

Educating the adult brain: How the neuroscience of learning can inform educational policy

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Abstract The acquisition of new skills in adulthood can positively affect an individual's quality of life, including their earning potential. In some cases, such as the learning of literacy in developing countries, it can provide an avenue to escape from poverty. In developed countries, job retraining in adulthood contributes to the flexibility of labour markets. For all adults, learning opportunities increase participation in society and family life. However, the popular view is that adults are less able to learn for an intrinsic reason: their brains are less plastic than in childhood. This article reviews what is currently known from neuroscientific research about how brain plasticity changes with age, with a particular focus on the ability to acquire new skills in adulthood. Anchoring their review in the examples of the adult acquisition of literacy and new motor skills, the authors address five specific questions: (1) Are sensitive periods in brain development relevant to learning complex educational skills like literacy? (2) Can adults become proficient in a new skill? (3) Can everyone learn equally effectively in adulthood? (4) What is the role of the learning environment? (5) Does adult education cost too much? They identify areas where further research is needed and conclude with a summary of principles for enhancing adult learning now established on a neuroscience foundation.

Keywords Lifelong learning · Adult education · Adult learning · Adult literacy · Brain plasticity · Sensitive periods · Educational neuroscience

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Résumé Former le cerveau adulte : comment les neurosciences de l'apprentissage peuvent éclairer les politiques éducatives – L'acquisition de nouvelles compétences à l'âge adulte peut avoir une influence positive sur la qualité de la vie d'un individu, y compris son potentiel de revenus. Dans certaines situations, tels que l'alphabétisation dans les pays en développement, elle peut permettre de sortir de la pauvreté. Dans les pays industrialisés, la reconversion professionnelle à l'âge adulte contribue à la flexibilité des marchés du travail. Chez tous les adultes, l'apprentissage augmente leur participation à la société et à la vie familiale. Néanmoins, l'opinion générale veut que les adultes soient moins aptes à apprendre, et ce pour une raison intrinsèque : leur cerveau serait moins malléable que dans l'enfance. Les auteurs recensent les connaissances actuelles de la recherche neuroscientifique sur l'évolution de la flexibilité du cerveau avec l'âge, en particulier sur la capacité d'acquérir de nouvelles compétences à l'âge adulte. Appuyant leur examen sur des exemples de l'acquisition des compétences de base et fondamentales chez les adultes, les auteurs traitent cinq questions spécifiques : (1) Les périodes sensibles au cours du développement cérébral affectent-elles l'apprentissage de compétences éducatives complexes telles que l'alphabétisation ? (2) Les adultes peuvent-ils devenir chevronnés dans une nouvelle compétence ? (3) Tous les adultes apprennent-ils avec la même efficacité ? (4) Quel est le rôle de l'environnement éducatif ? (5) Les coûts de l'éducation des adultes sont-ils trop élevés ? Les auteurs identifient les domaines appelant des études plus poussées et concluent par une synthèse des principes valorisant l'apprentissage des adultes désormais fondé sur une base neuroscientifique.

The role of neuroscience in education

Education is traditionally viewed as the process of developing skills and knowledge throughout childhood to prepare individuals for the adult world of work, social interaction and recreation. Yet learning in adulthood is increasingly a vital part of living in modern society, be it in order to keep pace with ever-advancing technology, to develop new employment prospects or to capitalise on opportunities that were not available to the individual during childhood. This is true across the world, but especially in developing nations where education in childhood is still not a universal provision. Learning inequality, for example with regard to literacy, impacts inequitably upon women in developing nations (UNESCO 2004) and the Afro-Caribbean population the world over (NCES 2006). The burden of illiteracy is estimated to have serious economic consequences: even in developed nations literacy level correlates with employment status (BIS 2009; NCES 2004). It is likely that a similar relationship would be found for other domains of learning such as numeracy, although no such data are currently available.

Education is a special case of learning, where the skills and experiences of previous generations are passed on. To talk about learning in any context is to talk about altering the brain. Every day our brains change through experience as we form memories, learn facts, associate faces with names, or even try new foods. All new

memories are established by changing patterns of neuronal firing in the brain. The aim of education is to guide that process of change in a way that is relevant to individuals and the society in which they live. Guidance can be optimised by understanding the process of learning, the neurophysiological conditions that allow it and the changes that learning causes in the brain. The field of *educational neuroscience* has emerged over the last decade with a specific remit to find the common ground between these two disciplines (Mareschal et al. 2013). Neuroscientists and educationalists have come together to begin to take the basic science of the biological mechanisms underpinning cognition and translate it into optimal classroom conditions and school curricula. Currently this field of research focuses largely on learning in the child brain. However, it is increasingly apparent that it could be equally fruitful to consider lifelong learning; a term taken here to mean learning new information and skills irrespective of the learner's age and in circumstances including, but not limited to, formal classrooms.

All animals, including humans, show windows of opportunity for learning certain skills as juveniles. What is notable for education is that these windows of opportunity, or *sensitive periods*, seem only to strictly apply to very basic functioning. Most complex skills can be acquired throughout life. However, this is not to say that learning occurs at an equivalent rate or can reach equivalent levels of proficiency across the lifespan. Structural and functional changes take place in the brain as humans age, which mean that learning conditions need to be altered to ensure maximally efficient learning, or sometimes to ensure that learning occurs at all. Neuroscientific principles infrequently inform real-world learning situations, yet they can illustrate the kinds of practical changes that can make a difference to the acquisition of new skills in adulthood in any learning arena. In this paper, we outline what is known about the neuroscience of learning later in life and draw out the principles that may be most relevant to the practical task of educating adults.

Sensitive periods

The human brain constantly changes throughout the lifespan and responds differently to environmental challenges and opportunities across that span. Periods during which the brain is most responsive to input from the environment are known as *sensitive periods*. During sensitive periods the brain is at its most flexible, or *plastic*. Importantly, the rate at which the brain matures is not uniform across different systems (see Huttenlocher 2002). Because sensitive periods are associated with the stage of maturation of a system, it follows that different brain systems show sensitive periods at different ages. Differential timing can be observed across domains. For example, the visual system shows an earlier period of maximum plasticity than the system responsible for critical thinking (see Knudsen 2004). Equally, differential timing can be observed within a given domain. For example, learning the speech sounds of a language shows an earlier period of maximum plasticity than learning the grammar of a language (e.g. Neville et al. 1992). Such non-uniformity has implications for education throughout childhood (Thomas and Knowland 2009; Thomas 2012).

In humans, typically the greatest maturational brain changes occur during early or mid-childhood, though some brain systems show substantial change right up to the end of adolescence. Throughout the period of early-to-mid childhood, the number of synapses (connections between neurons) is established. An initial over-proliferation is followed by a period of pruning, leaving those synapses which are regularly used and therefore functional. It is this process of commitment which defines the end of periods of maximum brain plasticity. Changes in plasticity are not strictly linked to chronological age but depend in part on experience. One theory holds that brain plasticity decreases as systems become increasingly specialised towards their adult functions, a process that involves interaction with the environment as much as age-related changes in the brain's substrate (Thomas and Johnson 2008). Notably though, in the hippocampus, where the consolidation of new memories occurs, new neurons are formed throughout life. This process is called *neurogenesis* and reflects the need for the environment to continue to influence memory formation throughout life.

While the phenomenon of sensitive periods is dependent on a property of neural circuits in the brain, these periods can also be thought of in terms of the associated adaptability in behaviour, which we will focus on here. Sensitive periods are highly adaptive as they allow an organism to be tuned to their individual environment. Too much brain plasticity in adulthood would result in information having to be constantly re-learned. A potential problem, however, is that if sensitive periods occur early in life, the environment available to an individual during that period should be relevant across that individual's lifespan. In the case of adult education, the learning environment changes across the lifespan. Educational neuroscience is therefore interested in ways to enhance brain plasticity and maximise learning in response to that change.

Sensitive periods are seen in virtually all species studied, from fruit flies (Barth et al. 1997) to humans. For example, in the wild, songbirds show a clear window of time during which they must learn their song (see Brenowitz and Beecher 2005), the same is true for normal visual perception in kittens (Hubel and Weisel 1970) and auditory responses in barn owls (see Pena and DeBello 2010). Some sensitive periods are more or less well-defined than others; some seem to end abruptly while others decline gradually (Knudsen 2004). In humans, the clearest evidence for sensitive periods comes from studies of basic perceptual systems. For example, congenital cataracts must be corrected within the first six weeks of life to optimise the subsequent development of visual acuity (Birch and Stager 1996). There is currently no equivalent evidence for sensitive periods in more conceptual learning.

A review of the neuroscience literature to address five questions

This paper is structured around answering five questions concerning the relevance of sensitive periods to learning in human adults. The five questions are as follows:

1. Are sensitive periods in brain development relevant to learning complex educational skills like literacy?
2. Can adults become proficient in a new skill?
3. Can everyone learn equally effectively in adulthood?

4. What is the role of the learning environment?
5. Does adult education cost too much?

Neuroscientific evidence regarding brain plasticity in humans comes from three principal sources: (1) recovery from brain injury occurring at different points in development; (2) the consequences of deprivation in early life (most often as a result of congenital auditory or visual impairments) with exposure to typical environments later; and, (3) learning new skills at different points across the lifespan. More direct evidence on the mechanisms of brain plasticity has been gained from behavioural and neuroanatomical studies on animals. All of these data are relevant, and can reveal different types of plasticity in the system. The most pertinent for education, though, are those which address the ability to learn. To anchor our review, we use the concrete examples of learning literacy and learning new motor skills in adulthood, both of which are highly relevant to employment.

Sensitive periods for education

Are sensitive periods in brain development relevant to learning complex skills like literacy?

The answer to this question is that although sensitive periods are seen in humans, and are of considerable importance to the development of perceptual and motor systems early in life, they are less pertinent to high-level cognition. While humans do show a gradual decline in capacity for the acquisition of new complex skills, brain-level changes in response to learning continue to be seen throughout adulthood.

A gradual reduction in brain plasticity in humans

The process of learning changes over developmental time; for example, infants absorb their native language(s), while adults have to actively study to achieve competence in a new language. This switch seems to happen gradually, but what exactly is changing? One theory states that learning a skill establishes and stabilises neural pathways such that it is subsequently more difficult to override those pathways as new information is presented. For example, learning the sounds relevant to your native language in infancy may make it more difficult to learn sounds relevant to another language later in life (Kuhl et al. 2008). Early learning actually hinders later learning. Under this view, brain systems show a gradual reduction in plasticity as pathways stabilise, amounting to a reduction in learning capacity as it becomes harder and harder to rewire circuits. In a sense, the brain gambles that the current environment will be the relevant one throughout the individual's life. The cognitive preeminence of humans is believed to be partly attributable to the extended period over which this gamble is made, providing the window for culture to shape brain structure.

Animal studies have demonstrated more starkly that brain plasticity is dependent not only on time but also on experience. When normal neuronal development is

prevented, the system remains plastic until it has had sufficient experience. For example, the maturation of the auditory system in rats can be extended by rearing animals in white noise. Levels of brain plasticity usually seen in younger rats are evident after reintroduction to a normal environment in adulthood (Chang and Merzenich 2003; Zhou et al. 2011). In fact, to our knowledge, no system has yet been found where the sensitive period absolutely cannot be altered by the nature of the environment in which the animal is raised.

Methods are now emerging which allow clinicians and researchers to *induce* plasticity in the adult human brain. Transcranial direct current stimulation (tDCS) applies a weak electrical current to the scalp, stimulating neurons and making them more responsive to stimuli in the environment (see Nitsche et al. 2008). This provides a window of opportunity to present learning materials, making it a potentially powerful tool in the acquisition of new skills. While most studies using electrical stimulation have focused on improving the performance of basic tasks, recently, Albert Snowball et al. (2013), using a technique called *transcranial random noise stimulation*, demonstrated improvements in learning and subsequent performance on complex arithmetic tasks. Electrical stimulation during learning increased the speed of both calculation-based and memory-recall-based arithmetic learning in young adults, an effect that was still measurable six months later. Another avenue recently explored is pharmacological support for skill learning in adulthood. A drug normally used as a mood-stabiliser and anti-epileptic has been found to enhance the learning of absolute pitch in adults (Gervain et al. 2013); this is particularly impressive as this low-level sensory skill has previously been demonstrated to show a sensitive period (Russo et al. 2003). The extent to which methodologies such as these could, or should, have practical applications in everyday learning scenarios is not yet clear, but they certainly demonstrate the capacity for ongoing brain plasticity throughout the lifespan.

Not all stimulation need be as invasive; engaging in voluntary exercise has also been shown to alter brain chemistry and the responsiveness of the adult brain to learning (see Cotman and Bertold 2002 for a review). In rats, voluntary exercise induces hippocampal neurogenesis (e.g. Kannangara et al. 2010) and in human adults physical exercise is associated both with enhanced performance on intelligence tests in young adults (Aberg et al. 2009) and increased hippocampal volume in the elderly (Erickson et al. 2009). It has been suggested that the evolutionary reason for this is that physical activity is linked to an increased likelihood of cognitive challenge (see Kempermann et al. 2010).

Changes in attention

Changes in attention control also influence learning throughout the lifespan. The ability to inhibit distracting stimuli develops over childhood, and children gradually learn to maintain currently relevant goals (Zelazo 2004). This shift could be summarised as a change from environmentally driven behaviour to internally driven behaviour (Craik and Bialystock 2006); it can fundamentally change the way in which an individual learns from the environment. The consequence is that adults may need to engage with stimuli in a way that children do not. The adult is selective

while the child is immersive. Animal studies suggest that in auditory development, for example, adult animals need to *respond* to a stimulus in order to learn from it, while juveniles can passively perceive the same stimulus and still learn (Keuroghlian and Knudsen 2007). While this difference reflects the need for deeper engagement with stimuli on the part of older animals, attention is necessary in order to learn at any age.

One particularly relevant aspect of engagement is that social situations induce learning. Songbirds gradually lose their ability to learn their species' song. Through the juvenile period learning is possible either from a live tutor or a tape player, but the period of learning from a live tutor extends further (Jones et al. 1996). Only the social situation induces the engagement necessary for learning in the older bird. A similar effect has been shown with human infants, where nine-month-olds were shown to be able to learn Mandarin speech sounds from a live tutor but not from the same amount of exposure to a televised tutor (Kuhl et al. 2003). The mechanisms underlying this effect are not well understood. The current thinking is that social interaction is rewarding and reward contingency increases brain plasticity through making stimuli more salient and engaging.

Malleability in the adult brain: the examples of literacy and motor skills

Learning does change across the lifespan, and if the environment is not altered in line with those changes, learning outcomes are reduced. However, significant changes at the brain level in response to acquiring new skills are seen throughout adulthood. In this section, we introduce two examples, drawn from the fields of literacy acquisition and motor skill learning.

Our first example is *literacy*. The ability to read text is a fundamental skill for living as an adult in the modern world: a world of websites and instant messages, a world of paperwork. Illiteracy in adulthood, estimated at around 800 million the world over (UNESCO 2004), therefore poses a major economic problem. Nowadays most literate adults read text every day of their lives, from ingredient names to e-mails yet reading has been important for any but the most highly educated only for the last 100 years. It has been postulated that the neural circuits for reading, having been put under little or no evolutionary pressure during that time, commandeered and adapted already established circuits specialised for skills such as visual pattern recognition. This concept is known as “neuronal recycling” (Dehaene and Cohen 2007).

The brain systems involved in reading are well-established. One particularly prominent area is a left posterior brain region known as the “visual word form area” (VWFA) (McCandliss et al. 2003). This is part of the same system which is active during other visual recognition tasks, including recognising faces and buildings. For our purposes, the most relevant research in this area involves illiterate adults learning to read later in life. Using brain imaging to assess brain activation during the presentation of text, Stanislas Dehaene et al. (2010a, b) compared literate adults with ex-illiterate adults (who learned to read after adolescence), and currently illiterate adults. The authors reported two important findings.

First, the VWFA responded not only to words but also to other visual stimuli such as faces, but this response to other stimuli was greater for illiterate adults than literate adults. The authors interpreted this as demonstrating competition, with different types of visual input competing for representation in the VWFA. A reduction in response to faces in the VWFA has also been reported in children as they learn to read (Cantlon et al. 2006). Again this suggests that the VWFA typically processes complex visual stimuli with which we have plenty of experience, and that with competition over time it comes to represent written words. Those participants in the Dehaene study who had learned to read in adulthood (the ex-illiterates) also showed substantial activity in the VWFA in response to faces, suggesting the written words had not come to dominate the area to the same extent as in those who learned to read in childhood. This may represent a limit on brain plasticity, supporting the notion that when a system has specialised (in this case to faces), it becomes increasingly hard to re-specialise (to words). If this is the case, it follows that adults will need more practice to establish literacy than children learning the same task. Alternatively, this finding may reflect the fact that the new adult readers had less practice and less time for words to take over this brain region. The second important finding was that Dehaene and his colleagues observed how learning to read also led to more active processing throughout the language system and the visual system, emphasising the potential benefit to wider cognition of learning new skills such as reading later in life. The neuronal recycling hypothesis supports the notion that neuronal systems gradually commit with experience, but also that some brain plasticity remains to allow learning when important new stimuli are presented.

We turn now to our second example: *motor skills*. The acquisition of new motor skills can be a key component of learning in later life; in the world of work this might relate to learning to touch-type or learning a new skill for a factory job. Neuroscientific research in this area predominantly relates to hobbies such as juggling, but the principles established adequately illustrate the neurophysiological underpinnings of developing new motor skills of varying speed and complexity.

Bogdan Draganski et al. (2004) showed for the first time that substantial changes in the volume of a localised brain region could result from learning a new motor skill in adulthood. The young adults in this study were taught to juggle over a period of three months, after which time substantial changes in grey matter volume were seen in both cerebral hemispheres in areas linking vision to motor control. However, grey matter volume fell back towards baseline after a further three months without training. The effect was quite localised, with only part of the brain circuit associated with acquiring the new skill showing activity-dependent change. The implication is that some areas of the cortex are more plastic in response to repeated activation than others. Similar changes in cortical volume have been observed in individuals who learn to touch-type in adulthood (Cannonieria et al. 2007), with the extent of change correlating with duration of practice.

Structural change may not occur only with respect to grey matter (neuronal cell bodies) but also white matter (axons which connect cell bodies and form large tracts in the brain). When the Draganski study was replicated (Scholz et al. 2009), white matter changes underlying the areas of affected grey matter were also revealed, suggesting that skill learning changed how relevant brain areas communicate with

each other. Although changes in white matter have been observed, this may represent a limiting factor for brain plasticity in adulthood. Sara Bengtsson et al. (2005) used a group of professional piano players to measure the relationship between white matter organisation and time spent practising in childhood, adolescence and adulthood. Time spent practising at different times in life was correlated with organisation in those white matter tracts which had not yet reached maturity. The implication is that white matter organisation is experience-dependent but may not always be flexible and may be a limiting factor in adult education in the case of some skills. The good news is that white matter tracts are known to mature relatively late, until at least age 30 in some cases.

In summary, learning capacity changes throughout the lifespan. The primary causes of this change involve slowly reducing capacity as the brain specialises, along with compounding attentional changes. Importantly, the adult brain shows considerable capacity for both structural and functional change in response to complex skill learning, although limiting factors on the extent of possible change may include white matter structure. Based on current understanding, sensitive periods are not a serious limiting factor in adult education, but they do point to changes in the expected rate of learning.

Can adults become proficient in a new skill?

The aim of practising a new skill is to achieve *automaticity*. Automaticity has different definitions (see Moors and De Houwer 2006), but the most usual definition in cognitive neuroscience is being able to carry out one task while performing another task simultaneously (Schneider and Shiffrin 1977). Typically, this means being able to perform a task without directed attention or thought, for example, driving a car while engaging in conversation. Carrying out dual tasks can actually improve performance in experts, though not in novices (Beilock et al. 2002). In the domain of reading, automaticity tends to mean being able to read a text quickly and fluently and understand its content. At the brain level, however, automaticity is equated with the second of two phases of learning a new skill. The first, fast, stage of learning is associated with the rapid progression of skill development. During this phase the aforementioned changes in cortical structure and function are observed. Changes in activity are often recorded in motor cortex and more anterior regions related to paying attention and keeping items active in memory. This is followed by a period of slower learning, or consolidation, which may last much longer. During this period, less behavioural change is noted, but consolidation is practice-independent, unlike the fast stage, and it is accompanied by changes to activity in sub-cortical areas (Floyer-Lea and Matthews 2005). With this brain-level shift, performance becomes faster, less variable and less prone to error (Martijn Jansma et al. 2001); this stage is therefore thought to represent habit formation, or automaticity.

Automaticity in the acquisition of new skills in adulthood is an important issue but for different reasons, depending on the skill at hand. With regard to reading, speed is a vital factor as a slight increase in the time it takes to decode each letter can result in substantial increases in time taken to read a passage, which in turn can

have a still greater impact on comprehension levels because the whole sentence cannot be “held in mind” while decoding meaning (Torgesen et al. 2001). Beyond speed, the issue of changes in attention can be important, for example a reduction in the amount of attention needed to perform a motor task in a factory means an associated reduction in distractibility, thereby impacting on output levels and safety.

Missing from this field of enquiry are comparative studies considering the development of automaticity in children and adults. How do trajectories of skill learning, in terms of behaviour and brain responses, differ? This could have an important impact on the different learning environments needed to maximise the acquisition of new skills at different ages. Can adults learn the same amount given the same learning period as children? For example, in the study by Dehaene et al. (outlined above), the ex-illiterate adults performed nearly as well as the literate adults in terms of reading accuracy, but they read more slowly. No work that we are aware of has yet been carried out on the maximum level of proficiency that adults are able to acquire when learning to read. Studies comparing literacy acquisition rates in adults and children are difficult to run due to multiple confounding factors. For example, one would need to replicate for the adult the intensity and duration of literacy practice experienced by children, taking into account that brain-level and behavioural changes associated with learning to read in childhood continue for at least ten years after onset (see McCandliss et al. 2003).

If individuals who learn to read as adults are not able to develop the same level of skill as those who learn as children, the implication would be that there is a restriction on the extent to which brain structure or function can change in adults. One possibility is that some low-level, sensory or motor, component of reading shows a sensitive period that limits the learning of this high-level, complex skill (see Abadzi 2003, 2012). Some recent evidence using electrophysiological measurements of brain activity supports the idea that in individuals learning to read as adults, word reading does not become an automatic skill (Avery et al. 2013). There are a number of candidate visual processes that are either uniquely or especially relevant to literacy acquisition. These include developing a large perceptual span, that is, being able to extract information accurately over a large area of the visual field; attending to fine visual details that differentiate individual letters whilst ignoring substantial gross differences such as font and case; maintaining very fine and rapid control of eye movements; and ensuring rapid speed of visual processing (Sabatini 2002). The development of sensory and motor aspects of reading such as these has been extensively investigated during childhood (see Rayner 1998), but largely ignored with respect to individuals acquiring literacy later in life. A priority for research should be to establish whether any of these low-level processes themselves show little or no progression as adults learn to read in order to identify those that might prove to be barriers to learning.

Research into the literacy disorder *developmental dyslexia* has shown that interventions are more successful if, instead of focusing on reading and writing from the outset, children are first encouraged to play with spoken word forms. This helps strengthen their representations of those forms (*phonological representations*) and provides a firmer footing for subsequent literacy acquisition (Bus and Ijzendoorn 1999). This research throws a spotlight on the issue of the order in which elements

of a skill are learned. Illiterate adults demonstrate profound difficulties with phonological processing (Greenberg et al. 1997), as do young children when they start learning to read. Adult readers are also less able to make use of phonological strategies to support their reading than are children of the same level of reading proficiency (Greenberg et al. 2002). However, while for children, developing phonological processing skills forms the foundation of reading programmes, in adult education, literacy programmes tend to focus on links between phonology and orthography. As phonological processing skills predict reading fluency and text comprehension (e.g. Katzir et al. 2006), a crucial piece of research is to consider the benefit of working on phonological processing skills with adult readers, to ready the phonological system for reading before moving to orthographic forms.

In summary, it is not yet clear to what extent automaticity can be established in domains relevant to adult education. Some skills, such as establishing new motor routines, show greater flexibility later in life than more cognitive tasks like literacy. Whatever the domain of learning though, practice is vital. In this section we have considered the gradual development of automaticity and the slow brain-level changes associated with skill learning. The issue of the order in which elements of a new skill are learned is an immediate lesson for educators and may be a fruitful area for future research.

Can everyone learn equally effectively in adulthood?

When it comes to constraints on learning, it is too simplistic to talk about the average brain. Everyone is different. Individual differences might be apparent with regard to attention and motivation, pre-existing experience or neural plasticity. For example, differences in the rate at which adults learn a new language have been repeatedly shown, from the establishment of a new perceptual and productive sound system (Hanulíková et al. 2012), to learning a set of grammatical rules. These differences have been attributed to neural, experiential and motivational factors. Genetic differences in adult brain plasticity have also been found: the extent to which cortical volume changes over adulthood, thought to reflect adaptation to changes in the environment, is substantially genetically driven and positively correlates with intelligence (Brans et al. 2010).

There is some evidence to show that variability in skill acquisition can be predicted prior to the commencement of skill learning and, furthermore, that this variability can be reduced, helping poorer learners to keep up. In the case of literacy acquisition, adult learners have been shown to demonstrate different profiles of strengths and weaknesses which predict their success in literacy programmes (Sebastian and Moretti 2012). High levels of phonological awareness, letter recognition and verbal reasoning predict better outcomes. Factors which predict performance are not just behavioural though. Brain imaging has been successfully used to predict the limits of individual ability to learn new motor skills (Tomassini et al. 2011). The behavioural learning of a new motor sequence has been shown to correlate with both the extent of change in activity in relevant brain regions, but also differences in the pre-existing structure of brain tissue. Future work in this area will

demonstrate whether the use of brain-based measures is informative over and above behavioural predictors of skill acquisition.

The example of learning a motor sequence may provide some insight into the basis of individual differences in skill acquisition. The *serial reaction time task* is a task in which participants respond with finger presses to a series of (usually) visual stimuli, which repeat without participants knowing it. Those who learn the sequence explicitly (i.e., can reproduce it without cues) are better at generating fast responses. Further research suggests a potential interaction between learning strategy and short-term memory ability: as those with better short-term memory perform better on tasks which involve explicit learning but do not have an advantage on tasks where learning occurs without participants being aware of it (Unsworth and Engle 2005). For those with superior short-term memory, then, adopting an explicit learning strategy will be particularly helpful.

How can the effects of individual differences in capacity or aptitude be minimised, such that those who struggle are not left behind? Focusing teaching on fundamental skills may help level the playing field. In the domain of literacy acquisition, teaching all children phonological processing skills reduces the impact of individual differences in phonological awareness on reading acquisition. Again, this reinforces the point that the order in which the elements of a skill are learned must be the correct one. It may turn out to be a general rule that finding the key limiting factor, be it working memory or attention, and focusing teaching on this factor will help all students progress at an equal rate. The educational value of ensuring that all students in a group are at an equivalent ability level has been demonstrated recently with respect to childhood education. A strong relationship is observed in classrooms in developing nations between degree of variability in age or ability level and educational outcomes (Duflo et al. 2008; Wang 2011), suggesting that reducing heterogeneity in ability in the classroom leads to more effective learning for all students.

We have, thus far, considered adult learners as a single group. Yet given that neurobiological changes in the brain occur throughout the lifespan, older adults might be expected to show lower levels of brain plasticity than younger adults, and corresponding difficulties acquiring new skills. Behavioural and cognitive decline in older age is well charted. The brains of aging adults show breakdown of the protective covering around neurons (*demyelination*), and disruption of coordination between brain regions which correlates with poor cognitive function from age 60 (Andrews-Hanna et al. 2007). Brain activity of aging adults has also been found to be less localised, and thereby less specialised (Cabeza 2002; Park and Reuter-Lorenz 2009). Behaviourally, older adults show particular decline in certain areas, including: difficulty performing more than one task at once; slow processing speed and greater variability in behavioural responses (see Mahncke et al. 2006). However, these changes in themselves do not mean that older adults are less responsive to learning opportunities.

An interesting study relating to brain plasticity in older age was conducted by Janina Boyke et al. (2008) who, in a follow-up to Draganski et al. (2004), taught older adults (mean age of 60) to juggle. The authors revealed very similar changes in brain structure in comparison to younger adults (see above), but behavioural

performance was less accomplished in comparison to the younger group. So, while the brain continues to demonstrate structural plasticity into late-life in response to learning motor tasks, greater structural change may be needed in the older brain to show the same change in behaviour.

Behavioural studies are beginning to show the conditions under which older adults learn most effectively, and which areas of cognition might be most beneficial for intervention to target. Louis Bherer et al. (2006) trained older and younger adults on a dual task where they had to divide their attention between two simultaneously performed activities. Given feedback on performance, both groups improved on the trained tasks to the same degree in terms of response speed, although the older group were slower and less accurate at the start of training. Bherer and his colleagues suggest that providing feedback on performance which allows participants to develop new strategies for learning may be particularly important for older adults. Enhanced sensitivity of older adults to feedback on task performance has been observed elsewhere (Wishart et al. 2002). An important next stage is to determine whether training on specific tasks, like the dual task adopted by Bherer, results in benefits for attention control which transfer beyond the specific task trained. If transference could be shown, then utilising residual brain plasticity to improve specific skills could stimulate cognitive function across domains. The importance of maintaining cognitive function and the potential to retrain is likely to become increasingly important as the workforce ages and labour flexibility increases.

Even within individuals, capacity for learning is not stable. For example, whether or not an individual has had a good night's sleep is proving to be important. In the case of motor skills, for example, when participants learn a finger-tapping task and then sleep before being re-tested, performance is enhanced (Doyon et al. 2009; Fischer et al. 2002; Morin et al. 2008; Walker et al. 2002), with both reduced error rates and increased speed. This is true irrespective of whether sleep occurs during the night or day (Fischer et al. 2002). At the brain level, activity in subcortical motor areas is greater for participants who have slept compared to those who have not (Debas et al. 2010), hinting at gains in automaticity.

In summary, not everyone can learn equally efficiently in adulthood. Multiple factors, including short-term memory, brain structure, age and previous experience will determine the progression made by an individual. Working on fundamental skills, sleeping well and engaging in physical exercise will help level the playing field and maximise progression for adult learners.

What is the role of the learning environment?

The environment (information, opportunities and support) makes an enormous difference to lifelong learning, and does so in multiple ways. This is a particularly important issue for adult educational neuroscience, as learning environments vary dramatically the world over. Environmental considerations can constitute substantial barriers to success for adult learners. Three different aspects of the environment will be addressed here. The first aspect is socioeconomic status, that is, the environment of the home and community. The second aspect is classroom

conditions. The third aspect is the way in which stimuli are presented in the classroom or other learning arena.

Socioeconomic status

Socioeconomic status (SES) is typically measured by factors such as family income or education. In fact, this broad term is likely to act as a proxy measure for a complex set of interacting causal factors. These factors may vary substantially across and within countries and impact on learning in more than one way. In many developing nations, low SES correlates with poor nutritional status (Adeladza 2009; Mohsena et al. 2010), which can have a fundamental impact on brain development and learning (Dani et al. 2005; and see Tanner and Finn-Stevenson 2002; and Bhargava 2001 for reviews and policy implications in developed and developing nations respectively). Nutrition should therefore be seen not only as fundamental for physical health but also as relevant to educational health. Even within developed nations nutritional gradients across SES have been reported (Darmon and Drewnowski 2008), and if children arrive at school hungry they are less able to concentrate. Poor educational outcomes are often coupled with low SES (see Hackman and Farah 2008 for a review of the effects of SES on cognitive ability). This effect may be mediated by a variety of factors including fewer books in the home (e.g. Constantino 2005; Guo and Harris 2000), poorer language skills (see Hackman and Farah 2008), or higher levels of vigilance induced by more chaotic environments at home (Chen et al. 2010). High vigilance in the home is thought to alter attentional mechanisms, resulting in poorer selective attention (Stevens et al. 2009). SES can therefore impact directly on developing brain systems as well as via interactions between those brain systems and the environment (see Thomas et al. 2013). Notably though, research in this area has focused on learning in childhood. Very little work has explored the extent to which SES might impact on learning in adulthood. Encouragingly, studies with rats suggest that exposure to an enriched environment in adulthood increases neurogenesis in the hippocampus fivefold and is associated with behavioural gains in learning (Kempermann et al. 2002).

Classroom conditions

An important factor related to attention in learning situations is environmental noise. This is likely to be especially relevant to learning in nations where resources are not available to provide dedicated spaces for learning. Noise refers to any stimuli that are not currently relevant in any sensory system. For example, in a classroom the relevant auditory signal is the teacher's voice, while noise might include things like traffic outside. In circumstances where learning environments are inadequate or where learning takes place in the workplace, noise could include not just irrelevant auditory stimuli, but also distraction from people walking by, uncomfortable seating or non-optimal temperature. Noise makes it harder to process the relevant signal as it takes time for the brain to untangle relevant from irrelevant input. Noisy conditions therefore make learning harder and require that learners pay closer attention. Children's performance on standard national tests is affected by

auditory noise, both within and outside of the classroom. This was found to be especially true for older children (Shield and Dockrell 2008) and was not explained by differences in SES. Amplification of the teacher's voice has been demonstrated to improve auditory comprehension in children in the UK (Dockrell and Shield 2012). Besides amplification, another way to cut through noise is to provide the same stimulus in multiple different modalities. For example, in a recent study of children learning to read, brain activity over visual cortex during letter perception was enhanced only for those children who had had sensori-motor experience with letters compared to those who had just experienced the letters visually (James 2010).

Research on the effects of noise needs to be extended to adult education; especially if sensitivity to noise continues to change into adulthood. All irrelevant distractors will affect learning outcomes in the way that auditory noise has been shown to, and the same principles of controlling and cutting through noise are likely to apply.

Manipulation of stimuli

We have already encountered some of the ways in which the presentation of stimuli can alter or enhance learning later in life, for example learning in a social context. Research on learning a sequence of finger movements, which relates closely to learning to type, and on second-language acquisition, points to the conditions for optimum learning in adulthood.

Motor sequence learning is strongly influenced by attention and motivation. At the brain level, plasticity can be modulated by attention. Learning a motor sequence (or any associative learning task) can be reduced or eliminated by directing participants' attention away from the hand (Stefan et al. 2004). Similarly, motivation is crucial. Mitsunari Abe et al. (2011) taught adult participants a motor control task under conditions of monetary reward, punishment or with no financial contingency. All groups learned the skill equally well but those in the reward group retained the learned skill better at re-test, even 30 days later, in comparison to the other two groups. This study illustrates well that the brain is far from being a passive learning device. The role that attention and motivation play in the process of establishing which stimuli are relevant to an individual is crucial. Attention effectively defines the subjective environment by determining which aspects of the physical world are actually processed. The term "environment" therefore refers not just to the inputs which are available to a system, but to those inputs which are attended to (or "taken up") by the system. Given the high dropout rates observed in voluntary adult education programmes, motivation is a crucial factor for the success of programmes both with respect to how likely participants are to finish and how effective learning will be. The application of technology to learning environments may be particularly pertinent here, for example, computer and video games are highly rewarding and therefore maintain learners' attention (Bavelier et al. 2010); they are also responsive to an individual's performance and therefore gradually advance learning.

Another factor which influences motor skill learning is the schedule used to present stimuli. When a task is practised at random intervals with other intervening tasks, as opposed to regular blocked practice, long-term retention is increased (Kantak et al. 2010; Lee and Simon 2004; Shea and Kohl 1991). One possible reason for this effect is that participants have to work harder to access the motor programme for a task performed randomly compared to one performed repeatedly. This finding holds for older as well as younger adults (Ho et al. 2010).

The field of second-language acquisition provides another example of optimal stimulus presentation. In humans, native speech sounds are learned during the first years of life, but with some understanding of the neural mechanisms supporting plasticity, new categories of speech sounds can be learned later in life. For example, the distinction between /r/ and /l/ in English is hard for native Japanese speakers to master, as no Japanese words rely on these two sounds being contrasted. However, if adult Japanese learners of English are presented with versions of these speech sounds that exaggerate the perceptual differences between them, and those exaggerations are gradually lessened, then new perceptual category learning can take place (McCandliss et al. 2002). Work with this group of adult learners has also illuminated the role that feedback plays in learning. Elizabeth Tricomi et al. (2006) manipulated the availability of performance feedback and reward during a speech sound learning task. The authors found improved behavioural performance when feedback was available and similar brain-level responses when either feedback or reward were provided. This suggests that learners engage with stimuli which they have previously performed correctly on or received reward from. Such research provides stark examples of how remaining brain plasticity in adulthood can be optimally engaged.

In summary, the environment exerts considerable influence on learning in adulthood, both in terms of affecting the development of the cognitive system, and in terms of providing conditions for optimum attention and reinforcement. We can therefore add attention, motivation, intermittent practice and perceptual exaggeration to the list of factors which can beneficially influence learning in adulthood. Some of this research, such as the benefit of intermittent practice, can be directly translated to multiple learning environments, while factors like the best way to maximise attention and motivation require further research. The practical implications for policymakers will vary depending on geography, both between and within countries. Socioeconomic status may correlate with the availability of learning opportunities the world over, while learning environments in developing nations are more likely to be subject to the detrimental effects of noise. Significant environmental factors are therefore likely to exacerbate one another.

Does adult education cost too much?

Neuroscientific evidence has been used to inform economic analyses of the costs of educational interventions at different ages. The work of James Heckman, advocating the economic advantages of early intervention, is particularly influential in this context (Heckman 2006, 2007; Cunha et al. 2010). Heckman's initial work was influenced by three main types of findings. First, he observed that job retraining

in older adults was not very cost-effective for society. Second, he noted that low-SES families often presented a larger cost to society, but that SES differences in the academic achievements of children were already present when these children began school and did not decrease across their schooling. Third, early intervention programmes in the U.S. targeting disadvantaged preschool children appeared to have long-term benefits for the children's academic and employment outcomes. He concluded that early interventions were most cost-effective, and should be targeted at disadvantaged children. To support his conclusions, Heckman appealed to neuroscience evidence concerning sensitive periods in brain development, suggesting that early intervention could help when the brain was most plastic, while in adults plasticity had decreased.

Heckman's arguments have been highly influential amongst policymakers. However, the mathematical models used to support the economic argument in fact support two conclusions. First, that society should invest early in its children to create potential; and second that society should invest late, throughout childhood, adolescence and early adulthood, to *realise* that potential. As we have seen in previous sections, neuroscientific research on sensitive periods does not support strong claims that there is any kind of cut-off after which educationally relevant skills cannot be learned. Sensitive period phenomena mostly relate to low-level perceptual and motor skills. A more realistic conclusion is that there is a gradual decline in human brain plasticity, uneven across abilities, but that teaching methods can be adapted to circumvent the limiting factors on the rate and ultimate proficiency of later learning. The key neuroscientific data in support of Heckman's argument would show that adults could not establish the same level of proficiency as children regardless of training time or technique. More needs to be done to disprove such a hypothesis, but certainly those data have not been forthcoming. As neuroscience begins to understand the learning adult brain, educational techniques which maximise the efficiency of learning in adulthood will gradually reduce the unit cost for a successful completer. The thrust of Heckman's economic work is to advocate data-driven approaches for rigorously evaluating educational techniques on the basis of effectiveness and cost, and then to rationally select techniques on that basis. So long as the cheapest and most effective methods are selected for a given age, this argument appears to be somewhat independent of the learners' age at which the methods are deployed.

A more in-depth evaluation of the neuroscience evidence used to support Heckman's analysis was recently presented by Paul Howard-Jones et al. (2012). These authors concluded that there is considerable potential for future work combining modern neuroscientific understanding with economic theory. However, among other reservations, the authors pointed out that the evidence on sensitive periods is mainly derived from the adverse effects of atypical environments, and that it cannot be generalised to the possible effects of enriched environments on otherwise normally developing children. In this sense, Heckman's model risks being misinterpreted by policymakers.

Even if adult education does remain more expensive in terms of achieving skill proficiency because of irreversible changes in neurobiology, the question heading this section should perhaps be rephrased to ask what is the cost of *not educating*

adults. With an aging workforce and increasing labour market flexibility of employees, requiring them to move quickly between sectors, cognitive flexibility is a requirement of economic success. Even beyond the workforce, there is a strong argument that investing in educational programmes for older adults is economically viable, as cognitive exercise has been shown to be highly effective in combating the onset of dementia, therefore saving the healthcare system substantial sums (see Valenzuela and Sachdev 2009).

Lifelong learning: principles and implications

Although the field of adult educational neuroscience is very much in its infancy, principles are emerging regarding learning in the adult brain which may already be of genuine benefit to educational practice after childhood. It should be noted that all of these ideas need to be corroborated through the replication of results, plus research translating work from animal models to humans, from children to adults and from the laboratory to real-world learning environments. It is also important to acknowledge that the goals of policymakers, along with the experience of learners, vary substantially across the world. No matter what the desired outcome though, neurobiology is universal, making the following principles of learning, as based on the currently available literature, universally applicable:

1. Practice is crucial if the goal, as it should be, is to achieve automaticity and not just competency. Investing in adult education is not a quick fix, but requires long-term commitment from all parties involved, as does learning in childhood.
2. Motivation to achieve and attention to stimuli are necessary aspects of learning in adulthood. This is true both with respect to reducing dropout rates, but also to aid long-term retention of new skills. Feedback on performance serves a similar function and may be particularly important for older adults.
3. Learning from a live tutor and actively engaging with materials, rather than relying on passive presentation, may be more important for adults than for children.
4. The order in which elements of a skill are taught is an important consideration in curriculum development. Working on fundamental skills such as attention control, or specific skills such as phonological awareness in the case of literacy, will help support the development of higher-order skills and reduce variability in outcomes. Reducing variability in student ability in the classroom will help everyone learn more effectively.
5. The learning environment should be as free from noise as possible. This is particularly relevant to learning in the workplace, where the level of irrelevant noise may be high. The use of multiple sources of information across modalities helps reduce the impact of noise on learning.
6. When learning a distinction which was not previously relevant to the individual, materials should initially exaggerate relevant perceptual features. This, in conjunction with intermittent practice, which requires learners to access new representations at unpredictable times, will optimise learning.

7. Getting a good night's sleep will consolidate learning in adults.

It is vital now that research in the field of adult educational neuroscience begins to answer specific questions which relate directly to different types of adult training. We consider the following four questions to be particularly pressing:

1. Can adults achieve the same level of automaticity in a new skill as children? And if so, under what conditions?
2. Are there low-level skills which limit complex skill acquisition, such as literacy, in adulthood?
3. What are the measurable benefits of voluntary exercise to skill learning in adulthood?
4. Can training attention control result in more effective and efficient learning across domains in older adults?

The primary message for policymakers is that learning is achievable across the lifespan, but that consideration must be given to both the strengths and limitations of the adult brain when designing educational programmes. Residual plasticity in the brain and ways of extending or modulating plasticity are therefore of key interest with respect to educational policy. This paper has shown how neuroscientific research informs the very practical and extremely important issue of learning in adulthood and has highlighted the main translatable messages that have so far emerged from the literature. We suggest that research in this area needs to take the leap from the laboratory to the classroom to start addressing specific questions relevant to individual policy areas. We believe that such research could have a substantial impact both in terms of economic gains and quality of life for individuals across the world.

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