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Brain Waves Module 2: Neuroscience: implications for education and lifelong learning

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Summary

Education is about enhancing learning, and neuroscience is about understanding the mental processes involved in learning. This common ground suggests a future in which educational practice can be transformed by science, just as medical practice was transformed by science about a century ago. In this report we consider some of the key insights from neuroscience that could eventually lead to such a transformation.

- Neuroscience research suggests that learning outcomes are not solely determined by the environment. Biological factors play an important role in accounting for differences in learning ability between individuals.
- By considering biological factors, research has advanced the understanding of specific learning difficulties, such as dyslexia and dyscalculia. Likewise, neuroscience is uncovering why certain types of learning are more rewarding than others.
- The brain changes constantly as a result of learning, and remains 'plastic' throughout life. Neuroscience has shown that learning a skill changes the brain and that these changes revert when practice of the skill ceases. Hence 'use it or lose it' is an important principle for lifelong learning.
- Resilience, our adaptive response to stress and adversity, can be built up through education with lifelong effects into old age.
- Both acquisition of knowledge and mastery of self-control benefit future learning. Thus, neuroscience has a key role in investigating means of boosting brain power.
- Some insights from neuroscience are relevant for the development and use of adaptive digital technologies. These technologies have the potential to create more learning opportunities inside and outside the classroom, and throughout life. This is exciting given the knock-on effects this could have on wellbeing, health, employment and the economy.
- There is great public interest in neuroscience, yet accessible high quality information is scarce. We urge caution in the rush to apply so-called brain-based methods, many of which do not yet have a sound basis in science. There are inspiring developments in basic science although practical applications are still some way off.
- The emerging field of educational neuroscience presents opportunities as well as challenges for education. It provides means to develop a common language and bridge the gulf between educators, psychologists and neuroscientists.

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1 Introduction

Education is the wellspring of our health, wealth and happiness. It allows human beings to transcend the physical limits of biological evolution. We know that education works through experiences that are dependent on processes in the brain, and yet we still understand far too little about these processes. Neuroscience studies have begun to shed light on the mental processes involved in learning. In this report we explore the extent to which these new scientific insights can inform our approach to education.

The rapid progress in research in neuroscience is producing new insights that have the potential to help us understand teaching and learning in new ways. Education is far more than learning facts and skills such as reading. It is not confined to the school years, but plays an important role throughout the lifespan and helps individuals cope with adversity. Flexibility through learning enables people of any age to adapt to challenges of economic upheaval, ill health, and ageing. The new field of 'educational neuroscience', sometimes called 'neuroeducation', investigates some of the basic processes involved in learning to become literate and numerate; but beyond this it also explores 'learning to learn', cognitive control and flexibility, motivation as well as social and emotional experience. With the effective engagement of all learners as well as teachers, parents and policy makers, the impact of this emerging discipline could be highly beneficial.

Education affects the wellbeing of individuals and has economic benefits.[1] The economic and social cost of an education system that does not facilitate learning for all and learning throughout life is high.[2–4] There is accumulating scientific knowledge that could benefit all groups of learners: children, young people, adults and older people. Small experimental steps have already been taken, from the application of particular reward programmes in learning,[5] to cognitive training of the elderly in care homes in order to reduce their need for medication.[6] In this report we touch on the widespread desire to enhance cognitive abilities, for instance through smart drugs. However, we propose that education is the most powerful and successful cognitive enhancer of all.

It is inspiring to see public enthusiasm for the application of neuroscience to education. This suggests that it will transfer readily into the support structures it needs in schools, further education, higher education and beyond. At the same time, enthusiasm is often accompanied by poor access to new knowledge and misconceptions of neuroscience findings.[7,8] We believe that a constructive balance between enthusiasm and scepticism, combined with better knowledge exchange between scientists and practitioners can help resolve this problem.

This report focuses on the implications for education of understanding neuroscience combined with cognitive psychology. The aims of this report are to:

- present important developments in neuroscience that have the potential to contribute to education;
- discuss the challenges that exist for educators and neuroscientists; and
- present policy recommendations to facilitate the translation of new developments into practice.

This is the second of four modules in the Royal Society Brain Waves series on neuroscience and society.

1 OECD (2010). *The High Cost of Low Educational Performance*, *The Long-run Economic Impact of Improving Educational Outcomes.* OECD: Paris.
2 Accurate figures are hard to find, *see Science and Technology Committee for a discussion, Evidence Check 1: Early literacy interventions*. www.publications.parliament.uk/pa/cm200910/cmselect/cmsctech/44/4405.htm#n28Oct Accessed 15 December 2010.
3 Every Child a Chance Trust estimate poor literacy to cost the UK £2.5 billion, Every Child a Chance (2009) Trust. *The long term costs of literacy difficulties, 2nd edition.* Every Child a Chance: London.
4 KPMG Foundation estimate poor numeracy to cost England £2.4 billion per year, KPMG Foundation (2006), *The long-term effects of literacy difficulties.* KPMG: London.

5 Howard-Jones PA & Demetriou S (2009). *Uncertainty and engagement with learning games*. Instructional Science 37, 519–536.
6 Wolinsky FD, Mahncke H, & Kosinski M et al. (2010). *The ACTIVE cognitive training trial and predicted medical expenditures.* BMC Health Services Research Volume: 9, 109.
7 Blakemore SJ & Frith U (2005). The Learning Brain: Lessons for Education. Oxford: Blackwell.
8 Goswami U (2004). Neuroscience and Education. British Journal of Educational Psychology 1–14.

2 Insights and opportunities

Neuroscience is the empirical study of the brain and connected nervous system. The brain is the organ that enables us to adapt to our environment—in essence, to learn. Neuroscience is shedding light on the influence of our genetic make-up on learning over our life span, in addition to environmental factors. This enables us to identify key indicators for educational outcomes, and provides a scientific basis for evaluating different teaching approaches. In this section, we set out some of the key insights and opportunities stemming from findings from neuroscience.

2.1 Both nature and nurture affect the learning brain

Individuals differ greatly in their response to education, and both genes and the environment contribute to these differences. Work with identical twins, who have the same genetic make-up, has shown that they are more similar in, for instance, personality[9], reading[10] and mathematical ability[11], than non-identical twins, who differ in their genetic make-up. While it is widely agreed that individual differences can have a genetic basis, genetic influences on brain development and brain function are not yet well understood.

For example, while genetic predispositions can partially explain differences in reading ability, there is no single gene that makes an individual a good or poor reader. Instead, there are multiple genes, the individual effects of which are small.[12] Furthermore genes can be turned on and off by environmental factors such as diet,[13,14] exposure to toxins[15] and social interactions.[16–18] And in terms of neurobiology (the biology of the brain and central nervous system), our current knowledge does not allow us to use measurement of activity in a brain region to tell whether an individual is a good or poor reader. There is enormous variation between individuals, and brain-behaviour relationships are complex.[19]

Genetic make-up alone does not shape a person's learning ability; genetic predisposition interacts with environmental influences at every level. Human learning abilities vary, in the same way that human height and blood pressure vary. And just as for height and blood pressure, while there are some rare genetic conditions that lead to extreme abnormality, most variations in learning capacity are caused by multiple genetic and environmental influences, each of which may have a small impact. Neuroscience has the potential to help us understand the genetic predispositions as manifest in the brain of each individual, and how these predispositions (nature) can be built on through education and upbringing (nurture).[20]

2.2 The brain is plastic

The brain is constantly changing and everything we do changes our brain. These changes can be short lived or longer lasting. When we sleep, walk, talk, observe, introspect, interact, attend, and learn, neurons fire. The brain has extraordinary adaptability, sometimes referred to as 'neuroplasticity'. This is due to the process by which connections between neurons are strengthened when they are simultaneously activated; often summarised as, 'neurons that fire together wire together'.[21] The effect is known as experience-dependent plasticity and is present throughout life.[22]

Neuroplasticity allows the brain to continuously take account of the environment. It also allows the brain to store the results of learning in the form of memories. In this way, the brain can prepare for future events based on experience. On the other hand, habit learning, which is very fast and durable, can be counterproductive for individuals and difficult to overcome, as for example in addiction.[23,24]

Key findings based on neuroplasticity include the following:

- Changes in the brain's structure and connectivity suggest there are sensitive periods in brain

9 Eaves L, Heath A, Martin N, Maes H, Neale M, & Kendler K, et al (1999). *Comparing the biological and cultural inheritance of personality and social attitudes in the Virginia 30,000 study of twins and their relatives.* Twin Research **2(2)**, 62–80.
10 Harlaar N, Spinath FM, Dale PS, & Plomin R (2005). *Genetic influences on early word recognition abilities and disabilities: a study of 7-year-old twins.* Journal of Child Psychology and Psychiatry **46**, 373–384.
11 Kovas Y, Haworth CMA, Petrill SA, & Plomin R (2007). *Mathematical ability of 10-year-old boys and girls: Genetic and environmental etiology of typical and low performance*. Journal of Learning Disabilities **40(6)**, 554–567.
12 Bishop DVM (2009). *Genes, cognition and communication: insights from neurodevelopmental disorders. The Year in Cognitive Neuroscience*: Annals of the New York Academy of Sciences Mar; **1156**, 1–18.
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14 Waterland RA & Jirtle RL (2003). *Transposable Elements: Targets for Early Nutritional Effects on Epigenetic Gene Regulation—Molecular and Cellular Biology* **23(15)**, 5293–5300.
15 Dolinoy DC & Jirtle RL (2008). *Environmental epigenomics in human health and disease.* Environmental and Molecular Mutagenesis **49(1)**, 4–8.
16 Rutter M, Dunn J, Plomin R, Simonoff E, Pickles A, Maughan B, Ormel J, Meyer J, & Eaves L (1997) – *Integrating nature and nurture: Implications of person-environment correlations and interactions for developmental psychopathology*. Development and Psychopathology **9(2)**, 335–364.
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21 Hebb D (1949). *The Organization of Behavior*. Wiley, New York.
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23 Hogarth L, Chase HW, & Baess K (2010). *Impaired goal-directed behavioural control in human impulsivity*. Q J Exp Psychol **10**,1–12.
24 de Wit S & Dickinson A (2009). *Associative theories of goal-directed behaviour: a case for animal-human translational models*. Psychol Res **73(4)**, 463–76.

development extending beyond childhood into adolescence.[25–30] Plasticity tends to decrease with age and this is particularly evident when we consider learning of a second language: mastery of speech sounds and grammatical structure is generally better in those introduced to a second language before puberty compared with later in life.[31,32] During adolescence, certain parts of the brain undergo more change than others. The areas of the brain undergoing most change control skills and abilities such as self awareness, internal control, perspective taking and responses to emotions such as guilt and embarrasement.[33]

- The overall pattern of neural development appears to be very similar between genders, but the pace of brain maturation appears to differ, with boys on average reaching full maturation at a slightly later age than girls.[34] At first glance this suggests that boys and girls might do better if educated separately, especially around puberty and early adolescence, when the gender difference in brain development is greatest. However, there are many factors that influence brain development, and gender is only one example of an individual difference that might influence learning and development.
- Dynamic changes to brain connectivity continue in later life. The wiring of the brain changes progressively during development for a surprisingly long time. For example, the connections in the frontal part of the brain involved in impulse control and other 'executive' functions are pruned progressively and adaptively during adolescence and beyond. Even after these developmental changes, activity-dependent plasticity is evident throughout life: For example, licensed London taxi drivers, who spend years acquiring 'the Knowledge' of London's complex layout, have greater grey matter volume in a region of the brain known to be essential for memory and navigation.[35]
- Just as athletes need to train their muscles, there are many skills where training needs to be continued to maintain brain changes. The phrase 'use it or lose it!' is very apt. In the taxi driver example above, a reversal in brain changes was found following retirement, when taxi drivers were no longer employing their spatial memory and navigation skills.[36] Changes in the adult brain following the acquisition of specific skills has also been shown for music,[37] juggling[38] and dance.[39] This illustrates what we mean by experience-dependent plasticity. The genetic specification of our brains only partly determines what we know and how we behave; much depends on environmental factors that determine what we experience. Education is prominent among these factors.
- There are limits to neuroplasticity as well as individual differences. Not all learning appears to be subject to sensitive periods, and unlearning habits is remarkably hard. There appear to be limits on how internal predispositions and external stimulation can affect learning. For instance, only half of those who attempt to qualify as London cabbies actually succeed. We also know that after brain injury some functions seem to be more amenable to rehabilitation than others, and some cannot be relearned at all.[40] However many different factors play a role in recovery and compensation, and both pharmacological treatments and training regimes are being studied as potential means for extending plasticity into adulthood.[41]

2.3 The brain's response to reward is influenced by expectations and uncertainty

Neuroscience research has revealed that the brain's response to reward[42] is influenced by many different factors

25 Thomas M & Knowland V (2009). *Sensitive Periods in Brain Development – Implications for Education Policy.* European Psychiatric Review **2(1)**, 17–20.
26 Knudsen EI (2004). *Sensitive Periods in the Development of the Brain and Behavior*. Journal of Cognitive Neuroscience **16(8)**, 1412–1425.
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28 Andresen SL (2003). *Trajectories of brain development: point of vulnerability or window of opportunity?* Neuroscience & Biobehavioral Reviews **27(1–2)**, 3–18.
29 Lenroot RK & Giedd JN (2006). *Brain development in children and adolescents: insights from anatomical magnetic resonance imaging*. Neuroscience & Biobehavioral Reviews **30(6)**, 718–729.
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32 Johnson JS & Newport EL (1989). *Critical period effects in second language learning: the influence of maturational state on the acquisition of English as a second language.* Cognitive Psychology 1989 **21(1)**, 60–99.
33 Blakemore SJ (2008). *The social brain in adolescence*. Nature Reviews Neuroscience **9(4)**, 267–277.
34 Giedd JN & Rapoport JL (2010). *Structural MRI of pediatric brain development: what have we learned and where are we going?* Neuron **67(5)**, 728–734.

35 Woollett K, Spiers HJ, & Maguire EA (2009). *Talent in the taxi: a model system for exploring expertise.* Phil Trans R Soc B **364(1522)**, 1407–1416.
36 See section 2.7 below for more in relation to cognitive decline.
37 Gaser C & Schlaug G (2003). *Brain Structures Differ between Musicians and Non-Musicians.* Journal of Neuroscience **23(27)**, 9240–9245.
38 Draganski B, Gaser C, Busch V, Schuierer G, Bogdahn U, & May A (2004). *Neuroplasticity: Changes in grey matter induced by training.* Nature **427**, 311–312.
39 Hanggi J, Koeneke S, Bezzola L, & Jancke L (2009). *Structural neuroplasticity in the sensorimotor network of professional female ballet dancers.* Human Brain Mapping **31(8)**, 1196–1206.
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42 Here we use a very broad definition of reward, which includes but is not restricted to 'primary rewards' (rewards that satisfy physiological needs such as the need for food) and 'secondary rewards (rewards based on values, such as social admiration).

including context[43] and individual differences.[44] Neuroscientists have studied the relationship between reward and learning in the context of reinforcement learning, in which we learn to attribute values to simple actions. In this type of learning, the individual's reward system responds to prediction error, which is the difference between the outcome we expect from an action and the outcome we actually get. It is this response of the reward system that allows us to learn which action has the most valuable outcome. Some neuroscientists think that just reducing prediction errors by making better predictions about outcomes can itself be rewarding. The brain's response to prediction error also supports other types of learning that are of great potential interest to educators, such as the ability to recall information.[45] Research also demonstrates that the degree of uncertainty about the reward one might receive is an important contributor to the magnitude of the neural response it generates[46] (and implicitly the reward's operational value). This challenges educational notions of a simple relationship between reward and motivation in school, and may suggest new ways to use reward more effectively in education to support learning.[47]

2.4 The brain has mechanisms for self-regulation

Together with findings from cognitive psychology, neuroscience is beginning to shed light on self-regulation and self control, that is, the inhibition of impulsive behaviour.

Recent research has shown that the ability to inhibit inappropriate behaviour, for example, stopping oneself making a previously rewarded response, develops relatively slowly during childhood, but continues to improve during adolescence and early adulthood.[48] This is probably because the brain regions involved in inhibition, in particular the prefrontal cortex, continue to change both in terms of structure and function, during adolescence and into the twenties.[49] In addition, there are large individual differences in our ability to exert self-control, which persist throughout life. For example, by age three, some children are much better than others at resisting temptation, and the ability to resist temptation (delayed gratification) at this age has been found to be associated with higher education attainment in later childhood and adolescence.[50] Research is under way to investigate to what extent cognitive training programmes can strengthen this ability.[51]

Understanding mechanisms underlying self-control might one day help to improve prospects for boosting this important life skill. In addition, it is important to learners and teachers who are dealing with lack of discipline or antisocial behaviour. Given that the self-reported ability to exert self-control has been found to be an important predictor of academic success,[52] understanding the neural basis of self-control and its shaping through appropriate methods would be valuable.

2.5 Education is a powerful form of cognitive enhancement

Cognitive enhancement usually refers to increased mental prowess, for instance, increased problem-solving ability or memory. Such enhancement is usually linked with the use of drugs or sophisticated technology. However, when compared with these means, education seems the most broadly and consistently successful cognitive enhancer of all.[53] Education provides, for instance, access to strategies for abstract thought, such as algebra or logic, which can be applied in solving a vast range of problems and can increase mental flexibility. Literacy and numeracy change the human brain,[54] but also enable human beings to perform feats that would not be possible without these cultural tools, including the achievements of science. The steady rise in IQ scores over the last decades is thought to be at least partially due to education.[55,56] Findings from neuroscience and cognitive enhancement include the following:

- Education can build up an individual's cognitive reserve and resilience, that is, their adaptive response to stressful and traumatic events and illness, including brain injury, mental disorder, and normal ageing. Cognitive reserve and resilience can be built up at any point during life. Research on cognitive reserve has found an inverse relationship between educational attainment and risk of dementia, which means that

43 Nieuwenhuis S, Heslenfeld DJ, Alting von Geusau NJ, Mars RB, Holroyd CB, & Yeung N (2005). *Activity in human reward-sensitive brain areas is strongly context dependent.* Neuroimage **25**, 1302.
44 Krebs RM, Schott BH, & Duzel E (2009). *Personality Traits Are Differentially Associated with Patterns of Reward and Novelty Processing in the Human Substantia Nigra/Ventral Tegmental Area*. Biological Psychiatry **65**, 103.
45 Howard-Jones PA, Bogacz R, Demetriou S, Leonards U, & Yoo J (2009). In *British Psychological Society Annual Conference* (Brighton).
46 Fiorillo CD, Tobler PN, & Schultz W (2003). *Discrete Coding of Reward Probability and Uncertainty by Dopamine Neurons*. Science **299**, 1898.
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48 Blakemore SJ & Choudhury S (2006). *Development of the adolescent brain: implications for executive function and social cognition.* Journal of Child Psychology and Psychiatry **47**, 296–297.
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keeping the mind active slows cognitive decline and improves cognitive abilities in older adults.[57,58]

- Physical health, exercise, sleep and nutrition are crucial to physical and mental wellbeing and their effects on cognitive functions are mediated by the brain. For example, neuroscience research on sleep and sleep deprivation can explain some highly specific effects on memory and other mental functions.[59] Both physical and mental exercise are known to benefit older people, for example by acting as protective factors against, and reducing the symptomatic impact of dementia.[60–64]
- Pharmacological cognitive enhancers, sometimes referred to as 'smart drugs', such as Ritalin or Modafinil, are typically prescribed to counteract cognitive deficits in diagnosed conditions. But they are increasingly being used 'off-licence' in people with normal brain function,[64] along with many other over-the-counter drugs. These smart drugs have been used to overcome jet-lag, reduce the need for sleep, and boost motivation and concentration, by affecting the role of neurotransmitters in certain cognitive processes. Research is needed in order to establish the side effects of taking such drugs, their long term consequences and the risks involved. This research needs to take account also of the ethical issues that arise from questions like access and fairness.[65,66]

2.6 There are individual differences in learning ability with a basis in the brain

There is wide variation in learning ability; some individuals struggle to learn in all domains, whereas others have specific difficulties for instance, with language, literacy, numeracy or self control. There is ample evidence that these individuals are at increased risk of poor social adaptation and unemployment. The costs to society[67] are thus substantial and there is an urgent need to find educational approaches that will work.

Current work in neuroscience is directed toward identifying the brain basis of learning difficulties. As this research advances, prospects are raised for identification and diagnosis, and for designing interventions that are suitable for different ages and may overcome or circumvent the learning difficulties. Even for those with severe learning difficulties, improved understanding of specific cognitive and neurological correlates of disorder can be harnessed to make education more effective.[68]

Much neuroscientific research has focused on more specific learning difficulties, such as developmental dyslexia and developmental dyscalculia, where mastery of reading or maths pose unusual difficulties for the child. Research has identified underlying cognitive deficits which can be assessed by experimental tests, and may explain other difficulties that are often associated with poor attainment. There is less research directed at other problems.[69] Many children have specific problems understanding or producing spoken language (specific language impairment), poor motor skills (developmental co-ordination disorder or developmental dyspraxia) or marked symptoms of inattention, hyperactivity and impulsivity (attention deficit hyperactivity disorder or ADHD).

These conditions are not confined to childhood but can be lifelong. There is no 'biological' test at present; only behavioural tests are available. Furthermore, there is no hard-and-fast dividing line between normality and abnormality: the diagnosis is made when an individual's difficulties are severe enough to interfere with everyday life and educational achievement. Many of those affected have more than one of these difficulties.[70]

Educational difficulties are common: a recent report found that in 2009 2.4 per cent of boys and 0.9 per cent of girls across all schools in England had statements of SEN (Special Educational Needs) and a further 23 per cent of boys and 14 per cent of girls were assessed as needing extra or different help from that provided as part of the school's usual curriculum (School Action or School Action Plus).[71]

Although research has shown there are brain correlates, or markers, for learning difficulties, these markers are subtle and complex. As yet it is not possible to predict or assess

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65 Maher B (2008). *Poll results: Look who's doping. Nature* **452**, 674.
66 See Brain Waves Module 1 Section 3.2 (neuropsychopharmacology), Text box 2, Section 4.3 (risks) and 4.3 (ethics) for broader discussion.
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70 Bishop D & Rutter M (2008). *Neurodevelopmental disorders: conceptual approaches*. In M Rutter, D Bishop, D Pine, S Scott, J Stevenson, E Taylor, & A Thapar (Eds). *Rutter's Child and Adolescent Psychiatry* (pp. 32–41). Blackwell: Oxford.
71 Taken from Department for Children, Schools and Families Statistical First Release 15/2008. 25 June 2008. Available online at http://www.education.gov.uk/rsgateway/DB/STA/t000851/index.shtml. Accessed 8 December 2010.

an individual's specific learning disability from a brain scan.[72] This is because even within a diagnostic category, such as developmental dyslexia, there is substantial anatomical variation from one individual to another. Improvements in the diagnosis of learning disabilities through technical advances in the variety of neuroimaging methods and through the refinement of cognitive tests can be expected in the next decade. In a similar vein, while there is strong evidence that genetic factors are implicated in specific learning disabilities,[73] one can seldom identify a single gene as responsible, because multiple genes are involved and their impact depends on the environment.[74]

Furthermore, even when a genetic risk or neurological basis for a learning disability can be identified, this does not mean the individual is unteachable; rather, it means that it is necessary to identify the specific barriers to learning for that person, and find alternative ways.

The study of dyslexia, using a combination of behavioural and neuroimaging methods, illustrates that it is possible to identify neuro-cognitive barriers to learning and to make suggestions for appropriate teaching methods. Other learning difficulties can benefit from the same kind of approach to uncovering underlying neural systems. Results from functional neuroimaging studies show that dyslexic children and adults have abnormal patterns of activation in areas of the brain involved in language and reading.[75,76] The application of knowledge gained from these studies to improve intervention is still at an early stage,[77,78] but educationally relevant randomised controlled trials of improving literacy are already available.[79]

The study of ADHD reminds us that the way the brain works is affected by levels of neurotransmitters that influence connectivity between brain regions and levels of excitation and inhibition. Neuroimaging studies combined with pharmaceutical intervention can give insights into underlying neural mechanisms such as behaviour control in ADHD, where one symptom is difficulty in impulse control.[80] A future goal is to devise cognitive training approaches that influence the same neural circuitry.

There is a widespread belief in some circles that ADHD is a convenient label used to explain away bad behaviour, with corresponding concern that medication is being used to control what is essentially normal behaviour.[81] Neuroscience provides concrete evidence of biological differences between children with ADHD and others, but nevertheless, we need to be alert to the possibility of over-diagnosis, since current diagnostic criteria are based solely on behavioural assessments. During school years and until adolescence, behaviour that might indicate specific problems with impulse control changes rapidly, in line with brain development. Thus, immaturity, which might be due to a child being born late in the school year, can be mistaken for ADHD.[82] On the other hand, under-diagnosis may happen in the context of uncritical acceptance of individual differences and reluctance to make any distinction between normal and abnormal behaviour. With refined methods of behavioural testing, informed by findings from neuroscience and genetics, it should become possible to improve on the current approach to diagnosis for all neuro-developmental disorders.[83]

2.7 Neuroscience informs adaptive learning technology

Neuroscientific findings can often identify a specific locus for a particular kind of learning difficulty. They may not determine the exact form an intervention should take, but they may well suggest the nature of the concept or skill to be targeted, and the kind of cognitive activity that needs to be strengthened. However, even where successful teaching approaches have been developed for learners who cannot keep up with the mainstream classes, widespread implementation may fail because there are too few specially trained teachers, and the level of frequent and individual attention that many learners need is unaffordable. Learning technologies have the potential to play a complementary role to that of the teacher in assisting the rehearsal of targeted learning activities. The experimental designs that give rise to neuroscientific insights can often be adapted to support remediation and transferred to technology-based platforms, such as laptops or mobile phones.

For example, research has identified poor grasp of 'number sense'—having an intuitive sense of, say, fiveness—as an underlying cause of arithmetical learning disability

72 Giedd JN & Rapoport JL (2010). *Structural MRI of pediatric brain development: what have we learned and where are we going?* Neuron **67(5)**, 728–734.
73 Willcutt EG, Pennington BF, Duncan L, Smith SD, Keenan JM, & Wadsworth S, et al (2010). Understanding the complex etiologies of developmental disorders: Behavioral and molecular genetic approaches. Journal of Developmental and Behavioral Pediatrics **31(7)**, 533–544.
74 For a discussion see www.deevybee.blogspot.com/2010/09/genes-for-optimism-dyslexia-and-obesity.html. Accessed 15 December 2010.
75 Maurer U, Brem S, Bucher K, Kranz F, Benz R, Steinhausen H-C, & Brandeis D (2007). *Impaired tuning of a fast occipito-temporal response for print in dyslexic children learning to read.* Brain **130**, 3200–3210.
76 Activity in left posterior superior temporal cortex is reduced (Turkeltaub PE, Gareau L, Flowers DL, Zeffiro TA, & Eden GF (2003). *Development of neural mechanisms for reading*. Nature Neuroscience **6(6)**, 767–773.).
77 Dehaene S (2009). *Reading in the Brain*. Viking Penguin: London.
78 Goswami U & Szucs D (2010). *Educational neuroscience: Developmental mechanisms: Towards a conceptual framework.* Neuroimage, Setp 7, Epub ahead of print.
79 Bowyer-Crane C, Snowling MJ, Duff FJ, Fieldsend E, Carroll JM, Miles J, et al (2008). *Improving early language and literacy skills: Differential effects of an oral language versus a phonology with reading intervention.* Journal of Child Psychology and Psychiatry, **49**, 422–432.
80 Chamberlain SR & Sahakian BJ (2006). *Attention deficit hyperactivity disorder has serious and immediate implications.* Education Journal **94**, 35–37.
81 See Brain Waves Module 1 Section 4.2 (risks) for a broader discussion.
82 Elder TE (2010). *The importance of relative standards in ADHD diagnoses: Evidence based on exact birth dates*. Journal of Health Economics **29(5)**, 641–656.
83 Morton J (2004). *Understanding Developmental Disorders; A Causal Modelling Approach*. Blackwells: Oxford.

(dyscalculia).[84,85] Computer games have been designed to give learners practice in understanding numbers that adapt to the learner's current skill-level; for example, by introducing larger numbers as the learner gets better; or by matching dot arrays with digits or number words. Adaptive game-like programs make use of the individual's natural reward system (see Section 2.3): they show the difference between the outcome the learner expects from an action and the outcome they actually observe. This helps them to learn which action has the most valuable outcome. Adaptive programmes emulate a teacher who constantly adapts to current learner understanding. Thus they enable far more practice than is often possible through one-to-one teaching.[86]

Although we must treat claims about brain-training programmes[87–90] and the use of neuroscience in diagnosis with the utmost caution, there is evidence to suggest that:

- With practice, high quality targeted training can improve performance on specific tasks. A key question is whether training effects transfer to other tasks. In most studies, training effects seem highly task-specific.[90] Nevertheless, there is currently considerable interest in a working memory training programme for children that is thought to lead to improvements in reasoning ability and self-regulation.[91,92] This work is particularly impressive because efficacy has been demonstrated in randomised controlled trials.
- Digital technologies can be developed to support individualised self-paced learning and highly specialised practice in a game-like way. Interactive games of this kind use a teacher-pupil model to adapt the task to the learner's needs, and a task model to provide meaningful feedback on their actions. This means interactive technologies can provide personalised help on a daily basis[93] in a way that is difficult to achieve in a demanding classroom environment.
- Further developments in neuroscience technology might provide effective support for people with significant sensory or physical deficits. Research into brain-computer interfaces brings new hope to those individuals who cannot control a computer, keyboard, or robotic arm in the normal way: in the future they may be able to use their own brain signals to perform the necessary actions.[94]
- Adaptive learning technologies that target remote learning can also be used to provide daily support for adult learners and individuals beyond retirement age, who for whatever reason are not attending classes on a regular basis. Digital media based on learning targets identified by neuroscience, for example, practicing links between speech sounds and letters in the case of reading difficulties, offer a more private learning context, but can still be linked to teachers online. Teachers would provide expert feedback on progress based on, but going beyond, the feedback from the adaptive software. Importantly lifelong learning and cognitive training have wider benefits for health and wellbeing.[95–98]

84 Von Aster MG & Shalev RS (2007). *Number development and developmental dyscalculia*. Developmental Medicine & Child Neurology **49(11)**, 868–873.

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

86 Butterworth B & Laurillard D (2010). *Low numeracy and dyscalculia: Identification and intervention*. ZDM Mathematics Education, Special issue on Cognitive neuroscience and mathematics learning **42(6)**, 527–539.

87 Owen AM, Hampshire A, Grahn JA, Stenton R, Dajani S, Burns AS, Howard RJ, & Ballard CG (2010). *Putting brain training to the test*. Nature **465(7299)**, 775–8. But see Klingberg 2010 [91].

88 Hyatt KJ & Brain Gym R (2007). *Building stronger brains or wishful thinking?* Remedial and special education **28(2)** 117–124.

89 Strong GK, Torgerson CJ, Torgerson D, & Hulme C (2010). *A systematic meta-analytic review of evidence for the effectiveness of the 'Fast ForWord' language intervention program.* Journal of Child Psychology and Psychiatry, Oct 15, 1469–7610.

90 Owen AM et al. (2010). See Ref 87.

91 Klingberg T (2010). *Training and plasticity of working memory*. Trends In Cognitive Sciences **14**, 317.

92 McNab F, Varrone A, Farde L, Jucaite A, Bystritsky P, Forssberg H, & Klingberg T (2009). *Changes in Cortical Dopamine D1 Receptor Binding Associated with Cognitive Training.* Science **323**, 800–802.

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

94 See Brain Waves Module 1 Section 3.3 for an extended discussion on brain-machine interfaces.

95 Government Office for Science (2008). *Foresight Project on Mental Capital and Wellbeing*. Government Office for Science: London.

96 Medical Research Council (2010). *Review of Mental Health Research Report of the Strategic Group*, Medical Research Council: London.

97 Sahakian BJ, Malloch G, & Kennard C (2010). *A UK strategy for mental health and wellbeing*. The Lancet **375**, 1854–55.

3 Challenges

Scientific proposals for educational neuroscience may seem alien or even unhelpful. This is due, in part to major cultural and vocabulary differences between the scientific research and education communities. Let us start by considering some common ground. Both perspectives recognise that if individuals do not master basic skills in language, literacy or numeracy, then there are serious challenges to educational attainment, vocational and social prospects. Both perspectives also recognise that education allows us to develop better ways of helping all individuals find a fulfilling and productive place in society. Despite these common aims, neuroscience is often accused of 'medicalising' the problems of people with educational difficulties.

3.1 The charges of reductionism and determinism

Critics of neuroscience fear that it represents:

- a reductionist view that overemphasises the role of the brain at the expense of a holistic understanding of cultural life based on interpretation and empathy;
- a determinist view that our neurological inheritance sets us on a path that is unchangeable.[98]

However, a neuroscience perspective recognises that each person constitutes an intricate system operating at neural, cognitive, and social levels, with multiple interactions taking place between processes and levels.[99] Neuroscience is a key component of this system and is therefore a key contributor to enriching explanations of human thought and behaviour. Furthermore, it is a mistake to regard biological predispositions as deterministic; their impact is probabilistic and context-dependent. The important point, as section 2 describes, is that there are educational difficulties that have a biological basis, and cannot be attributed solely to parents', teachers' or society's expectations. If in these cases the biological risk factors are not taken into account, important opportunities to optimise learning will be missed.

3.2 The inappropriate exploitation of neuroscience

A web search using Google with the keywords 'Learning', 'Teaching', and 'Brain' indicates that there is a huge demand for applications of brain science to education.[100] Thus despite philosophical reservations, there is considerable enthusiasm for neuroscience and its applications. This can, however, lead to problems.

For example, commercial interests have been quick to respond to the demand of the enthusiasts and promote their credibility with testimonials of reportedly trustworthy individuals. There is already a glut of books, games, training courses, and nutritional supplements, all claiming to improve learning and to be backed by science. This is problematic because the sheer volume of information from a range of sources makes it difficult to identify what is independent, accurate and authoritative. At worst, this industry creates 'neuro-myths' that can damage the credibility and impact of authentic research.[101,102]

3.3 Building a common language

'Knowledge needs to go in both directions' is a quote that typifies the sentiments expressed by neuroscience, policy and teaching communities, and is taken from a recent Royal Society and Wellcome Trust stakeholder discussion 'Education: What's the brain got to do with it?'[103]

If educational neuroscience is to develop into an effective new discipline, and make a significant impact on the quality of learning for all learners, we need a long-term dialogue between neuroscientists and a wide range of other researchers and professionals from a variety of backgrounds.[104]

To address the need for engagement that was highlighted at the Royal Society and Wellcome Trust stakeholder meeting, the Working Group believes a professionally managed web-based forum would be helpful. Such a forum would help bring together practitioners and scientists in a continuing dialogue. This would go a long way towards counteracting misconceptions on either side. For example, neuroscientists could provide evaluations of commercially offered programmes and current research findings. Educators could provide evaluations of teaching programmes; and representatives from different disciplines could provide critical reviews. A flexible tool, such as this type of forum, would serve multiple purposes, for example, increasing general knowledge about brain science for teachers and learners. This would also instil the scepticism that is needed to evaluate novel educational programmes.

A knowledge-sharing mechanism is clearly a worthwhile aim. However, aligning the needs and interests of different professions presents a substantial challenge.[105] There are significant differences in assumptions, theories, phenomena of interest, and vocabulary.[106]

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98 See Brain Waves Module 1 Section 3.4 and Text Box 5 for a broader discussion.
99 Rosenzweig MR, Breedlove SM, & Leiman AL (2001). *Biological Psychology: An Introduction to Behavioral, Cognitive, and Clinical Neuroscience.* Sinauer Associates Inc: Sunderland, MA.
100 See also Pickering SJ & Howard-Jones PA (2007). *Educators' views on the role of neuroscience in education: Findings from a study of UK and international perspectives*. Mind, Brain and Education **1**, 109–113, for a survey.
101 See Geake J (2008). *Neuromyths in Education*, Educational Research **50(2)**,123–133 and Waterhouse L (2006) *Multiple intelligences, the Mozart effect, and emotional intelligence: A critical review*. Educational Psychologist **41(4)**, 207–225 for example reviews.
102 See Weisberg DS et al. (2008) for more discussion, Weisberg DS, Keil FC, Goodstein J, Rawson E, & Gray JR (2008). *The Seductive Allure of Neuroscience Explanations.* Journal of Cognitive Neuroscience **20(3)**, 470–477.
103 See Appendix 2 for details.
104 See Brain Waves Module 1 Section 4.4 (governance) for a broader discussion.
105 Kalra P & O'Keefe JK (2010). *Making disciplinary perspectives explicit and other best practices for interdisciplinary work in educational neuroscience*. Front. Neurosci. Conference Abstract: EARLI SIG22 - Neuroscience and Education.
106 Royal Society and Wellcome Trust stakeholder meeting, Education: What's the brain got to do with it? 7 September 2010, see Appendix 2.

4 Recommendations

Growing understanding of the neurological basis of learning could help most individuals to become fulfilled and productive members of society who can respond with resilience to changing circumstances in their lives. This applies not only to children of school age who are getting to grips with literacy and numeracy, but also to adolescents whose career choices lie before them, and adults contributing to the economy through their use of skills in the workforce. It also applies to the elderly who wish to maintain existing skills, and learn new ones to help counteract the effects of decline. In this section we set out key findings and recommendations from the emerging field of educational neuroscience which might inform education policy across all ages.

4.1 Strengthening the science base for education

Neuroscience research aims to characterise the mechanisms of learning and the sources of individual differences in learning ability. It is therefore a tool for science-based education policy, which can help assess the performance and impact of different educational approaches. In addition, neuroscience can provide knowledge of how education offers wider policy benefits, in health, employment and wellbeing.[107,108]

Recommendation 1

Neuroscience should be used as a tool in educational policy.

Neuroscience evidence should inform the assessment of different education policy options and their impacts where available and relevant. Neuroscience evidence should also be considered in diverse policy areas such as health and employment.

Stronger links *within* the research community and *between* researchers and the education system (schools, further education, higher education and institutes for lifelong learning) are needed in order to improve understanding of the implications of neuroscience for education. Department for Education, Department for Business Innovation and Skills and Devolved Administration equivalents as well as research funders, such as the Economic and Social Research Council and Wellcome Trust, should provide incentives to support mechanisms to develop cross-sector links.

4.2 Informing teacher training and continued professional development

Findings from neuroscience that characterise different learning processes can support and enhance teachers' own experiences of how individuals learn. These findings can be used to inform alternative teaching approaches for learners of different abilities. However, at present neuroscience rarely features as part of initial teacher training courses or as part of continued professional development.[109,110]

Recommendation 2

Training and continued professional development should include a component of neuroscience relevant to educational issues, in particular, but not restricted to, Special Educational Needs.

Teacher training providers for Special Education Needs across all ages should consider including a focus on the neurobiological underpinnings of learning difficulties such as dyslexia, dyscalculia and ADHD. This training should be extended to teachers for all ages.

4.3 Informing adaptive technologies for learning and cognitive training

New educational technologies provide opportunities for personalised learning that our education system cannot otherwise afford. They can also open up learning opportunities outside the classroom and hence improve access to those currently excluded from education in adulthood and in later life. Insights from neuroscience, for example how the brain benefits from exercise, and how the brain understands numeracy, can help inform the design of educational technologies. To this end, links between neuroscientists and the digital technologies industry could be strengthened.

Recommendation 3

Neuroscience should inform adaptive learning technology.

Neuroscience can make valuable contributions to the development of adaptive technologies for learning. The Technology Strategy Board should promote knowledge exchange and collaboration between basic researchers, front-line practitioners and the private sector in order to inform and critically evaluate the impact and development of new technologies.

107 Beddington J, Cooper GL, Field J, Goswami U, Huppert FA, Jenkins R, Jones HS, Kirkwood TBL, Sahakian BJ, & Thomas SM (2008). *The mental wealth of nations.* Nature 455, 1057–1060.
108 Sahakian BJ, Malloch G, & Kennard C (2010). *A UK strategy for mental health and wellbeing*. The Lancet 375, 1854.
109 Royal Society and Wellcome Trust stakeholder meeting, Education: What's the brain got to do with it? 7 September 2010.
110 See Royal Society State of the Nation Report on 5–14 Science and Mathematics Education (2010), which calls for more specialist training for primary science and maths teachers in particular.

4.4 Building bridges and increasing knowledge of neuroscience

A growing corpus of neuroscience evidence already exists which is relevant for education. However, for some, this evidence can be difficult to access and evaluate. Findings from neuroscience are all too easily misinterpreted and applied out of context. A continued dialogue among the research base (that includes neuroscientists, cognitive psychologists and social scientists) as well as frontline teachers across all ages and the policy community is required. Good work in building bridges has already started.[111]

Recommendation 4

Knowledge exchange should be increased.

A knowledge exchange network is required to bridge disciplines, this should include a professionally monitored web forum to permit regular feedback between practitioners and scientists and to ensure that research is critically discussed, evaluated and effectively applied. High quality information about neuroscience on a web forum could also be made available to the general public, for example by the BBC and/or Open University. Members of the public will benefit from learning about the changes that are going on in their own brains and how this can affect their own learning.

111 See the Economic and Social Sciences Research Council Teaching and Learning Research Programme (TLRP) Commentaries available at www.tlrp.org/pub/commentaries.html. Accessed 15 December 2010.

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