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Understanding the Brain: the Birth of a Learning Science

New insights on learning through cognitive and brain science

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UNDERSTANDING THE BRAIN: THE BIRTH OF A LEARNING SCIENCE
NEW INSIGHTS ON LEARNING THROUGH COGNITIVE AND BRAIN SCIENCE

The following paper, taken from the recent publication of the same title, provide an overview and bring together the key messages and potential policy implications, showing how neuroscientific research is already contributing to education and learning policy and practice. The themes include discussion of lifelong learning; ageing; holistic approaches to education; the nature of adolescence; ages for particular forms of learning and the curriculum; addressing the "3 Ds" (dyslexia, dyscalculia, and dementia); and assessment and selection issues in which neuroscience might increasingly be involved. The chapter also points to areas needing further educational neuroscientific research that have emerged from the different chapters of the report.

Overview

After two decades of pioneering work in brain research, the education community has started to realise that "understanding the brain" can help to open new pathways to improve educational research, policies and practice. This report synthesises progress on the brain¬informed approach to learning, and uses this to address key issues for the education community. It offers no glib solutions nor does it claim that brain-based learning is a panacea. It does provide an objective assessment of the current state of the research at the intersection of cognitive neuroscience and learning, and maps research and policy implications for the next decade.

Part I "The Learning Brain" is the main report, which is the distillation from all the analyses and events over the past seven years of the OECD/CERI "Learning Sciences and Brain Research" project. Part II "Collaborative Articles" contains three articles devoted to the "learning brain" in early childhood, adolescence and adulthood, respectively. These have been written, in each case, by three experts who have combined their experience and knowledge in synergy of the different perspectives of neuroscience and education. Annex A reproduces some insights and dialogue that have emerged from the project's interactive website, open to civil society and including notably a teachers' forum. Annex B updates the reader with developments in neuroimaging technology which have proved so fundamental to the advances discussed in this report.

The first chapter offers a novel "ABC" of the contents of the report by listing and discussing keywords in alphabetical order. This serves both to give short summaries of complex concepts and to steer the reader towards the relevant chapter(s) providing the more in-depth coverage. This is followed in the first half of the following chapter by a short but essential overview of the brain's architecture and functioning.

How the brain learns throughout life

Neuroscientists have well established that the brain has a highly robust and well-developed capacity to change in response to environmental demands, a process called plasticity. This involves creating and strengthening some neuronal connections and weakening or eliminating others. The degree of modification depends on the type of learning that takes place, with long-term learning leading to more profound modification. It also depends on the period of learning, with infants experiencing extraordinary growth of new synapses. But a profound message is that plasticity is a core feature of the brain throughout life.

There are optimal or "sensitive periods" during which particular types of learning are most effective, despite this lifetime plasticity. For sensory stimuli such as speech sounds, and for certain emotional and cognitive experiences such as language exposure, there are relatively tight and early sensitive periods. Other skills, such as vocabulary acquisition, do not pass through tight sensitive periods and can be learned equally well at any time over the lifespan.

Neuroimaging of adolescents now shows us that the adolescent brain is far from mature, and undergoes extensive structural changes well past puberty. Adolescence is an extremely important period in terms of emotional development partly due to a surge of hormones in the brain; the still under-developed pre-frontal cortex among teenagers may be one explanation for their unstable behaviour. We have captured this combination of emotional immaturity and high cognitive potential in the phrase "high horsepower, poor steering".

In older adults, fluency or experience with a task can reduce brain activity levels – in one sense this is greater processing efficiency. But the brain also declines the more we stop using it and with age. Studies have shown that learning can be an effective way to counteract the reduced functioning of the brain: the more there are opportunities for older and elderly people to continue learning (whether through adult education, work or social activities), the higher the chances of deferring the onset or delaying the acceleration of neurodegenerative diseases.

The importance of environment

Findings from brain research indicate how nurturing is crucial to the learning process, and are beginning to provide indication of appropriate learning environments. Many of the environmental factors conducive to improved brain functioning are everyday matters – the quality of social environment and interactions, nutrition, physical exercise, and sleep – which may seem too obvious and so easily overlooked in their impact on education. By conditioning our minds and bodies correctly, it is possible to take advantage of the brain's potential for plasticity and to facilitate the learning process. This calls for holistic approaches which recognise the close interdependence of physical and intellectual well-being and the close interplay of the emotional and cognitive.

In the centre of the brain is the set of structures known as the limbic system, historically called the "emotional brain". Evidence is now accumulating that our emotions do re-sculpt neural tissue. In situations of excessive stress or intense fear, social judgment and cognitive performance suffer through compromise to the neural processes of emotional regulation. Some stress is essential to meet challenges and can lead to better cognition and learning, but beyond a certain level it has the opposite effect. Concerning positive emotions, one of most powerful triggers that motivates people to learn is the illumination that comes with the grasp of new concepts – the brain responds very well to this. A primary goal of early education should be to ensure that children have this experience of "enlightenment" as early as possible and become aware of just how pleasurable learning can be.

Managing one's emotions is one of the key skills of being an effective learner; self-regulation is one of the most important behavioural and emotional skills that children and older people need in their social environments. Emotions direct (or disrupt) psychological processes, such as the ability to focus attention, solve problems, and support relationships. Neuroscience, drawing on cognitive psychology and child development research, starts to identify critical brain regions whose activity and development are directly related to self-control.

Language, literacy and the brain

The brain is biologically primed to acquire language right from the very start of life; the process of language acquisition needs the catalyst of experience. There is an inverse relationship between age and the effectiveness of learning many aspects of language – in general, the younger the age of exposure, the more successful the learning – and neuroscience has started to identify how the brain processes language differently among young children compared with more mature people. This understanding is relevant to education policies especially regarding foreign language instruction which often does not begin until adolescence. Adolescents and adults, of course, can also learn a language anew, but it presents greater difficulties.

The dual importance in the brain of sounds (phonetics) and of the direct processing of meaning (semantics) can inform the classic debate in teaching reading between the development of specific phonetic skills, sometimes referered to as "syllabic instruction", and "whole language" text immersion. Understanding how both processes are at work argues for a balanced approach to literacy instruction that may target more phonetics or more "whole language" learning, depending on the morphology of the language concerned.

Much of the brain circuitry involved in reading is shared across languages but there are some differences, where specific aspects of a language call on distinct functions, such as different decoding or word recognition strategies. Within alphabetical languages, the main difference discussed in this report is the importance of the "depth" of a language's orthography: a "deep" language (which maps sounds onto letters with a wide range of variability) such as English or French contrasts with "shallow", much more "consistent" languages such as Finnish or Turkish. In these cases, particular brain structures get brought into play to support aspects of reading which are distinctive to these particular languages.

Dyslexia is widespread and occurs across cultural and socioeconomic boundaries. Atypical cortical features which have been localised in the left hemisphere in regions to the rear of the brain are commonly associated with dyslexia, which results in impairment in processing the sound elements of language. While the linguistic consequences of these difficulties are relatively minor (*e.g.* confusing words which sound alike), the impairment can be much more significant for literacy as mapping phonetic sounds to orthographic symbols is the crux of reading in alphabetic languages. Neuroscience is opening new avenues of identification and intervention.

Numeracy and the brain

Numeracy, like literacy, is created in the brain through the synergy of biology and experience. Just as certain brain structures are designed through evolution for language, there are analogous structures for the quantitative sense. And, also as with language, genetically-defined brain structures alone cannot support mathematics as they need to be co-ordinated with those supplementary neural circuits not specifically destined for this task but shaped by experience to do so. Hence, the important role of education – whether in schools, at home, or in play; and hence, the valuable role for neuroscience in helping address this educational challenge.

Although the neuroscientific research on numeracy is still in its infancy, the field has already made significant progress in the past decade. It shows that even very simple numerical operations are distributed in different parts of the brain and require the co-ordination of multiple structures. The mere representation of numbers involves a complex circuit that brings together sense of magnitude, and visual and verbal representations. Calculation calls on other complex distributed networks, varying according to the operation in question: subtraction is critically dependent on the inferior parietal circuit, while addition and multiplication engage yet others. Research on advanced mathematics is currently sparse, but it seems that it calls on at least partially distinct circuitry.

Understanding the underlying developmental pathways to mathematics from a brain perspective can help shape the design of teaching strategies. Different instructional methods lead to the creation of neural pathways that vary in effectiveness: drill learning, for instance, develops neural pathways that are less effective than those developed through strategy learning. Support is growing from neuroscience for teaching strategies which involve learning in rich detail rather than the identification of correct/incorrect responses. This is broadly consistent with formative assessment.

Though the neural underpinnings of dyscalculia – the numerical equivalent of dyslexia – are still under-researched, the discovery of biological characteristics associated with specific mathematics impairments suggests that mathematics is far from a purely cultural construction: it requires the full functioning and integrity of specific brain structures. It is likely that the deficient neural circuitry underlying dyscalculia can be addressed through targeted intervention because of the "plasticity" – the flexibility – of the neural circuitries involved in mathematics.

Dispelling "neuromyths"

Over the past few years, there has been a growing number of misconceptions circulating about the brain – "neuromyths". They are relevant to education as many have been developed as ideas about, or approaches to, how we learn. These misconceptions often have their origins in some element of sound science, which makes identifying and refuting them the more difficult. As they are incomplete, extrapolated beyond the evidence, or plain false, they need to be dispelled in order to prevent education running into a series of dead-ends.

Each "myth" or set of myths is discussed in terms of how they have emerged into popular discourse, and of why they are not sustained by neuroscientific evidence. They are grouped as follows:

- "There is no time to lose as everything important about the brain is decided by the age of three."
- "There are critical periods when certain matters must be taught and learnt."
- "But I read somewhere that we only use 10% of our brain anyway."
- "I'm a 'left-brain', she's a 'right-brain' person."
- "Let's face it – men and boys just have different brains from women and girls."
- "A young child's brain can only manage to learn one language at a time."
- "Improve your memory!"
- "Learn while you sleep!"

The ethics and organisation of educational neuroscience

The importance and promise of this new field are not the reason to duck fundamental ethical questions which now arise.

For which purposes and for whom? It is already important to re-think the use and possible abuse of brain imaging. How to ensure, for example, that the medical information it gives is kept confidential, and not handed over to commercial organisations or indeed educational institutions? The more accurately that brain imaging allows the identification of specific, formerly "hidden", aspects of individuals, the more it needs to be asked how this should be used in education.

The use of products affecting the brain: The boundary between medical and non-medical use is not always clear, and questions arise especially about healthy individuals consuming substances that affect the brain. Should parents, for instance, have the right to give their children substances to stimulate their scholarly achievements, with inherent risks and parallels to doping in sport?

Brain meets machine: Advances are constantly being made in combining living organs with technology. The advantages of such developments are obvious for those with disabilities who are thus enabled, say, to control machines from a distance. That the same technology could be applied to control individuals' behaviour equally obviously raises profound concerns.

An overly scientific approach to education? Neurosciences can importantly inform education but if, say, "good" teachers were to be identified by verifying their impact on students' brains, this would be an entirely different scenario. It is one which runs the risk of creating an education system which is excessively scientific and highly conformist.

Though educational neuroscience is still in its early days, it will develop strategically if it is trans-disciplinary, serving both the scientific and educational communities, and international in reach. Creating a common lexicon is one critical step; another is establishing shared methodology. A reciprocal relationship should be established between educational practice and research on learning which is analogous to the relationship between medicine and biology, co-creating and sustaining a continuous, bi-directional flow to support brain¬informed educational practice.

A number of institutions, networks and initiatives have already been established to show the way ahead. Vignette descriptions of several leading examples are available in this report. They include the JST-RISTEX, Japan Science and Technology's Research Institute of Science and Technology for Society; Transfer Centre for Neuroscience and Learning, Ulm, Germany; Learning Lab, Denmark; Centre for Neuroscience in Education: University of Cambridge, United Kingdom; and "Mind, Brain, and Education", Harvard Graduate School of Education, United States.

Key messages and themes for the future

Educational neuroscience is generating valuable new knowledge to inform educational policy and practice: On many questions, neuroscience builds on the conclusions of existing knowledge and everyday observation but its important contribution is in enabling the move from correlation to causation – understanding the mechanisms behind familiar patterns – to help identify effective solutions. On other questions, neuroscience is generating new knowledge, thereby opening up new avenues.

Brain research provides important neuroscientific evidence to support the broad aim of lifelong learning: Far from supporting ageist notions that education is the province only of the young – the powerful learning capacity of young people notwithstanding – neuroscience confirms that learning is a lifelong activity and that the more it continues the more effective it is.

Neuroscience buttresses support for education's wider benefits, especially for ageing populations: Neuroscience provides powerful additional arguments on the "wider benefits" of education (beyond the purely economic that counts so highly in policy-making) as it is identifying learning interventions as a valuable part of the strategy to address the enormous and costly problems of ageing dementia in our societies.

The need for holistic approaches based on the interdependence of body and mind, the emotional and the cognitive: Far from the focus on the brain reinforcing an exclusively cognitive, performance-driven bias, it suggests the need for holistic approaches which recognise the close inter-dependence of physical and intellectual well-being, and the close interplay of the emotional and cognitive, the analytical and the creative arts.

Understanding adolescence – high horsepower, poor steering: The insights on adolescence are especially important as this is when so much takes place in an individual's educational career, with long-lasting consequences. At this time, young people have well-developed cognitive capacity (high horsepower) but emotional immaturity (poor steering). This cannot imply that important choices should simply be delayed until adulthood, but it does suggest that these choices should not definitively close doors.

Better informing the curriculum and education's phases and levels with neuroscientific insights: The message is a nuanced one: there are no "critical periods" when learning must take place but there are "sensitive periods" when the individual is particularly primed to engage in specific learning activities (language learning is discussed in detail). The report's message of an early strong foundation for lifetimes of learning reinforces the key role of early childhood education and basic schooling.

Ensuring neuroscience's contribution to major learning challenges, including the "3Ds": dyslexia, dyscalculia, and dementia. On dyslexia, for instance, its causes were unknown until recently. Now it is understood to result primarily from atypical features of the auditory cortex (and possibly, in some cases, of the visual cortex) and it is possible to identify these features at a very young age. Early interventions are usually more successful than later interventions, but both are possible.

More personalised assessment to improve learning, not to select and exclude: Neuroimaging potentially offers a powerful additional mechanism on which to identify individuals learning characteristics and base personalisation; but, at the same time, it may also lead to even more powerful devices for selection and exclusion than are currently available.

Key areas are identified as priorities for further educational neuroscientific research, not as an exhaustive agenda but as deriving directly from the report. This agenda for further research – covering the better scientific understanding of such matters as the optimal timing for different forms of learning, emotional development and regulation, how specific materials and environments shape learning, and the continued analysis of language and mathematics in the brain – would, if realised, be well on the way to the birth to a trans-disciplinary learning science.

This is the aspiration which concludes this report and gives it its title. It is also the report's aspiration that it will be possible to harness the burgeoning knowledge on learning to create an educational system that is both personalised to the individual and universally relevant to all.

Conclusions and Future Prospects

After seven years of a pioneering activity on learning sciences, it would be tempting on the one hand to exaggerate the claims that can be made, but also easy to hide behind the plea that further research is needed before we can reach any conclusions. On the latter, it is certainly true that more research is needed, and some key lines for further research are suggested below. On the former, this concluding chapter largely abstains from specific recommendations. The field is still too young, and the connections between neuroscience and education too complex, for this to be justified. There are few instances where neuroscientific findings, however rich intellectually and promising for the future, can be used categorically to justify specific recommendations for policy or practice. Indeed, one of the messages from this activity, made already in the 2002 Understanding the Brain – Towards a New Learning Science report, is that we should beware of simplistic or reductionist approaches, which may grab headlines or offer lucrative opportunities but which are a distortion of the knowledge base.

This chapter brings together the main themes and conclusions from the preceding analysis. It is possible to put forward some broad propositions or challenges which can open up and refresh the debate on the future shape and character of our education systems. If we witness the birth of a science of learning, new ideas and evidence will rapidly arise and transform the current landscape. We do not need to wait for that research; part of CERI's mission has always been to help OECD countries think through their future agendas. The conclusions are at quite a high level of generality, precisely in order to give the necessary impetus to carry the discussion across the very broad terrain mapped out in the preceding chapters.

Key messages and conclusions

> The most important scientific revolutions all include, as their only common feature, the dethronement of human arrogance from one pedestal after another of previous convictions about our centrality in the cosmos.
>
> Stephen Jay Gould

Educational neuroscience is generating valuable new knowledge to inform educational policy and practice

The sweep of this volume – from the learning that takes place in the earliest years of infancy through to that of the elderly, from knowledge related to specific subject areas through to that concerned with emotions and motivation, from the remedial to the more general understanding of learning – shows how wide-ranging is the contribution that neuroscience can make to educational policy and practice. It has shown that the contribution of neuroscience to education takes different forms.

On many questions, neuroscience builds on the conclusions of existing knowledge from other sources, such as psychological study, classroom observation or achievement surveys. Examples discussed in this volume – such as the role of diet to improve educational performance, the turbulence of puberty, or that confidence and motivation can be critical to educational success – are not new. But the neuroscientific contribution is important even for results already known because:

- It is opening up understanding of "causation" not just "correlation"; and moving important questions from the realm of the intuitive or ideological into that of evidence;

- By revealing the mechanisms through which effects are produced, it can help identify effective interventions and solutions.

On other questions, neuroscience is generating new knowledge, opening up new avenues. Without understanding the brain, for instance, it would not be possible to know the different patterns of brain activities associated with expert performers compared with novices (as a means to understanding comprehension and mastery), or how learning can be an effective response to the decline of ageing, or why certain learning difficulties are apparent in particular students even when they seem to be coping well with other educational demands.

To these two key contributions can be added a third – that of dispelling neuromyths. Such distortions, discussed in detail in Chapter 6, risk to distract serious educational practice with the faddish, off-the-shelf solutions of the airport lounge bookshop.

Another key set of distinct contributions by neuroscience to education is:

- Research which is deepening the knowledge base of what constitutes learning as a central aspect of human and social life, and in ways which cut across the different institutional arrangements called "education".

- Neuroscience is developing the means for revealing hitherto hidden characteristics in individuals, which may be used for remedial purposes – to overcome reading problems or dyscalculia for instance. Eventually, they may also be used to select or improve performance or exclude, raising a raft of thorny ethical issues as discussed in Chapter 7.

- It is, along with other disciplines, able to inform how best to design and arrange different educational practices, especially as regards the match between findings on how best learning takes place and when, on the one hand, and how education is conventionally organised, on the other. It is another question whether that knowledge is being sufficiently acted upon at present.

Brain research provides important neurological evidence to support the broad aim of lifelong learning and confirms the wider benefits of learning, especially for ageing populations

One of the most powerful set of findings concerned with learning concerns the brain's remarkable properties of "plasticity" – to adapt, to grow in relation to experienced needs and practice, and to prune itself when parts become unnecessary – which continues throughout the lifespan, including far further into old age than had previously been imagined. The demands made on the individual and on his or her learning are key to the plasticity – the more you learn, the more you can learn. Far from supporting ageist notions that education is best concentrated on the young – the powerful learning capacity of young people notwithstanding – neuroscience has shown that learning is a lifelong activity and that the more that it continues the more effective it is.

As the demands for having an evidence-base on which to ground policy and practice grow, so has it become even more important to broaden the understanding of the "wider benefits" of education beyond the economic criteria which so often dominate policy cost-benefit analyses. There is growing evidence to show for instance that educational participation can have powerful benefits in terms of health or civic participation (see also CERI work on the "Social Outcomes of Learning"). This report has underpinned the arguments about the wider benefits of learning: the enormous and costly problems represented by senile dementia in ever-ageing populations can be addressed through the learning interventions being identified through neuroscience.

Combinations of improved diagnostics, opportunities to exercise, appropriate and validated pharmacological treatment, and good educational intervention can do much to maintain positive well-being and to prevent deterioration.

We need holistic approaches based on the interdependence of body and mind, the emotional and the cognitive

With such a strong focus on cognitive performance – in countries and internationally – there is the risk of developing a narrow understanding of what education is for. Far from the focus on the brain reinforcing an exclusively cognitive, performance-driven bias, it actually suggests the need for holistic approaches which recognise the close interdependence of physical and intellectual well-being, and the close interplay of the emotional and cognitive, the analytical and the creative arts.

The ways in which the benefits of good diet, exercise, and sleep impact on learning are increasingly understood through their effects in the brain. For older people, cognitive engagement (such as playing chess or doing crossword puzzles), regular physical exercise, and an active social life promote learning and can delay degeneration of the ageing brain (see Chapter 2).

The analysis of this report shows not only how emotions play a key part in the functioning of the brain, but the processes whereby the emotions affect all the others. Especially important for educational purposes is the analysis of fear and stress, which shows how they, for instance, reduce analytical capacity, and vice versa how positive emotions open doors within the brain.

This is just as relevant for the adult student confronted by an uncomfortable return to education as it does for the young person confronted by the unfamiliar demands of secondary or higher education. It has an equity dimension, for fear of failure, lack of confidence, and such problems as "maths anxiety" (Chapters 3 and 5) are likely to be found in significantly greater measure among those from less privileged backgrounds.

We need to understand better what adolescence is (high horsepower, poor steering)

This report is particularly revealing about the nature of adolescence in terms of the stage of brain development in the teenage years and particularly in terms of emotional maturation.

The insights provided by neuroscience on adolescence and the changes which take place during the teenage years are especially important as this is the period when so much takes place in an individual's educational career. The secondary phase of education is conventionally covered by this phase, with key decisions to be made with long-lasting consequences regarding personal, educational, and career options. At this time, young people are in the midst of adolescence, with well-developed cognitive capacity (high horsepower) but emotional immaturity (poor steering).

Clearly, this cannot imply that important choices should simply be delayed until adulthood. It does suggest, with the additional powerful weight of neurological evidence, that the options taken should not take the form of definitively closing doors. There needs to be stronger differentiation of further learning opportunities (formal and informal) and greater recognition of the trajectories of adolescent maturation.

Neuroscience also has developed the key concept "emotional regulation". Managing emotions is one of the key skills of being an effective learner. Emotional regulation affects complex factors such as the ability to focus attention, solve problems, and support relationships. Given the "poor steering" of adolescence and the value of fostering emotional maturity in young people at this key stage, it may well be fruitful to consider how this might be introduced into the curriculum and to develop programmes to do this.

We need to consider timing and periodicity when dealing with curriculum issues

The work of psychologists like Piaget has long influenced our understanding of learning linked to individual development. Educational neuroscience is now permitting the qualification of the Piagetian models (including demonstration of the capacities already possessed by young infants), while broadening the understanding of timing and optimal learning through the study of "sensitive" periods.

The message emerging from this report is a nuanced one: there are no "critical periods" when learning must take place, and indeed the neuroscientific understanding of lifetime "plasticity" shows that people are always open to new learning. On the other hand, it has given precision to the notion of "sensitive periods" – the ages when the individual is particularly primed to engage in specific learning activities.

The example of language learning has featured prominently in this report, and is a key subject in an increasingly global world. In general, the earlier foreign language instruction begins, the more efficient and effective it can be. Such learning shows distinct patterns of brain activity in infants compared with school-age children compared with adults: at older ages more areas of the brain are activated and learning is less efficient. Even so, adults are perfectly capable of learning a new language.

This report has also dispelled myths about the dangers of multilingual learning interfering with native language competence; indeed, children learning another language reinforce the competences in their mother tongue.

These are important questions for education. These findings deepen the basis on which to pose questions about when in the lifespan certain types of learning should best be undertaken, grounded on evidence rather than tradition. They support the importance of laying a very strong foundation for lifelong learning, hence further emphasise the key role of early childhood education and basic schooling, not as ends in themselves but as giving the best possible start.

At the same time, the report (Chapter 6) has warned against over-emphasising the determining importance of the ages birth to three years on later learning.

Neuroscience can make a key contribution to major learning challenges

The contribution that neuroscience is already making to the diagnosis and identification of effective interventions is most clear in what might be termed the "3-Ds": dyslexia, dyscalculia, and dementia.

Dyslexia: Until recently, the causes of dyslexia were unknown, but now it is understood that it results primarily from atypical features of the auditory cortex (and maybe, sometimes, of the visual cortex). Only recently has it been possible to identify these features at a very young age. Early interventions are usually more successful than later interventions, but both are possible.

Dyscalculia is now understood to have comparable causes as dyslexia, though early identification and hence interventions are well less developed.

Dementia: The very significant findings about learning and dementia have been mentioned above, and education is being identified as an effective, desirable source of "prevention" to among other things delay the onset of Alzheimer's symptoms and reduce their gravity.

On the more general understanding of literacy (Chapter 4), the dual importance of phonological and direct semantic processing in the brain during reading in English suggests that a balanced approach to literacy instruction may be most effective for non¬shallow alphabetic languages. As for shallow orthographies, neuroscience seems to confirm the appropriateness of "syllabic methods" to learn reading, and there is interesting potential to be explored in comparisons between alphabetic and non-alphabetic languages on reading acquisition.

On numeracy (Chapter 5), since humans are born with a biological inclination to understand the world numerically, formal mathematics instruction should build upon existing informal numerical understandings. Because number and space are tightly linked in the brain, instructional methods that link number with space are powerful teaching tools.

More personalised assessment to improve learning, not to select and exclude

The potential of brain imaging could have very far-reaching consequences for education, as well as raising critical ethical issues. Knowledge about how the brain functions, and about how competence and mastery are reflected in brain structures and processes, can be applied at a system-wide level, interrogating conventional educational arrangements and practices to ask whether we organise them for optimal learning. Many conventional forms of assessment, where success can be boosted by cramming, have been shown to be "brain-unfriendly" with low retained comprehension.

But beyond these general findings, the results of neuroscience may eventually also be applied on individual learners to find out such matters as whether they really comprehend certain material, or about their levels of motivation or anxiety. Used properly, this individual focus may add fundamentally powerful diagnostic tools to the process of formative assessment (OECD, 2005) and personalised learning.

This relates to the pursuit in a number of countries of greater "personalisation" of curricula and educational practices (OECD, 2006). Neuroimaging potentially offers a powerful additional mechanism on which to base personalisation. At the same time, studies of the brain show that individual characteristics are far from fixed – there is constant interaction between genetic function and experience and plasticity, such that the notion of what constitutes an individual's capacities should be treated with considerable caution.

But, on the other side, such individual applications of neuroimaging may also lead to even more powerful devices for selection and exclusion than are currently available. A biological CV would be open to profound risks, while being potentially attractive to such users as universities or employers. It would be an abuse of the valuable tools of neuroimaging if they were deployed in the negative ways of rejecting students or candidates on the grounds that they do not show sufficient learning capacity or potential (especially when the plasticity of the brain shows how open to development is the capacity to learn). The excessively "scientific" conception of education described in Chapter 7 – used as the basis for selecting students and teachers alike – would be anathema to many.

Key areas for further educational neuroscientific research

> If we value the pursuit of knowledge, we must be free to follow wherever that search may lead us.
>
> Adlai E. Stevenson Jr.

The below research areas do not pretend to be exhaustive of interesting fields of educational neuroscientific enquiry; instead, they have emerged from the analysis of this report as priority areas. Some of them represent the need to deepen knowledge where at present our understanding is sketchy.

It is also about setting an educational agenda for neuroscience as well as the medical agenda which has naturally tended to dominate it up to now. It is for the neuroscientific community to realise how valuable its contributions are to better understanding the key human activity of learning for educational purposes as it applies for all – gifted through disabled, young through old – and not only for those requiring remediation.

- Better understanding of optimal timing for what forms of learning, especially in relation to adolescents and older adults where the review shows that the knowledge base is not yet well developed (Chapter 2). This includes "sensitive periods" – when the capacity to learn is greatest – in specific areas such as language learning.

- Understanding the interaction between increasing knowledge and declining executive function and memory. More research into the ageing process, and not only among the elderly but also adults in their middle years – both in terms of capacity to learn and in terms of the role of learning to delay the deleterious effects of ageing.

- Much is needed on emotions in the brain. Further investigation using psychological and neuroimaging studies is needed of the neurobiological mechanisms which underlie the impact of stress on learning and memory, and the factors that could reduce or regulate it. A specific question for further investigation is how the adolescent's emotional brain interacts with different kinds of classroom environments.

- Better understanding of how laboratory conditions influence findings, and the applicability and transferability of results in different settings other than those in which they were generated. The key role of appropriate learning materials and specific environments needs to be analysed so as to move away from the crude formulations which ask whether environment does or does not make a difference.

- Confirmatory studies showing how beneficial nutrition can impact positively on brain development and more studies directly related to the educational domain. The same applies to physical exercise, sleep, music and creative expression.

- Much more is needed on what types of learning requires the interaction of others and on the role of cultural differences. This should be further broken down in terms of student demographic (especially gender) and socio-cultural differences, but it is also a minefield for misinterpretation. Neuroscience should certainly not be brought into the service of racist or sexist stereotypes.

- Research can help lead to the better understanding of multi-dimensional pathways to competence, for instance in reading. The need to expand the focus to real-world educational situations and applications, *e.g.* whole sentences rather than single words or characters.

- It would be very useful to further build up the differentiated map of mathematics in the brain, which builds on the insights gained already on the apparently paradoxical combination of dissociable skills and brain functions, on the one hand, and interconnectivity, on the other. Identification of approaches to overcome "mathematics anxiety" would be very useful.

- Understanding different brain activity – neural networks, role of cognitive function and memory – among "experts" as compared with average learners as compared with those with genuine problems. This will inform both the identification of successful learning and of effective, targeted teaching methods.

Birth of a learning science

Recent advances in neuroscience have produced powerful insights while educational research has accumulated a substantial knowledge base. A neuroscientific perspective adds a new, important dimension to the study of learning in education, and educational knowledge could help direct neuroscience research towards more relevant areas. Because both fields are well-developed, however, they have deeply-rooted disciplinary cultures with field-specific methods and language which make it extremely difficult for experts from one field to use the knowledge from the other. A new trans-disciplinarity is needed which brings the different communities and perspectives together. This needs it to be a reciprocal relationship, analogous to the relationship between medicine and biology, to sustain the continuous, bi-directional flow of information necessary to support brain-informed, evidence-based educational practice. Researchers and practitioners can work together to identify educationally-relevant research goals and discuss potential implications of research results. Once brain-informed educational practices are implemented, practitioners should systematically examine their effectiveness and provide classroom results as feedback to refine research directions. Establishing research schools with educational practice intimately connected to brain research is a promising way to stabilise trans-disciplinary work.

Educational neuroscience can help to drive the creation of a real learning science. It might even serve as a model of trans-disciplinarity for other fields to emulate. We hope that this publication will help give birth to this real learning science, as well as a model for continued trans-disciplinary fusion.

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