "Calcularis – A Therapy Software for Enhancing Numerical Cognition." Paper presented at the EARLI meeting of the Special Interest Group on Neuroscience and Educaction, London.

Kim, S., and T. W. James. 2010. "Enhanced Effectiveness in Visuo-Haptic Object-Selective Brain Regions with Increasing Stimulus Salience." *Human Brain Mapping* 31 (5): 678–693.

King-Casas, B., D. Tomlin, C. Anen, C. F. Camerer, S. R. Quartz, and P. R. Montague. 2005. "Getting to Know You: Reputation and Trust in a Two-Person Economic Exchange." *Science* 308 (5718): 78–83.

Klingberg, T., E. Fernell, P. J. Olesen, M. Johnson, P. Gustafsson, K. Dahlstrom, C. G. Gillberg, H. Forssberg, and H. Westerberg. 2005. "Computerized Training of Working Memory in Children with ADHD – A Randomized, Controlled Trial." *Journal of the American Academy of Child and Adolescent Psychiatry* 44 (2): 177–186.

Koepp, M. J., R. N. Gunn, A. D. Lawrence, V. J. Cunningham, A. Dagher, T. Jones, D. J. Brooks, C. J. Bench, P. M. Grasby. 1998. "Evidence for Striatal Dopamine Release During a Video Game." *Nature* 393 (6682): 266–268.

Koizumi, H. 2004. "The Concept of 'Developing the Brain': A New Science for Learning and Education." *Brain and Development* 26 (7): 434–441.

Kounios, J., J. I. Fleck, D. L. Green, L. Payne, J. L. Stevenson, E. M. Bowden, and M. Jung-Beeman. 2008. "The Origins of Insight in Resting-State Brain Activity." *Neuropsychologia* 46 (1): 281–291.

Krach, S., F. Hegel, B. Wrede, G. Sagerer, F. Binkofski, and T. Kircher. 2008. "Can Machines Think? Interaction and Perspective Taking with Robots Investigated via fMRI." *PLoS ONE* 3 (7): e2597.

Kucian, K., U. Grond, S. Rotzer, B. Henzi, C. Schoenmann, F. Plangger, M. Gaelli, E. Martin, and M. von Aster. 2011. "Mental Number Line Training in Children with Developmental Dyscalculia." *Neuroimage* 57 (3): 782–795.

Li, R. J., U. Polat, W. Makous, and D. Bavelier. 2009. "Enhancing the Contrast Sensitivity Function Through Action Video Game Training." *Nature Neuroscience* 12 (5): 549–551.

Lim, S., and B. Reeves. 2009. "Being in the Game: Effects of Avatar Choice and Point of View on Psychophysiological Responses During Play." *Media Psychology* 12 (4): 348–370.

Logie, R. H., and S. Della Sala. 2010. "Brain Training in Schools, Where Is the Evidence?" *British Journal of Educational Technology* 41 (6): E127–E128.

Lyytinen, H., M. Ronimus, A. Alanko, A. M. Poikkeus, and M. Taanila. 2007. "Early Identification of Dyslexia and the Use of Computer Game-Based Practice to Support Reading Acquisition." *Nordic Psychology* 59 (2): 109–126.

Maguire, E. A., D. S. Gadian, I. S. Johnsrude, C. D. Good, J. Ashburner, R. S. Frackowiak, and C. D. Frith. 2000. “Navigation Related Structural Change in the Hippocampi of Taxi Drivers.” *Proceedings of the National Academy of Sciences (USA)*, 97 (8): 4398–4403.
McCandliss, B. D. 2010. “Educational Neuroscience: The Early Years.” *Proceedings of the National Academy of Sciences of the United States of America* 107 (18): 8049–8050.
Melby-Lervag, M., and C. Hulme. 2013. “Is Working Memory Training Effective? A Meta-Analytic Review.” *Developmental Psychology* 49 (2): 270–291.
Meltzoff, A. N., P. K. Kuhl, J. Movellan, and T. J. Sejnowski. 2009. “Foundations for a New Science of Learning.” *Science* 325 (5938): 284–288.
Miller, G. 2005. “Neuroscience – Economic Game Shows How the Brain Builds Trust.” *Science* 308 (5718): 36–36.
Nouchi, R., Y. Taki, H. Takeuchi, H. Hashizume, T. Nozawa, T. Kambara, A. Sekiguchi, et al. 2013. “Brain Training Game Boosts Executive Functions, Working Memory and Processing Speed in the Young Adults: A Randomized Controlled Trial.” *PLoS ONE* 8 (2).
OECD. 2007. *Understanding the Brain: Birth of a New Learning Science*. Paris: OECD.
Ozcelik, E., N. E. Cagiltay, and N. S. Ozcelik. 2013. “The Effect of Uncertainty on Learning in Game-Like Environments.” *Computers & Education* 67: 12–20.
Paivio, A., and K. Csapo. 1973. “Picture Superiority in Free Recall: Imagery or Dual Coding?” *Cognitive Psychology* 5 (5): 176–206.
Rabipour, S., and A. Raz. 2012. “Training the Brain: Fact and Fad in Cognitive and Behavioral Remediation.” *Brain and Cognition* 79 (2): 159–179.
Rasanen, P., J. Salminen, A. J. Wilson, P. Aunio, and S. Dehaene. 2009. “Computer-Assisted Intervention for Children with Low Numeracy Skills.” *Cognitive Development* 24 (4): 450–472.
Raymond, J., I. Sajid, L. Parkinson, and J. H. Gruzelier. 2005. “Biofeedback and Dance Performance: A Preliminary Investigation.” *Applied Psychophysiology and Biofeedback* 30 (1): 65–73.
Ros, T., M. A. M. Munneke, D. Ruge, J. H. Gruzelier, and J. C. Rothwell. 2010. “Endogenous Control of Waking Brain Rhythms Induces Neuroplasticity in Humans.” *European Journal of Neuroscience* 31 (4): 770–778.
Rosser, J. C., P. J. Lynch, L. Cuddihy, D. A. Gentile, J. Klonsky, and R. Merrell. 2007. “The Impact of Video Games on Training Surgeons in the 21st Century.” *Archives of Surgery* 142 (2): 181–186.
Royal Society. 2011. *Brain Waves Module 2: Neuroscience: Implications for Education and Lifelong Learning*. London: Royal Society.
Shipstead, Z., T. S. Redick, and R. W. Engle. 2012. “Is Working Memory Training Effective?” *Psychological Bulletin* 138 (4): 628–654.
Shohamy, D., and R. A. Adcock. 2010. “Dopamine and Adaptive Memory.” *Trends in Cognitive Sciences* 14 (10): 464–472.
Stewart, W. J. 2008. *Technology Futures*. London: Government Office for Science.
Szafir, D., and B. Mutlu. 2012. “Pay Attention! Designing Adaptive Agents That Monitor and Improve User Engagement.” Paper presented at the ACM SIGCHI conference on human factors in computing systems.
Thorell, L. B., S. Lindqvist, S. B. Nutley, G. Bohlin, and T. Klingberg. 2009. “Training and Transfer Effects of Executive Functions in Preschool Children.” *Developmental Science* 12 (1): 106–113.

Tsai, C. L., and W. L. Heinrichs. 1994. "Acquisition of Eye-Hand Coordination Skills for Videoendoscopic Surgery." *Journal of American Association Gynecological Laparoscopy* 1 (4): S37.

Vassileva, J. 2008. "Toward Social Learning Environments." *IEEE Transactions on Learning Technologies* 1 (4): 199–214.

Weinstein, A. M. 2010. "Computer and Video Game Addiction – A Comparison Between Game Users and Non-Game Users." *American Journal of Drug and Alcohol Abuse* 36 (5): 268–276.

Wilson, A. J., S. Dehaene, O. Dubois, and M. Fayol. 2009. "Effects of an Adaptive Game Intervention on Accessing Number Sense in Low-Socioeconomic-Status Kindergarten Children." *Mind, Brain, and Education* 3 (4): 224–234.

Wilson, A. J., S. Dehaene, P. Pinel, S. K. Revkin, L. Cohen, and D. Cohen. 2006. "Principles Underlying the Design of 'The Number Race', an Adaptive Computer Game for Remediation of Dyscalculia." *Behavioral and Brain Functions* 2 (19).

Zondle. 2013. "Zondle Team Play." Accessed September 12, 2013. https://www.zondle.com/publicPages/zondleTeamPlay_guideStart.aspx