Brain Research, Learning and Emotions: implications for education research, policy and practice

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Recent advances in neuroscience heighten its relevance to education research, policy and practice. Newly developed imaging technologies enable scientists to peer into the learning brain for the first time. Researchers are tackling such questions as: Can too much stress disrupt learning? Is the brain primed for certain types of learning during specific periods in development? Are children’s brains developmentally ready to learn mathematics in primary school?

Education research is gradually accumulating a knowledge base linking educational policies and practices with learning outcomes. However, we often lack detailed explanations of how and why these outcomes arise. Studies are often based on correlations, linking a policy or practice with a certain outcome while leaving the process in a ‘black box’. Brain research allows us to look deeper into the underlying learning processes and shed more light on causal relationships.

This article discusses the following core concepts of the emerging field of educational neuroscience and explores implications for education research, policy and practice.

- Human development is shaped by a synergy of biology and experience
- Emotion is fundamental to learning
- There are developmental sensitivities for certain aspects of language learning
- The literate brain can be created through multiple developmental pathways
- Mathematics is created in the brain with biology and instruction

Human Development is Shaped by a Synergy of Biology and Experience

Early pioneers in human development saw a false dichotomy between genetics and experience and described human development as if it were a dramatic sporting event: nature vs. nurture. Some, such as Gesell (1925) argued that the emergence of skills is driven primarily by genes. Others, such as Watson (1929) asserted that the environment determines all behaviours. While these early works laid an important foundation of the respective involvement of both genetics and the environment, contemporary researchers agree that human development involves a dynamic interplay of nature and nurture (OECD, 2007).

Any sleepless parent of newborn babies knows that when they are born, they powerfully influence their environment. When they learn the alphabet from Sesame Street, it is clear that they are also influenced by their environment. Throughout life, we are both shaped by and shaping our environment. As the poet Khalil
Gibran (1911) so eloquently expressed, ‘I am a poet who composes what the world proses and proses what the world composes’. Nature and nurture work hand in hand. Nurture involves all the contexts in which individuals develop, including home, school, community and society, each of which is embedded in a given culture. Nature influences how we respond to these contexts. The brain has genetically-programmed biases for making sense of the environment around us. For example, infants seem to be born with a biological inclination to interpret the world numerically (Wynn, 1998; Fergison, Dehaene & Spelke, 2004). The brain also seems to be biologically primed to learn language (Pinker, 1995). Biology contributes to individual differences in how we respond to our environment as well. For example, a young child who tends to be passive may thrive in a highly structured classroom environment, while a more active child may feel constricted and frustrated.

As individuals interact with the world — challenging a friend to a game of chess, playing the violin, or reading an article in the European Journal of Education — these experiences actually shape the physical structure of the brain (Squire & Kandel, 1999). The brain is made up of networks of interconnecting nerve cells — neurons — and supporting glial cells. Experience gradually modifies the connections between neurons following a ‘use it or lose it’ rule. That is, connections that are most active are stabilised and strengthened, while less active connections are weakened or eliminated. Gradually, these modifications aggregate to significant changes in brain structure and function (see Box 1 for a detailed explanation of this process).

Culture plays a pervasive role in shaping our experiences (and therefore our brains). Culture involves values, aspirations, expectations and practices. It influences a wide range of experiences, such as how much time children spend in school or how teachers tend to respond to mistakes. Given the sweeping effects of culture on daily experiences, it is disconcerting that research in this area is relatively thin. The literature on human development is overwhelmingly based on studies of middle-class individuals of European-American ancestry (National Research Council, 2000). More cross-cultural research is needed to disentangle how various aspects of culture shape the brain, human development and education outcomes.

A major contribution of neuroscience to education is the scientific confirmation that the brain develops through a dynamic and continuous interaction between biology and experience. The brain’s abilities are constructed over time. This principle underscores the need for dynamic developmental approaches in the study of learning, such as skill theory (Fischer, Immordino-Yang & Waber, 2007). Skill theory recognises that proficiency can be reached through multiple developmental pathways. Through this lens, neuroscience can enable the design of more effective and inclusive instruction. For example, consider literacy instruction. Researchers are working to delineate developmental pathways to reading skills in terms of underlying neural circuits. This differentiated understanding can inform the design of effective instruction. Moreover, researchers can pinpoint neural causes of reading disorders along typical pathways, which facilitates targeted intervention and enables researchers to map out alternative developmental pathways. Because the brain is dynamic and constructed over time, children should not be assigned to permanent schooling tracks at a young age. This policy is inconsistent with the dynamic nature of human development.

Since abilities develop over time, school should focus on the process of learning rather than on performance. A key aspect of creating a school culture that empha-
Box 1. Experience shapes the brain.

The figure below shows a synaptic connection between two neurons. Each neuron is made up of three main parts: dendrites, a cell body, and an axon (Squire and Kandel, 1999). Dendrites receive chemical signals from other cells in response to experience. Dendrites relay signals to the cell body and, if the signals are strong enough when they reach the cell body, they trigger an electrical signal called an action potential. The action potential then travels along the axon. When it reaches the end of the axon, it prompts the release of chemical signals to the dendrites of other cells. A neuron that is sending information is termed a presynaptic neuron and a neuron that is receiving information is termed a postsynaptic neuron. There is a small space called the synaptic cleft between the axon of a presynaptic neuron and the dendrites of a postsynaptic neuron. The relative activity level at each synaptic connection regulates whether the connection is stabilised, strengthened, weakened or eliminated. Connections with relatively high activity are stabilised and strengthened, while connections with relatively low activity are weakened and, eventually, eliminated. As connections between neurons are modified, the brain is gradually shaped to reflect experience.

Box 2. Formative assessment

Formative assessment involves the frequent assessment of students’ understanding for the purpose of identifying learning needs, giving feedback, and tailoring teaching strategies to meet student needs. It promotes higher levels of student achievement and greater equity of student outcomes. Key components of formative assessment include:

- A classroom culture that focuses on learning rather than performance
- Transparent learning process to help students develop meta-cognitive skills
- Varied instructional methods to meet a range of different needs
- A variety of assessments techniques, including portfolios, logbooks and rubrics
- Frequent feedback throughout the learning process

For information about formative assessment, see OECD’s (2005) *Formative assessment: Improving learning in secondary classrooms*.

**Emotion is Fundamental to Learning**

Over 2,000 years ago, Plato declared that all learning has an emotional base, but it is only recently that neuroscientists have begun to uncover the biological interdependence of learning and emotion. Scientific evidence that emotion is fundamental to learning settles long-standing ideological debates concerning whether schools are responsible for emotional development. If schools are involved in intellectual development, they are inherently involved in emotional development. Learning is likely to be more effective if educators help to minimise stress and fear at school, teach students emotional regulation strategies, and provide a positive learning environment that is motivating to students.

The major brain networks involved in learning can be classified into the recognition network, strategic network and affective network (Figure 1) (Rose & Strangeman, 2007). The recognition network receives sensory information from the environment and transforms it into knowledge. It identifies and categorises what students see, hear or read. The strategic network is recruited for planning and coordinating goal-oriented actions. Finally, the affective network is involved in

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**Figure 1. Major networks involved in learning**

*Source: David Rose, *Universal Design for Learning*"
emotional dimensions of learning such as interest, motivation and stress. When faced with a learning task, such as reading Shakespeare’s Sonnets, all these networks work together to guide the learning process — the recognition network identifies letters, words and Shakespeare’s tone, the strategic network focuses attention on the goal of understanding the text and monitors progress toward that goal, and the affective network manages the motivation to continue reading (maybe if I learn to write like Shakespeare, Rose will go to the dance with me).

The affective network is primarily comprised of a set of structures in the centre of the brain collectively known as the limbic system. Historically called the ‘seat of emotion’, the limbic system contains many brain regions that play a central role in emotional processes, including the amygdala and hippocampus (MacLean, 1949, 1952). The limbic system is highly connected with cortical areas involved in cognitive processing (LeDoux, 2000).

Emotion shapes and is shaped by cognitive processing. Fear conditioning provides an illustrative example of these interactions. Fear conditioning involves the repeated pairing of an initially neutral stimulus, termed the conditioned stimulus (CS), with a noxious unconditioned stimulus (US). As a result of this pairing, an organism learns to respond to the CS with fear (Pavlov, 1927; LeDoux, 2000). Consider, for example, the following scenario. Patricia, a high school student, struggles with mathematics. The last few times she answered a mathematics question she got it wrong and felt terribly embarrassed, which formed an association between mathematics (CS) and negative emotions (US). Her teacher had just asked her to come to the blackboard to solve a problem. This caused an immediate transfer of this emotionally-charged association to the amygdala, which elicits fear. Meanwhile, a slower, cortically-driven cognitive appraisal of the situation is occurring: she remembers her difficulty completing her mathematics homework last night, notices the problem on the board contains complicated graphs, and realises that the boy she has a crush on is watching her from a front-row seat. These various thoughts converge to a cognitive confirmation that this is a threatening situation, which reinforces her progressing fear response and disrupts her ability to concentrate on solving the mathematics problem.

Since emotion is shaped by cognitive processing, students can learn to regulate their emotions. They can use cognitive appraisal to cool negative emotional reactions (Higgins & Kruglanski, 1999; Fischer & Bidell, 2006). For example, consider what could happen in the example above if Patricia regulates her emotions. When the teacher asks Patricia to come to the blackboard to solve a mathematics problem, the amygdala produces fear. However, Patricia cognitively appraises the situation: she reassures herself that last night’s homework was difficult for everyone, reminds herself that she understood the unit on graphing quite well, and decides that her crush looks quite confused himself. These cortically-driven thoughts signal to the amygdala that the situation is not as threatening as it seemed at first, which slows the fear response, allowing her to focus on solving the problem.

Because high levels of stress disrupt learning (McEwen & Sapolsky, 1995), school should provide a secure learning environment. Teachers can be responsive to the emotional needs of students and make it a priority to eliminate unnecessary stress or fear, such as that associated with bullying. Educators can also decrease stress by creating a school culture focused on nurturing learning rather than judging performance. As discussed above, using formative assessment can help to
create a school culture focused on the process of learning (OECD, 2005). Teachers can also support a culture of learning by approaching mistakes as opportunities to identify learning gaps and develop understanding (Stigler & Stevenson, 1991).

The ability to regulate emotions is a predictor of academic outcomes (OECD, 2007). Students who can effectively regulate their emotions are more resilient in the face of failure and more likely to have strong social networks, which provide important social capital (OECD, 2007). Teachers can help students to develop strategies for coping with stressful or negative experiences. A key aspect of this is to teach students how to use language to communicate difficulties (Noddings, 1992).

While negative emotions, such as fear and stress, can disrupt learning, positive emotions drive learning. The brain uses emotion to direct action — approaching positive situations and avoiding negative ones (Fischer & Bidell, 2005). Accordingly, motivation is emotionally-based. In reference to school reform, Sizer (1992) begins, ‘A good — a necessary — place to start is with how to attract and hold students’ attention, how to instil in them a commitment to think hard’ (p. 86). His statement begins with, but then corrects, a commonly held assumption that motivating students is a ‘good’ goal to be achieved after the more basic goal of learning. Contrary to this assumption, brain research reveals that motivation is fundamental to learning (OECD, 2007).

A distinction can be drawn between intrinsic motivation, or motivation to engage in an activity for its own sake, and extrinsic motivation, or motivation arising from an external source. Intrinsic and extrinsic motivation are not mutually exclusive and can work together to contribute to a student’s overall motivation (Lepper & Henderlong, 2000). However, traditional education systems focusing on reward and punishment only engender extrinsic motivation. Intrinsic motivation promotes sustainable involvement in school and lifelong learning (OECD, 2007).

Teachers can increase intrinsic motivation by promoting students’ sense of competence, autonomy and relatedness (Ryan & Deci, 2000). Formative assessment can support students’ sense of competence because it provides scaffolding throughout the learning process that promotes success. Teachers can encourage a sense of autonomy by providing students with meta-cognitive strategies for guiding their own learning and incorporating choice into the curriculum to allow them to explore their interests. Educators can support relatedness, or a feeling of social connection, by creating a sense of community in the school.

**Developmental Sensitivities for Certain Aspects of Language Learning**

There are developmental sensitivities when language circuits are most receptive to particular experience-dependent modifications at certain stages of an individual’s development. Newborns are born with an ability to discern subtle phonetic changes along a continuous range, but experience with a particular language in the first ten months renders the brain sensitive to sounds that are relevant to that language (Gopnik, Meltzoff & Kuhl, 1999). For example, the consonant sounds *r* and *l* occur along a continuous spectrum, and all newborns hear the sounds this way. The brains of babies immersed in an English-speaking environment, however, are gradually modified to perceive this continuous spectrogram as two distinct categories, *r* and *l*. A prototypical representation of each phoneme is
developed, and incoming sounds are matched to these representations and sorted as either \textit{r} or \textit{l}. Babies immersed in a Japanese-speaking environment, by contrast, do not form these prototypes, as this distinction is not relevant to Japanese. Instead, they form prototypes of sounds relevant to Japanese, and normally lose the ability to discriminate between \textit{r} and \textit{l} by the age of ten months\textsuperscript{7}. This phenomenon occurs for varied sound distinctions across many languages (Gopnik, Meltzoff & Kuhl, 1999). Therefore, the brain is optimally suited to acquire the sound prototypes of languages to which it is exposed in the first ten months from birth.

There is also a developmental sensitivity for learning the grammar of a language: the earlier a language is learned, the more efficiently the brain can master its grammar (Neville & Bruer, 2001). If the brain is exposed to a foreign language between 1 and 3 years of age, grammar is processed by the left hemisphere as in a native speaker but even delaying learning until between 4 and 6 years of age means that the brain processes grammatical information with both hemispheres. When the initial exposure occurs at the ages of 11, 12 or 13 years, corresponding to the early stage of secondary schooling, brain imaging studies reveal an aberrant activation pattern (OECD, 2007). Delaying exposure to language therefore leads the brain to use a different strategy for processing grammar. This is consistent with behavioural findings that later exposure to a second language results in significant deficits in grammatical processing (Fledge & Fletcher, 1992). The pattern seems thus to be that early exposure to grammar leads to a highly effective processing strategy, in contrast with alternative, and less efficient, processing strategies associated with later exposure.

In addition, there is a sensitive period for acquiring the accent of a language (Neville & Bruer, 2001). This aspect of phonological processing is most effectively learned before 12 years of age. Developmental sensitivities are for very specific linguistic functions, however, and there are other aspects of phonology which do not seem to have a sensitive period. In sum, 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 language learning. This is at odds with the education policies of numerous countries where foreign language instruction does not begin until adolescence. While further research is needed to develop a complete map of developmental sensitivities for learning various aspects of language, the implications of the current findings are clear: The earlier foreign language instruction begins, the more efficient and effective it is likely to be. However, for early instruction to be effective, it must be age-appropriate. It would not be useful to take rule-based methods designed for older students and insert them into early childhood classrooms. It is necessary for early foreign language instruction to be appropriately designed for young children.

Although early language learning is most efficient and effective, it is possible to learn language throughout the lifespan; adolescents and adults can also learn a foreign language, albeit with greater difficulty. Indeed, if they are immersed in a new language environment, they can learn the language very well, though particular aspects, such as accent, may never develop as completely as they would have done if the language had been learned earlier. There are also individual differences such that the degree and duration of developmental sensitivities vary from one individual to the next. Some individuals are able to master almost all aspects of a foreign language into adulthood.
As you cast your eyes over the shapes and squiggles on a page, you are suddenly in contact with the thoughts of a person on a crisp autumn day in Boston some time ago. This remarkable ability of words to defy the limits of time and space enables cumulative cultural evolution. As you read this page, you are not only in contact with the thoughts of a single person on a particular day, you are also indirectly in contact with the collective wisdom of the cultural history underpinning those thoughts (Tomasetto, 1999). Without literacy as a mechanism for transmitting information across the boundaries of time and space, the capacity of human thought to build on itself would be severely constrained within the limits of memory — literacy is fundamental to human progress.

Learning to read requires the mastery of a collection of complex skills. First, the knowledge of morphology — the forms of either letters of an alphabet, syllabic symbols, or ideograms — must be acquired. Then, orthographic symbols must be understood as labels that can be mapped onto sounds, without which the alphabetic symbols on this page would remain arbitrary shapes. Moreover, an understanding of phonetics is a vital, but by itself insufficient, tool for decoding words. In alphabetic languages with deep orthographies, such as English or French, grapheme-phoneme combinations are variable, with English having the highest degree of irregular representation among alphabetic languages. Reading, particularly in languages with deep orthographies, therefore involves the use of supplementary strategies in addition to the phonological decoding of symbols into sounds. These strategies include using context clues, recognising whole words, and noticing partial-word analogies such as are that are common to both ‘late’ and ‘gate’. Moreover, once a word has been decoded, understanding the meaning of the text requires additional skills. There is the semantic knowledge of word meanings. In addition, knowledge of syntactic rules governing the arrangements of words to show their relations to each other is also critical to meaning: ‘Orsino loves Olivia’ does not mean the same thing as ‘Olivia loves Orsino’. Furthermore, each word must be integrated with previously-read words, which requires the co-ordination of different component functions and a working memory system. The neural circuitry underlying literacy, which supports all of these skills, is guided by the interaction of biology and experience.

Research aimed at delineating the cortical areas supporting reading is rapidly accumulating. The most comprehensive and well-supported model of reading to date is the dual route theory (Jobard, Crivello & Tzourio-Mazoyer, 2003) which provides a framework for describing reading in the brain at the level of the word. As you look at the words on this page, this stimulus is first processed by the primary visual cortex, which is part of the recognition network. The dual route theory posits that processing and then follows one of two complementary pathways. One pathway involves an intermediate step of converting letters/words into sounds, which involves Broca’s area. The other pathway consists of a direct transfer of letters/word to meaning and seems to involve the ‘visual word form area’ (VWFA). Neuroscientists are only beginning to investigate reading at the level of whole sentences.

An understanding of literacy in the brain can inform reading instruction. The dual importance in the brain of phonological processing, on the one hand, and direct processing of meaning, on the other, can inform the classic debate between...
top-down and bottom-up approaches to reading instruction — ‘whole language’
text immersion and phonetics, respectively. The dual importance of both processes
in the brain suggests that a balanced approach to literacy instruction that targets
both ‘whole language’ learning and the development of phonetic skills may be most
effective9. Reports by the US’ National Reading Panel (2000) and National Research
Council (Snow, Burns, & Griffin, 1998) confirm the educational benefits of a
balanced approach to reading instruction.

Though much of the neural circuitry underlying reading is the same across
different languages, there are also some important differences. Literacy in different
languages sometimes requires distinct functions, such as different decoding or
word recognition strategies. In these cases, distinct brain structures are often
brought into play to support these aspects of reading which are distinctive to these
particular languages. Therefore, the dual route theory of reading, which was
developed mainly on research with English speakers, may require modification to
describe reading in languages with less complex spelling and orthographic fea-
tures, such as Italian, Spanish, Finnish and Turkish. The direct route for accessing
meaning without sounding words out is likely to be less critical in languages with
shallow orthographies, such as Italian, than in those with deep orthographies, such
as English. Brain research supports the hypothesis that the routes involved differ
according to the depth of the orthographical structure. The ‘visual word form area’
(VWFA) implicated in identifying word meaning based on non-phonological pro-
prieties in English speakers appears to be less critical for Italian speakers (Paulesu
et al., 2001). Indeed, preliminary results suggest that the brain of Italian native
speakers employs a more efficient strategy when reading text than English native
speakers. Remarkably, this strategy is used even when Italian native speakers read
in English, suggesting that the brain circuitry underlying reading for Italian native
speakers develops in a different way than that underlying reading for English native
speakers. Since the underlying neural circuitry differs across languages with dif-
ferent orthographic structures, the most effective balance of phonetic and ‘whole
language’ instruction may vary across different languages.

Research suggests that the forms of words in a language also influence the way
literacy develops in the brain. Imaging studies reveal that Chinese native speakers
employ additional areas of the brain for reading compared with English native
speakers, and these areas are activated when Chinese native speakers read in
English (Tan et al., 2003). Specifically, Chinese native speakers engage areas of the
brain associated with spatial information processing, which come into play because
of the spatial representation of Chinese language characters (ideograms). Together
with the results on orthographic complexity and reading strategy, these findings
indicate that certain aspects of literacy are created in distinctive ways in the brain,
depending on experience with the printed form of a particular language. This
work underscores the usefulness of a dynamic developmental approach to literacy
instruction that recognises that reading proficiency can be reached through
multiple developmental pathways (Fischer, Immordino-Yang & Waber, 2007).

Neuroscientists are making significant progress in understanding dyslexia, a
biologically-based language impairment defined broadly as a reading difficulty that
does not result from global intellectual deficits (Lyon, Shaywitz & Shaywitz, 2003).
Dyslexia is variable and multifaceted, but commonly involves difficulties in pho-
nological processing. Scientists have identified atypical cortical features underlying
dyslexia, enabling researchers to design targeted interventions that can help
children with dyslexia learn to read. Early interventions are most effective, so it is very important for teachers to be aware of indicators of dyslexia, which include: insensitivity to rhyme, failure or delay in learning the sounds of letters, hesitant and choppy reading, and poor spelling (Shaywitz, 2003). As researchers are developing a complex understanding of how literacy can be created in the brain, dyslexia is quickly being transformed from a disability that seriously hinders learning to an alternative developmental pathway to achieving the same end goal of a literate brain.

Mathematics is Created in the Brain with Biology and Instruction

With their supple cheeks and wobbly head, infants seem a docile blank slate. Indeed, it was long believed that they were born without any quantitative abilities and discovered the world through fumbling sensory exploration. Many influential developmental theories underestimate young children’s numerical understandings, including Piaget’s (1952) theory of cognitive development.

Recent research reveals that the infant brain is equipped with a quantitative sense (Wynn, 1998; Ferigenson, Dehaene & Spelke, 2004). Babies have a concept of ‘one’, ‘two’ and ‘three’. Infants can precisely discriminate these quantities from one another and from larger quantities. Moreover, they may have an abstracted concept of these numerical quantities that is insensitive to modality as they seem to connect the ‘two-ness’ common to two sounds and two objects (Starkey, Spelke & Gelman, 1990). Babies can also approximately discriminate between larger numbers. There is even evidence that they can perform mathematical operations with these numbers. When one object is placed behind a screen followed by a second object, they expect to see two objects when the screen is removed, suggesting that they know that one plus one should equal two (Wynn, 1992). They can also perform approximate calculations, such as computing that five plus five equals about ten (McCrink & Wynn, 2004).

Contrary to the naive conception of the infant as a fumbling blank slate, this research suggests that babies are already engaged in purposeful quantitative organisation of the world. They seem to be endowed with a number sense that is used as a perceptual tool to interpret the world numerically, i.e. babies are born with an intuitive inclination to use numbers to understand the world and they build upon this understanding throughout early childhood. Young children therefore have a substantial foundation of informal mathematical understandings by the time they enter formal education. Primary school teachers should use this early knowledge base to facilitate understanding of formal mathematics.

The quantitative sense of infants most likely resides in the parietal lobe. The parietal cortex plays a fundamental role in a variety of mathematical operations (Dehaene, 1997). Damage to this area has devastating effects on mathematical abilities. For example, patients with parietal damage sometimes cannot answer a question as simple as, which number falls between 3 and 5. However, they often have no difficulty solving analogous serial tasks across other domains, such as identifying which month falls between June and August, or which musical note is between do and mi. They are also often able to solve concrete problems that they cannot solve abstractly. For example, they usually know that there are two hours between 9 a.m. and 11 a.m., but are often unable to subtract 9 from 11 in symbolic notation.
This pattern of results exemplifies two principles about mathematics in the brain. First, mathematics is at least partially dissociable from other cognitive domains. Second, abilities within the domain of mathematics can be dissociable from one another. The first of these principles supports the notion of a multiplicity of partially distinct intelligences (Gardner, 1983). It suggests at least that deficits or talents in particular domains do not necessarily imply deficits or talents in other domains. A child may, for example, struggle with reading but have excellent mathematics abilities. Therefore, it is important that teachers provide flexible pathways to mathematical knowledge which include multiple means and methods of representation and assessment (Rose & Strangeman, 2007). Without such flexibility, difficulties in other domains may unnecessarily interfere with mathematics learning. Consider, for example, children with dyslexia learning mathematics. These children would have difficulties accessing mathematical knowledge from printed textbooks and would struggle to demonstrate their understanding on paper-and-pencil exams. These types of avoidable problems impede learning and mask mathematics abilities. If students are given the option of alternative means of representation and assessment, such as electronic text with text-to-speech software, children with dyslexia would not fall behind in mathematics while their reading skills are developing. This example illustrates the importance of providing flexible pathways to learning mathematics.

Abilities within the domain of mathematics can also be dissociable from one another; teachers cannot assume that difficulties or talents in one area of mathematics are indicative of global mathematical ability. Ability in a certain mathematical skill is not necessarily predictive of ability in another, raising questions about the validity of the criteria used when tracking children into ability groups. Since the sequencing of curricula is not informed by a knowledge of which abilities are distinct in the brain, a child may be capable of excelling at a skill classified as advanced, yet struggle with a prerequisite skill. As a result, this child could be erroneously tracked into a low ability group, thereby stifling their potential. Future neuroscience research may lead to the construction of a differentiated map of mathematics in the brain. However, until this has been achieved, the validity of the criteria used for tracking in mathematics is questionable.

The parietal circuit critical for numeracy is also involved in the representation of space, and these two functions are intertwined (Dehaene, 1997). For example, many patients with acalculia also experience spatial difficulties, such as in distinguishing left from right (Mayer et al., 1999). More generally, young children conceptualise number as spatially oriented before being formally introduced to the number line. Indeed, there may well be a biological predisposition to associate number with space. Therefore, teaching tools such as the number line and concrete spatial manipulatives (i.e. blocks, rods, board games, measuring tools, etc.) can reinforce and solidify children’s intuitive mathematical understandings. Educational research confirms the value of such techniques. An intervention programme conducted by Griffin, Case and Siegler (1994) with a central focus on the association between number and space showed clear success. The programme made use of the number line, as well as a variety of concrete manipulatives that link number and space. The results were striking: forty 20-minute sessions propelled children who were lagging behind their peers to the top of their class.

As demonstrated by Griffin, Case and Siegler’s (1994) intervention programme, instruction can have powerful effects on mathematics achievement. These
achievement gains are likely to reflect underlying neural changes because different instructional methods can create different underlying neural pathways to mathematical knowledge. Delazer et al. (2005) found that learning by drill, which involved learning to associate a specific result with two operands, was encoded in a different neural substrate than learning by strategy, which consisted of applying a sequence of arithmetic operations. This means that two children may both answer that 10 plus 10 equals 20, but if one child has memorised this fact while the other is applying the strategy of double-digit addition, the children are engaging distinct neural circuitry. Teaching by strategy seems to lead to a more robust neural encoding of mathematical information than teaching by drill and results in great accuracy and transferability.

These results have important implications for student assessment. Since the process by which knowledge is encoded influences its underlying neural circuitry, dichotomous correct/incorrect measures of assessment are inadequate for assessing understanding, as they cannot differentiate between, for example, knowledge which has been encoded as fact and knowledge encoded through strategy. More sensitive measures of assessment are necessary to assess underlying understanding. Process-focused assessments with an emphasis on the delineation of learning pathways are more accurate and useful than single-shot, dichotomous correct/incorrect measures.

Some children have serious difficulties with mathematics because of dyscalculia, the mathematical analog of dyslexia. Dyscalculia is most likely caused by a biologically-based impairment of number sense — the early understandings of numerical quantities and their relations (Landerl, Bevan & Butterworth, 2004). Scientists are only beginning to investigate the neural underpinnings of dyscalculia. Further research is needed to identify underlying causes and develop interventions.

Negative emotions also commonly disrupt mathematics learning. Some children have a condition termed math anxiety that is characterised by fear of mathematics (Ashcraft, 2002). This emotional state disrupts cognitive strategies and working memory (Ashcraft & Kirk, 2001). Math anxiety is an important issue in mathematics education and merits further research aimed at identifying appropriate remedies. Mathematics is created in the brain with biology and instruction, and difficulties in mathematics should be approached within this framework.

Brain-informed Policy Recommendations

The neuroscience findings discussed above have important implications for education policy. This section provides a summary of brain-informed policy recommendations.

Focus on the learning environment

Genes and the environment continuously interact to shape brain structure and function. Though certain genetic tendencies exist, the environment greatly influences brain development. Therefore, it is often possible and desirable to shift policy from a focus on treating the individual towards a focus on restructuring the environment.
Make use of formative assessment

The brain is dynamic and constructed over time. Formative assessment is a powerful tool for guiding the development of abilities. Hence, countries may want to promote the use of formative assessments by, for instance, embedding guidelines on formative assessment in the national or state curriculum.

Take into account the importance of emotions

Emotion is fundamental to learning. Brain research suggests that it would be best to have schools provide a positive learning environment that is motivating to students, and teachers trained to teach children emotional regulation skills. Because emotion is fundamental to learning, it is valuable to support research that considers emotional dimensions of learning, such as research on math anxiety.

Consider sensitive periods for language learning

The earlier foreign language instruction begins, the more efficiently and effectively the brain is able to learn its accent and grammar. Beginning foreign language instruction in pre-primary or primary school therefore gives students a biological advantage for learning certain aspects of that language.

Inform reading instruction with neuroscience findings

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. Countries whose national language(s) are non-shallow and alphabetic could support the use of a balanced approach to literacy instruction by including standards targeting both phonological and whole language processing in the national or state curriculum. Teacher training programmes would ideally include information about literacy in the brain. It is particularly crucial that teachers are trained to recognise indicators of dyslexia because early dyslexia interventions are generally more successful than later interventions.

Inform mathematics instruction with neuroscience findings

Since humans are born with a biological inclination to understand the world numerically, formal mathematics instruction might build on existing informal numerical understandings. Because number and space are tightly linked in the brain, instructional methods that link these are powerful teaching tools. It would be useful to update teacher training programmes to include information about mathematics and the brain.

Conclusion

Neuroscience can inform the design of more effective and inclusive instruction. Understanding learning in the brain can inform the design of instruction that is...
more consistent with how we are biologically-inclined to learn. Consider the following three illustrative examples. First, brain research reveals that emotion is fundamental to learning and instruction that neglects emotional dimensions of learning is likely to be ineffective. Second, the brain has developmental sensitivities for certain aspects of language learning and beginning foreign language instruction in pre-primary or primary school gives students a biological advantage. Third, number and space are linked in the brain and teaching tools that make use of this metaphor can reinforce students' intuitive mathematical understandings.

Neuroscience can also help educators to design more inclusive instruction. The brain is highly adaptive and the neural circuitry underlying literacy and mathematics is constructed through an interaction of biology and experience. Neuroscience can help researchers to delineate many possible developmental pathways to proficiency, enabling educators to differentiate instruction to accommodate a wider range of individual differences. For example, as researchers identify biological underpinnings of dyslexia and develop targeted interventions, educators are able to guide children with dyslexia along alternative developmental pathways to learning to read.

The field of educational neuroscience (also called Mind, Brain and Education) is rapidly emerging. Continued progress requires a reciprocal integration of research and practice, and we anticipate that educational policy and practice will continually be updated as new research in this field provides important insights into how we learn.

NOTES

1. This article is based on findings from the ‘Learning Science and Brain Research’ project, conducted at the Centre for Educational Research and Innovation (CERI) of the Organisation for Economic Co-operation and Development (OECD). The opinions and arguments in this article are the authors' sole responsibility and do not necessarily reflect those of the OECD or of the governments of their member countries.

2. In this article, the terms ‘neuroscience’ and ‘brain research’ are used interchangeably and broadly to encompass all closely related and overlapping fields, including neurobiology, cognitive neuroscience, behavioural neuroscience and cognitive science.

3. Neurons are cells specialised for the transmission of information in the nervous system.

4. Glial cells are specialised cells that nourish and support neurons.

5. Amygdala is a part of the brain involved in emotions and memory. Each hemisphere contains an amygdale and is located deep in the brain, near the inner surface of each temporal lobe. Hippocampus is a sea-horse shaped structure located within the brain and considered to be an important part of the limbic system. It functions in learning, memory and emotions.


7. Although this ability is lost in natural circumstances, it is possible for adults to learn to discriminate between the English sounds /r/ and /l/ with exaggerated contrasted exposure (McClelland, Fiez & McCandliss, 2002).

8. This section is, in great part, taken from chapter 4 of OECD's (2007) Understanding the brain: Birth of a learning science.
9. This statement must be qualified as brain research supporting the dual route theory of reading which was conducted primarily with English speakers who had presumably followed a normative developmental pathway for learning to read. Therefore, implications of this work could be less relevant for children who learn to read in other languages or follow atypical developmental pathways. In particular, the transferability of research across languages with different levels of orthographic complexity or from alphabetic to non-alphabetic languages is questionable.

10. This section is, in great part, taken from chapter 5 of OECD’s (2007) *Understanding the brain: Birth of a learning science*.

11. The parietal lobe is one of the four subdivisions of the cerebral cortex. It plays a role in sensory processes, attention and language. It is involved in many functions, such as processing spatial information, body image, orienting to locations, etc.

12. Do and mi correspond to C and E, respectively.

13. Acalculia is a severe mathematical impairment associated with parietal damage.

REFERENCES


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NATIONAL READING PANEL (2000) Teaching Children to Read: An Evidence-based Assessment of the Scientific Research Literature on Reading and its Implications for Reading Instruction, National Institute of Child Health and Human Development (Washington D.C., National Reading Panel).


