

# PERSPECTIVES

## SCIENCE AND SOCIETY

# Neuroscience and education: myths and messages

Paul A. Howard-Jones

**Abstract** | For several decades, myths about the brain — neuromyths — have persisted in schools and colleges, often being used to justify ineffective approaches to teaching. Many of these myths are biased distortions of scientific fact. Cultural conditions, such as differences in terminology and language, have contributed to a ‘gap’ between neuroscience and education that has shielded these distortions from scrutiny. In recent years, scientific communications across this gap have increased, although the messages are often distorted by the same conditions and biases as those responsible for neuromyths. In the future, the establishment of a new field of inquiry that is dedicated to bridging neuroscience and education may help to inform and to improve these communications.

Imagine having a brain that is only 10% active, that shrinks when you drink less than 6 to 8 glasses of water a day and that increases its interhemispheric connectivity when you rub two invisible buttons on your chest. For neuroscientists, such a brain is difficult — if not impossible — to contemplate, but such notions are commonly held by teachers across the world<sup>1–7</sup>. These unscientific ideas are often associated with ineffective or unevaluated approaches to teaching in the classroom, thereby affecting children’s learning in subject areas beyond science. Misunderstanding about brain function and development also relates to teachers’ opinions on issues such as learning disorders and so, in turn, may influence the outcomes of students with these disorders.

Some have suggested that the long-standing prevalence of neuromyths in the classroom indicates the need for caution when including neuroscience in educational thinking<sup>8,9</sup>. Others have suggested that these misunderstandings show that the distance between these two fields is too great for them to inform each other<sup>10</sup> or even that there is an ‘in principle’ incompatibility between them<sup>11</sup>.

However, the study of neuromyths and how they develop may provide a valuable source of insight into the challenges of interdisciplinary communication between

neuroscience and education, and into how these challenges might be addressed. Understanding the cultural distance to be travelled between neuroscience and education — and the biases that distort communications along the way — may support a dispassionate assessment of the progress in developing a bridge across these diverse disciplines and of what is needed to complete it. The purpose of this Perspective article is to review what we know about neuromyths and the forces that have helped them to grow; to understand the role of these forces in contemporary communications on topics at the interface of neuroscience and education; and to consider how communications between neuroscience and education might be improved in the future.

## Neuromyths in education

The first use of the term neuromyth has been attributed to the neurosurgeon Alan Crockard<sup>9</sup>, who coined it in the 1980s when he referred to unscientific ideas about the brain in medical culture<sup>12</sup>. In 2002, the Brain and Learning project of the UK’s Organization of Economic Co-operation and Development (OECD)<sup>13</sup> drew attention to the many misconceptions about the mind and brain that arise outside of the medical and scientific communities. They redefined the term neuromyth as a “misconception generated by

a misunderstanding, a misreading or a misquoting of facts scientifically established (by brain research) to make a case for use of brain research in education and other contexts” (REF. 13).

Surveys of teachers in countries with very different cultures have revealed similarly high levels of belief in several neuromyths (TABLE 1). This prevalence may reflect the fact that neuroscience is rarely included in the training of teachers, who are therefore ill-prepared to be critical of ideas and educational programmes that claim a neuroscientific basis.

## Seeds of confusion — how myths begin.

Although some writers have used words such as fraud and scam to describe their distrust of unscrutinised brain-based interventions<sup>14,15</sup>, examples of cases in which entrepreneurs have knowingly set out to mislead educators are difficult to find. It is more likely that such interventions originate from uninformed interpretations of genuine scientific facts and are promoted by victims of their own wishful thinking who hold a “sincere but deluded fixation on some eccentric theory that the holder is absolutely sure will revolutionize science and society” (REF. 16).

There is often some remaining trace of scientific origins in even the most bizarre of neuromyths — a seed from which the myth sprung forth and which may still be contributing to its potency. For example, although a daily intake of 6 to 8 glasses of water is a contentious recommendation with its own mythical origin<sup>17</sup> — and there is no evidence for underperformance among school children who fail to meet it — studies<sup>18,19</sup> have shown that dehydration can influence cognitive function. This finding may help to explain why more than a quarter of UK teachers who were sampled in a study believed that failing to meet this quota would cause their brain to shrink (TABLE 1).

Perhaps the most popular and influential myth is that a student learns most effectively when they are taught in their preferred learning style. This idea has acquired various justifications that claim to have a neuroscientific basis. The implicit assumption seems to be that, because different regions of the cortex have crucial roles in visual, auditory and sensory processing, learners should receive

Table 1 | Prevalence of neuromyths amongst practising teachers in five different international contexts

| Myth*                                                                                                                                    | Percentage of teachers who “agree” (rather than “disagree” or “don’t know”) |                              |                     |                     |                    |
|------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|------------------------------|---------------------|---------------------|--------------------|
|                                                                                                                                          | United Kingdom<br>(n = 137)                                                 | The Netherlands<br>(n = 105) | Turkey<br>(n = 278) | Greece<br>(n = 174) | China<br>(n = 238) |
| We mostly only use 10% of our brain                                                                                                      | 48                                                                          | 46                           | 50                  | 43                  | 59                 |
| Individuals learn better when they receive information in their preferred learning style (for example, visual, auditory or kinaesthetic) | 93                                                                          | 96                           | 97                  | 96                  | 97                 |
| Short bouts of co-ordination exercises can improve integration of left and right hemispheric brain function                              | 88                                                                          | 82                           | 72                  | 60                  | 84                 |
| Differences in hemispheric dominance (left brain or right brain) can help to explain individual differences amongst learners             | 91                                                                          | 86                           | 79                  | 74                  | 71                 |
| Children are less attentive after sugary drinks and snacks                                                                               | 57                                                                          | 55                           | 44                  | 46                  | 62                 |
| Drinking less than 6 to 8 glasses of water a day can cause the brain to shrink                                                           | 29                                                                          | 16                           | 25                  | 11                  | 5                  |
| Learning problems associated with developmental differences in brain function cannot be remediated by education                          | 16                                                                          | 19                           | 22                  | 33                  | 50                 |

\*The table shows some of the most popular myths reported in four different studies from the United Kingdom<sup>1</sup>, The Netherlands<sup>1</sup>, Turkey<sup>4</sup>, Greece<sup>2</sup> and China<sup>7</sup>. In all studies, teachers were asked to indicate their levels of agreement with statements reflecting several popular myths, shown as “agree”, “don’t know” or “disagree”. The table shows the percentages of teachers within each sample who responded with “agree”.

information in visual, auditory or kinaesthetic forms according to which part of their brain works better<sup>20</sup>. The brain’s interconnectivity makes such an assumption unsound, and reviews of educational literature and controlled laboratory studies fail to support this approach to teaching<sup>21–23</sup>. However, it is true that there may be preferences and, perhaps more importantly, that presenting information in multiple sensory modes can support learning<sup>24</sup>.

**Cultural conditions — a space for myths to thrive.** Cultural conditions, such as differences in the terminology and language used by neuroscientists and educators, can be implicated in the processes that transform scientific knowledge into self-propagating and misleading ideas<sup>25</sup>. The international popularity of many neuromyths suggests a global dimension to these factors.

One condition that is likely to favour the propagation of a myth is when counter-evidence — as well as the neuroscientific findings on which the myth was (wrongly) based — is difficult to access, which effectively protects the myth from scrutiny. When such counter-evidence and findings are complex and/or can only be found in neuroscience journals, it is easy for non-specialists to miss, misinterpret or ignore them and the myth can therefore spread unchecked; for example, according to ‘left-brain right-brain’ theory<sup>26</sup>, learners’ dispositions arise from the extent to which their left or right brain is

dominant. Although the details of such categorization varies with different educational programmes, ‘intuitive learners’ are often considered as more ‘right-brained’ and ‘step-wise sequential learners’ as more ‘left-brained’ (REFS 27–30). Some educational texts encourage teachers to determine whether a child is left-brained or right-brained before they attempt to teach them<sup>30</sup>. The scientific fact that seeded this myth is not difficult to find: some types of cognitive process are lateralized with regard to the additional neural activity associated with them. Neuroimaging studies, when appropriately interpreted, have shown the distributed nature of neural activity during everyday tasks. However, an uninformed interpretation of images showing ‘hot spots,’ as reproduced in popular and accessible articles, can promote the idea that there are isolated functional units. To non-specialists, apparently well-defined and static islands on one side of a brain are more suggestive of a new phrenology than of a statistical map indicating where activity has exceeded an arbitrary threshold. Considering functionality in terms of independent left and right hemispheres is the simplest form of such phrenology and categorizing learners as left-brained or right-brained just takes this misguided idea one stage further.

The threat of scrutiny is lowest for ideas that are untestable. Multiple Intelligences theory has proved popular with teachers as a welcome argument against intelligence quotient (IQ)-based education. It encourages

them to characterize learners in terms of a small number of relatively independent ‘intelligences’ — for example, linguistic, musical and interpersonal<sup>31</sup>. Multiple Intelligences theory claims to be drawn from a range of disciplines, including neuroscience, which — it has been claimed — is “amazingly supportive of the general thrust of Multiple Intelligences theory” (REF. 32). However, the general processing complexity of the brain makes it unlikely that anything resembling Multiple Intelligences theory can ever be used to describe it, and it seems neither accurate nor useful to reduce the vast range of complex individual differences at neural and cognitive levels to any limited number of capabilities<sup>33</sup>. However, the neuromythological part of Multiple Intelligences theory (that is, its relation to neuroscience) is difficult to test, not least because the task for Multiple Intelligences theorists of defining the types and number of intelligences remains a work in progress.

A language barrier also separates non-specialists from neuroscience evidence. Apart from the technical jargon, there are many familiar words that have new meanings attached to them (including ‘learning’). When we asked trainee teachers whether a student could learn something without attending to it, a surprising 43% thought this was possible<sup>3</sup>. It is possible that teachers interpret the word ‘attention’ (as in ‘paying attention’) as indicating a particular set of overt behaviours (for example, not

talking, looking at the teacher, and so on) rather than as the allocation of cognitive processing resources.

**Biases — how myths are shaped.** Although protection from scrutiny provides a fertile ground for the seeds of neuromyths to germinate and thrive, their shape and form may be influenced by cultural, emotional and even developmental biases; for example, the mind–brain relationship cannot be simplified to an easily digested fact. Oversimplification of this relationship provides a perfect opportunity for introducing biases from which misunderstandings then develop. Although at infancy we tend not to regard mind and brain as being distinctly different<sup>34</sup>, developmental research suggests that children acquire a bias towards ideas about mind and brain<sup>35</sup>. Our beliefs about the mind–brain relationship may shape our notions of free will and, in turn, influence decisions regarding issues of personal well-being and whether to help others<sup>36,37</sup>. From a perspective that tends towards dualism (compared with a materialist perspective), brain development is less open to influence through the mind and is, in other words, more biologically programmed and provides a stronger constraint on learning. The potential effect of such a belief in the classroom can be seen in studies of Chinese teachers and UK trainee teachers; those who favoured a stronger genetic influence on educational outcome also held stronger ideas of biologically defined limits on what their pupils could achieve, which suggests that the teachers felt less able to help them<sup>37</sup>. Factors that bias educators' ideas about the mind–brain relationship can also include strong cultural forces — such as religious belief — that greatly vary across national boundaries. In the UK, where half of the population report no affiliation with any religion<sup>38</sup>, only 15% of trainee teachers believed that the mind results from the spirit or the soul acting on the brain. By contrast, in Greece — which stands out among European states in terms of how religious its people are<sup>39</sup> — 72% of trainee teachers believed in this idea<sup>2</sup>.

Wishful and anxious thinking have also been proposed as important emotional biases that contribute to the distortion of sound evidence<sup>25</sup>. Low-cost and easily implemented classroom approaches can certainly cultivate wishfulness amongst educators, especially if they are fun and therefore likely to be well received by students. The association with neuroscience can be expected to further boost the apparent credibility of the explanation used to promote them<sup>40</sup>, as well as their

desirability<sup>41</sup>. The allure of explanations involving the brain has probably helped to promote programmes such as Brain Gym. As part of this programme, learners are told “brain buttons (soft tissue under the clavicle to the left and right of the sternum) are massaged deeply with one hand while holding the navel with the other hand” (REF. 42). This is supposed to improve many things, including your “flow of electromagnetic energy”, your ability to send messages from your right brain hemisphere to the left side of the body, your tendency to reverse letters and your ability to keep your place while reading. Leaving aside any flaws in its theoretical basis, there is a lack of published research in high-quality journals to make claims about the practical effectiveness of Brain Gym to raise achievement. Of the studies published elsewhere, the lack of information about the exercises undertaken and/or the insufficient or inappropriate analysis of the results is considered to undermine their credibility<sup>43</sup>.

To summarize, the neuromyths that have flourished in areas of public and educational understanding of the brain are comfortably protected from the evidence and concepts that are required to efface them. This protection is provided by the scientific concepts being fundamentally complex, by the fact that evidence is hidden in technical journals that have their own technical language and/or by the fact that there cannot be any direct evidence (for example, because the myth is untestable). Protected from scrutiny, a range of emotional, developmental and cultural biases have influenced the types of unscientific ideas that have emerged.

### Communication begins: out with the old?

In the past 10–15 years, there have been several critical analyses of the ways in which neuroscience may, and may not, be able to helpfully inform educational theory, policy and practice<sup>44,45</sup>. Tentative political interest has been evident from initiatives such as the OECD's supranational project Learning Sciences and Brain Research<sup>46</sup> and in a recent review by the UK's Royal Society<sup>47</sup>. Many journal articles, reports and books have reviewed insights from neuroscience that have potential relevance to education and their authors have often used these opportunities to dismiss popular misunderstandings along the way. These reviews have helped to promote the idea that knowledge from neuroscience might have value for education, and an increasing number of reputable neuroscientists have published work for educational audiences.

There are, of course, some who do not share this enthusiasm. Following a conference in Santiago, Chile, on Early Education and Human Brain Development in 2007, 136 scientists signed a declaration that stated “neuroscientific research, at this stage in its development, does not offer scientific guidelines for policy, practice, or parenting.” (REF. 48). Although few would disagree with this statement, its sceptical tone is clear. The editorial article that reported the declaration stated that brain research was “not ready to relate neuronal processes to classroom outcomes” and referred to the possibility of generating popular misunderstandings about the brain as a “serious downside” to this venture<sup>49</sup>. Despite such warnings, there are now many individuals who are pursuing interdisciplinary empirical research that relates our understanding of the neural processes of learning to classroom outcomes such as learning to read and learning to use formal mathematics. It may be significant that the individuals leading these efforts include several signatories of the Santiago declaration.

As formal communications across the divide between neuroscience and education have become more frequent, it seems prudent to ask how more recent findings in neuroscience are being interpreted by people in the field of education. Below, I discuss four areas in which neuroscience has influenced — or is close to influencing — educational attitudes and approaches, in order to explore whether the old biases and cultural conditions responsible for neuromyths can still be detected. Has the opening of this communication started to dissipate the old neuromyths and the forces that created them?

**Early development and the enduring ‘myth of three’.** Neuroscience findings are increasing our understanding of how factors such as sleep<sup>50</sup>, stress<sup>51</sup> and nutrition<sup>52</sup> influence infant development. Neural markers have also been identified that might be used to detect preschool children who are at risk of developing learning disorders<sup>53</sup>. As communication has improved between neuroscientists, educators and policy makers, efforts have been made to ‘set the record straight’ about issues such as the ‘myth of three’ (REF. 54) — that is, the myth that time from 0 to 3 years is a critical period during which the great majority of brain development occurs and after which the trajectory of human development is chiefly fixed<sup>55</sup>. The factual seeds of this idea include recognition that there

are critical and sensitive periods in the development of particular brain systems. The myth has helped to promote the genuine importance of preschool experiences as fundamental for later learning, but it is an oversimplification that has also led to misunderstandings. These include a sense that adults are in a race against time to provide stimulation to their infants before their synapses are lost<sup>56</sup>. This anxiety has been exploited by a host of manufacturers offering toys to stimulate the brain<sup>57</sup>. Neurodevelopmental studies have so far provided little support for the idea that only early childhood can be considered as a special time for learning<sup>58</sup>, and neither research in neuroscience<sup>59</sup> nor in education<sup>60</sup> provide simple messages about the ages at which investment in education gives maximum return. Rather, findings suggest that the success of educational interventions aiming to improve the learning and well-being of children requires attention to be paid to the specific needs and characteristics of the children and the type of intervention, as well as the timing<sup>61</sup>.

Although attempts to dissipate the myth of three have gained pace, the related neuroscience has also grown in size and complexity. Accordingly, many individuals working in education, including policy makers, are still susceptible to accepting simple models of brain development without questioning their relation to current understanding. The bias towards simplicity, combined with the persisting cultural gap between neuroscience and education, has helped the myth of three to emerge in new forms. One notable example is the misinterpretation of early work by the economist James Heckman<sup>62</sup> (BOX 1), who drew on concepts of critical (or sensitive) periods in brain development to derive his simple 'more begets more' principle<sup>62</sup>. The graph most often associated with this principle is a plot of a mathematical function that assumes that the brain is a continuously developing, unitary entity (BOX 1). This graphical expression of the principle suggests that the return (in terms of additional mental capacity) for public investment in an individual's education is markedly diminished if the investment occurs after infancy. However,

it is important to note that it is not a graph of empirical data. In international discussions about whether students should be expected to invest financially in their own higher education, this model has been used to support statements such as "expanding higher education based on contributions from those who benefit from it rather than based on general tax revenues is the most direct way to ensure equity in education outcomes" (REF. 13). In other words, the neuroscientific basis of the model has been overinterpreted in order to provide an allegedly scientific argument for withdrawing the public funding of university education. In the UK, the graph has appeared in educational policy documents<sup>63</sup> as a plot of empirical data (BOX 1).

However, this simple model considerably detracts from our modern understanding of the brain<sup>58</sup>. Human development and learning arise from a range of interrelated neural circuits subserving a range of cognitive and other skills, which develop at different rates until early adulthood, sometimes in a discontinuous manner. In addition, the concept of the sensitive period in brain development was based on findings that an impoverished rearing environment resulted in impaired development<sup>44</sup>, but that does not necessarily mean that enriching the environment of normally developing children (for example, so-called 'hot-housing') will result in a similarly marked improvement in their brain development. Therefore, the relevance of the sensitive period concept may depend on how a child has already developed. A later and more sophisticated model of educational investment represents mental ability as comprising two types: cognitive and non-cognitive<sup>64</sup>. This model, when adjusted to fit the outcomes of a sample of 2207 children, again emphasized the importance of early investment, but particularly so for disadvantaged children. It also made more nuanced predictions about the targeting of investment. However, the earlier simple model (BOX 1) remains most popular in discussions of policy, in which it is sometimes referenced as summarizing findings in neuro-cognitive development without a consideration of its limiting assumptions (for example, REF. 65). The use of such theoretical models as proxies for actual neuroscientific data in educational policy seems likely if the intersection between neuroscience and education remains fairly uncharted and unpopulated by those with expertise in both areas.

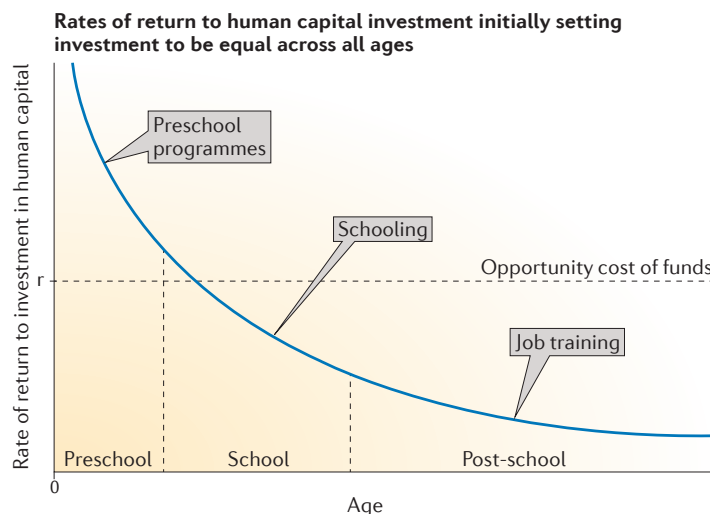
**Difference and biological determinism.** The use and meaning of labels such as 'attention deficit hyperactivity disorder (ADHD)' and 'dyslexic' has educational

## Box 1 | Heckman economics as a proxy for neuroscience in educational policy

The 'myth of three' (that is, the belief that the trajectory of neurodevelopment is essentially fixed after 3 years of age) can still be found in different forms in educational discussions. For example, an early economic model of educational investment by Heckman<sup>62</sup> is sometimes confused by educators as representing neuroscientific evidence for the myth of three. This model was created by drawing on concepts such as critical (or sensitive) periods in brain development to justify a simple 'more begets more' principle of accumulating mental ability<sup>62</sup>. The model combined this principle with assumptions that the brain is a continuously developing and unitary entity. This allowed prediction of the return (in terms of additional mental capacity over a lifetime) from investing an additional (marginal) dollar in education at different ages. The outcome of this prediction is the sweeping downward curve shown here<sup>97</sup> (where  $r$  is the costs of the funds) that implies the economic return from investing a dollar in the education of a child under 3 years old is many times greater than if that dollar was invested in a teenager's education. Some policy makers seem to interpret this graph as a plot of evidence which "shows that investment early in life produces better returns" (REF. 63). However, the graph does not show a plot of actual evidence; rather, it shows predicted returns from investment in education<sup>62</sup>.

Moreover, the prediction is based on a model whose assumptions are some way short of the current understanding of human brain development and mental ability<sup>64</sup>.

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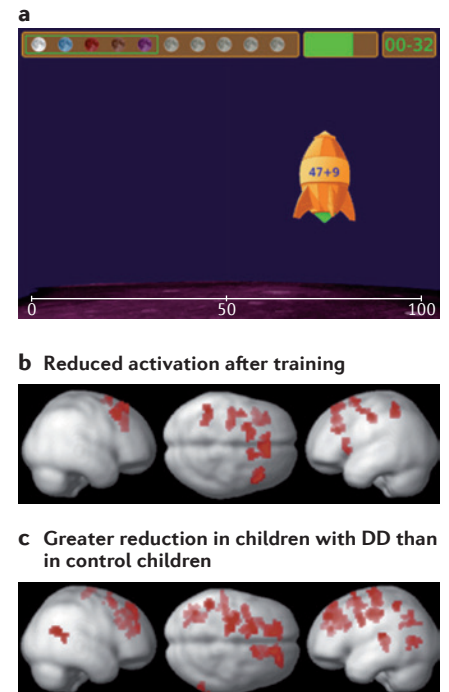


implications for resource allocation, teachers' attitudes and students' achievements. Neurobiological findings should and do feature in expert discussions about learning disorders, including their definition, causes and treatment. In less scientific debates on these subjects, a dualistic non-plastic mind-brain model — in which the brain cannot be influenced by the mind — has fuelled arguments both in support of and against the existence of particular learning disorders. To individuals inclined towards such a model, differences in functional imaging data between groups of learners with and without a disorder may seem to be biologically determined and immutable symptoms and therefore make the disorder 'more real'. For example, ripostes to recent arguments about whether ADHD exists<sup>66</sup> have emphasized statements such as "ADHD is a real medical disorder, with real brain differences" (REF. 67). Conversely, for people who believe that all 'proper' disorders are biologically determined and immutable, the finding that symptoms of children diagnosed with a disorder can be reduced through teaching means that these children never had a 'real' disorder to begin with. For example, in the 2005 British Broadcasting Corporation (BBC) television documentary *The Dyslexia Myth* (Mills Productions), the effectiveness of mainstream remediation classes for dyslexic readers was presented as evidence that dyslexia does not exist<sup>68</sup>. Educators' ideas are influenced by these media representations<sup>69</sup>, and until ideas from neurobiology are more meaningfully integrated into educational training and institutions this influence is likely to continue. This has implications for the children they teach, not least because the achievement of students diagnosed with a learning disorder partly depends on their teachers' implicit attitude to the disorder<sup>70</sup>. Recent studies provide evidence against ideas of biologically determined and fixed qualitative differences between individuals with and without diagnosis of a developmental disorder (FIG. 1). These studies could be helpful in dissuading teachers of these ideas but, without improved communications between neuroscience and education, one cannot assume this dissuasion will happen quickly. For example, although early research fuelled a visual theory of causation for dyslexia, this was no longer accepted as the general consensus by 1994 (REF. 71). Rather, the long-standing and most widely accepted explanation involves a weakness in phonological coding<sup>72</sup>. An intervention attempting to target the visual system involves the use of

tinted overlays to overcome the associated 'structural brain deficit' (REF. 73), but the authors of a double-blind study investigating this approach reported no evidence of positive benefit<sup>74</sup>. They indicated the 'magic bullet' simplicity of the idea of using coloured filters to explain the popularity of this intervention, combined with a mass of anecdotal evidence that may also be linked to the placebo effect. Nevertheless, a majority of preschool teachers in a survey in Southwest USA still considered dyslexia as a visual perception deficit rather than a problem with phonological processing and thought that the idea that dyslexic children could be helped by using coloured lenses or coloured overlays was "probably or definitely true" (REF. 69).

#### *Engagement and dopamine mythology.*

Insight into the relationship between reward and declarative memory formation<sup>75</sup> has prompted educational research that uses novel reward schedules to improve learning<sup>76</sup>. Initial studies show that offering uncertain rewards, which are thought to increase mid-brain dopamine uptake<sup>77</sup>, can increase the rate at which curriculum material is learnt<sup>78</sup>. In our own attempts to translate these findings into classroom learning games, we have encountered new potential for neuromyths. This has partly been a matter of language. For example, educators' understanding of the term 'motivation' extends well beyond its common usage in neuroscience (that is, motivation as a short-term visceral desire to approach)<sup>79</sup>; it also includes motivation towards longer-term goals such as a university career. In addition, many teachers already possess preconceptions about dopamine that influence their understanding of our messages and, thereby, their practice with regard to their students. Some associate it with pleasure, with one teacher claiming that "a good working environment will release dopamine, and then they feel good and it is remembered as something positive" (REF. 80). However, we are often asked whether our learning games will cause students to become pathological gamblers or drug addicts. Primitive neurobiological explanations involving dopamine have now established themselves as part of the folk perceptions of addiction<sup>81</sup>. Dopamine mediates many important cognitive processes and is not restricted to explanations of drugs and risk-taking, but anxieties around such activities have strengthened in the public imagination its association with all types of out-of-control behaviour and danger. The frequency of dopamine's appearance in press stories has



**Figure 1 | Imaging studies of interventions are of particular interest to education.** **a** | An imaging study of developmental dyscalculia (DD) involved a computer-based 'mental number line' training, in which children learned to respond to number-related questions by moving a joystick in order to land a spaceship on a number line<sup>98</sup>. **b,c** | After training, children with and without DD improved their arithmetic ability and showed reduced activation in a range of mainly frontal regions when performing a number line task (part **b** shows data for both groups combined). Both behavioural and neural changes were greater for the DD group (part **c** shows brain areas in which the post-training reduction in activity was greater for the DD group than for the control group). Studies such as this, which focus both on problematic learner differences and their remediation, are helpful and relevant to education. Firstly, they provide insight into the biology of individual differences which, when integrated with educational expertise, may form the basis of more effective approaches to teach children with learning disorders in the future. More immediately and more generally, they show the plasticity of the brain and indicate that brain function can be improved by a student practising well-designed tasks. Such studies highlight not only how learning disorders may be associated with distinct neurological differences but also how such differences may be responsive to appropriate teaching. This can help to foster the types of positive teacher attitudes towards learning disorders that are associated with better outcomes for the students who are diagnosed with them<sup>70</sup>. Figure reprinted from *Neuroimage*, 57, Kucian, K. et al., Mental number line training in children with developmental dyscalculia. 782–795, © (2011), with permission from Elsevier.

resulted in it being dubbed “the media’s neurotransmitter of choice” (REF. 82). Dopamine is linked in the media to problems as diverse as gun culture<sup>83</sup>, the overconsumption of cupcakes<sup>84</sup> and obsessing about e-mails<sup>85</sup>. This has helped to intertwine dopamine and all types of addictive behaviour in the public consciousness and to contribute to the world of pseudoneuroscience, in which different meanings can be attached to the same terms and terms borrowed from neuroscience can be merged with others to create new phrases. I discovered this when a BBC journalist asked me to use the term ‘dopamine hit’ when describing students experiencing a learning game because, she explained, people knew what that term meant. This is a phrase that has also arisen in our conversations with teachers. When used as a noun, ‘hit’ is commonly used as the slang term for a unit of an illegal drug<sup>86</sup>. It seems that messages for educators — however scientifically sound the underlying concepts are — will come into contact with other ideas that are less scientific, which may influence the message that is received. Working with educators has allowed us to identify such misconceptions early in the process of translation and to work collaboratively in developing resources that anticipate and explicitly address such confusions.

**Adolescence and brake failure.** Under-standing brain function has already contributed to interventions for teenagers; for example, major changes in sleep regulation processes in the brain have helped to explain why teenagers can be ill-prepared for learning early in the morning<sup>87,88</sup>. An improved understanding of the biology of teenage sleep issues has helped to justify interventions to shift the school day and to improve attendance, as well as reducing sleepiness<sup>89</sup> and raising self-reported motivation<sup>90</sup>. Neuroscience has also provided insights into the continuing maturation of brain regions involved in social cognition and self-awareness that may inform future school-based interventions for teenagers, for example, for tackling anti-social behaviour<sup>91</sup>.

Increased risk-taking during adolescence has been explained in terms of a dual-systems framework of neurodevelopment that relates increased reward-seeking to an early adolescent peak in dopaminergic activity; the pre-frontal cortex and its connections to regions involved in control and coordination of affect and cognition are slower to mature<sup>92</sup>. These changes have been described as being responsible for an individual temporarily having ‘all gas and no brakes’ during adolescence. This metaphor is frequently used to help educators

to understand the behaviour of their students. For example, in a Canadian teachers’ journal, psychologist Aaron White advises “because the frontal lobes are involved in controlling impulses and making good decisions, adolescents often fail to fully consider the consequences of their actions until it’s too late. They are all gas and no brakes!” (REF. 93). Similar representations of the dual-systems framework can be found in the popular press<sup>94</sup>. However, the metaphor can suggest that an individual is completely detached from their own free will and that they are ‘immune’ to the normative social influences around them (that is, their teachers and parents). This creates moral and practical dilemmas regarding how teachers should and can respond effectively, for example, to teenagers behaving disruptively in class. Arguments over whether such poor behaviour can be blamed on the brain partly mirror those raised in relation to teenage crime. In education, as in the law courts, our moral intuitions about legal responsibility are entwined with culturally inherited ideas of free will and a dualist mind–brain relationship, both of which are likely to be influenced by sophisticated thinking about the mind and its neural basis<sup>95</sup>. In other words, through interaction with existing biases, our intuitions about moral responsibility are likely to be influenced by the field of neuroscience, despite the field itself making few claims for authority in this area. On a practical level, teachers also want to know how best to interact with the developing neural circuitry of teenagers and how to encourage their students to improve their behavioural self-control. For teachers, the ‘gas and no brakes’ message appears to imply that “upskilling the driver does not present as a possible solution, since poor/weak brakes (the immature PFC [prefrontal cortex]) — or no brakes at all — cannot be fixed” (REF. 94). It seems that many teachers are exposed to a version of the dual-systems framework that may already be influencing their practice but not necessarily in ways that most appropriately relate the neuroscience to educational understanding. It has been suggested that neuroscientists have a responsibility to reduce neurodevelopmental complexity into accessible, data-informed messages for non-scientists<sup>96</sup> and this may work well in some ‘real-world’ domains. However, in education, effective communication may require neuroscientists to work in collaboration with those who are more familiar with the cultural conditions and concepts of education — that is, the educators themselves — to ensure that the content of the communication is fit for purpose.

## Conclusions and the future

Neuromyths are misconceptions about the brain that flourish when cultural conditions protect them from scrutiny. Their form is influenced by a range of biases in how we think about the brain. Some long-standing neuromyths are present in products for educators and this has helped them to spread in classrooms across the world. Genuine communication between neuroscience and education has developed considerably in recent years, but many of the biases and conditions responsible for neuromyths still remain and can be observed hampering efforts to introduce ideas about the brain into educational thinking. We see new neuromyths on the horizon and old neuromyths arising in new forms, we see ‘boiled-down’ messages from neuroscience revealing themselves as inadequate, and we see confusions about the mind–brain relationship and neural plasticity in discussions about educational investment and learning disorders.

More interdisciplinary collaboration between neuroscience and education may help to identify and to address misunderstandings as they arise, and may help to develop concepts and messages that are both scientifically valid and educationally informative. A new field focused on such collaboration is now emerging, although it is too new for its many proponents to have settled on a name for it — ‘Brain, Mind and Education’, ‘Neuroeducation’ and ‘Educational Neuroscience’ being current contenders. A field dedicated to the interaction between neuroscience and education will not only inform educational approaches but also may encourage scientific insight regarding the relationship of neural processes to the complex behaviours that are observed in the classroom. Research centres combining neuroscience and education are forming around the world, often offering postgraduate courses. Although individual approaches in these centres vary, there is a common appreciation of the size of the challenge that lies ahead, of the marked differences in concepts and language between neuroscience and education, and of the need for neuroscientists and educators to work together when attempting to bridge these two disciplines. In the future, such collaboration will be greatly needed if we wish education to be enriched rather than misled by neuroscience.

Paul A. Howard-Jones is at the Graduate School of Education, University of Bristol, 35 Berkeley Square, Bristol BS8 1JA, UK. e-mail: [paul.howard-jones@bris.ac.uk](mailto:paul.howard-jones@bris.ac.uk)

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## Competing interests statement

The author declares no competing interests.