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Understanding the Brain: The Birth of a Learning Science

PART I

Chapter 4

Literacy and the Brain

Just because some of us can read and write and do a little math, that doesn't mean we deserve to conquer the Universse.

Kurt Vonnegut

This chapter describes the state of knowledge on the functioning of the brain in relation to language and reading. It helps us to address questions about when and how literacy might best be acquired and the desirable environment that supports it. Such information will be useful for those responsible for policies to enhance language and literacy education, professional educators, and indeed parents who are thinking how best to read with their children. Special attention is given to differences in languages with "deep" (such as English) *and "shallow" orthographies (such as Finnish). Dyslexia is specifically discussed, and what the evidence surveyed in this chapter has to say about possible remedial strategies.*

As you cast your eyes over the shapes and squiggles on this page, you are suddenly in contact with the thoughts of a person on a chilly January afternoon in Paris some time ago. This remarkable ability of words to defy the limits of time and space is of tremendous importance and enables the cumulative evolution of culture. As you read this page, you are not only in contact with the thoughts of a single person on a particular day in Paris, but indirectly, with the collective wisdom of the cultural history underpinning those thoughts (Tomasello, 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 the labels – spelling – that can be mapped onto sounds, without which the alphabetic symbols on this page would remain arbitrary shapes. Moreover, an understanding of phonetics – mapping words to sounds – is a vital, but by itself insufficient, tool for decoding words. In alphabetic languages with deep orthographies, such as English or French,[1] grapheme-phoneme combinations are variable, with English having the highest degree of "irregular" representation among alphabetic languages, at more than a thousand possible letter combinations used to represent the 42 sounds of the language. 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 *ate* 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. More than this, 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. And more even than all this, 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 calls for all these skills, is guided by the interaction and synergy between the brain and experience, and hence the applicability of a dynamic developmental framework, such as skill theory, to the understanding of literacy

1. Languages with "deep" orthographies are those in which sounds map onto letters with a high degree of variability. In these languages, it is often not possible to determine letter-sound associations accurately without the context of the whole word. Consider, for example, the following combination of letters in English: *ghoti*. If the *gh* is pronounced as in *laugh*, the *o* pronounced as in *women*, and the *ti* pronounced as in *nation*, *ghoti* can be read as "fish". In languages with shallow orthographies, by contrast, the correspondences between letters and sounds are close to one-to-one. In Finnish, for example, there are 23 associations that match the exact number of letters.

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(Fischer, Immordino-Yang and Waber, 2007). Skill theory recognises that reading proficiency can be reached through multiple developmental pathways. Through this lens, neuroscience can enable the design of more effective and inclusive reading instruction.

Language and developmental sensitivities

The brain is biologically primed to acquire language. Chomsky (1959) proposed that the brain is equipped with a recipe for making sequences of sound into representations of meaning that is analogous to the system for translating sensory information into representations of objects. That is, the brain is designed through evolution to process certain stimuli according to universal language rules. There are indeed brain structures specialised for language: research has established the role played by the left inferior frontal gyrus and the left posterior middle gyrus (Broca's area and Wernicke's area, respectively. See Figure 2.3). Broca's area, long understood as implicated in language production, is now associated with a broader range of linguistic functions (Bookheimer, 2002). Wernicke's area is involved in semantics (Bookheimer *et al.*, 1998; Thompson-Schill *et al.*, 1999). Critically, these structures are for higher levels of processing, and therefore are not restricted to the simpler processing of incoming auditory stimuli – hearing *per se*. Visual information can also be processed linguistically, as in the case of sign language.

Though certain brain structures are biologically primed for language, the process of language acquisition needs the catalyst of experience. There are developmental sensitivities (the windows of learning opportunity referred to in Chapter 1) as language circuits are most receptive to particular experience-dependent modifications at certain stages of the 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 relevant to that language (Gopnik, Meltzoff and 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 *r* or *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 actually lose the ability to discriminate between *r* and *l* by ten months of age. This phenomenon occurs for varied sound distinctions across many languages (Gopnik, Meltzoff and 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.[2]

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 and 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,

2. But it remains possible for adults to learn sound discrimination. McClelland, Fiez and McCandliss (2002) have shown that, thanks to an exaggerated contrasted exposure, Japanese adults can learn to discriminate between the English sounds /r/ and /l/, even if this contrast is alien to Japanese language.

12 or 13 years, corresponding to the early stage of secondary schooling, brain imaging studies reveal an aberrant activation pattern. 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 and 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 and 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 even 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, in other words, that early foreign language instruction is appropriately designed for young children.

Although the early learning of language is most efficient and effective, it is important to note that 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,[3] 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.

Literacy in the brain

In contrast to language, there are no brain structures designed by evolution to acquire *literacy*. Experience does not trigger a set of biologically-inclined processes leading to literacy, as in the case of language. Instead, experience progressively creates the capacity for literacy in the brain through cumulative neural modifications, expressed by Pinker (1995) as "Children are wired for sound, but print is an optional accessory that must be painstakingly bolted on". Experience with the printed word gradually builds brain circuitry to support reading.

The crucial role of experience in building neural circuitry capable of supporting literacy suggests that attention needs to be given to differences in the degree to which early

3. For a foreigner speaking in a given language, the benefit of acquiring a "native speaker accent" is not clear anyway. As long as one can make oneself understood, what is wrong with "having a foreign accent"? But education systems too often still assume that the ultimate goal for learners is (or should be) "to reach the level of a native speaker" (which one, by the way?), even as far as phonetics is concerned.

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home environments provide a foundation of pre-literacy skills. For example, Hart and Risley (2003) report that the sheer number of words that American children from disadvantaged socioeconomic backgrounds were exposed to by the age of 3 lagged behind that of non-disadvantaged children by 30 million word occurrences. Such limited exposure could be insufficient to support the development of pre-literacy skills in the brain, thereby chronically impeding later reading skills. These children may well be capable of catching up through later experience, but the reality is that they very often do not (Wolf, 2007). Therefore, of policy relevance from this work:

Initiatives aimed at ensuring that all children have sufficient opportunities to develop pre-literacy skills in early childhood are essential.

While the brain is not necessarily biologically inclined to acquire literacy, it is biologically inclined to adapt to experience. It is, for instance, endowed with language circuitry capable of processing visual input. The brain's plastic capacities of adaptability enable the stimuli coming from experience to utilise language structures when constructing the neural circuitry capable of supporting literacy. This is often expressed as literacy being built "on top of" language. In the terms of Vygotsky's classic metaphor, language structures provide scaffolding for literacy to be constructed in the brain (Vygotsky, 1978).

Since literacy is built, in part, with language circuitry, future research should investigate the possibility that developmental sensitivities for certain aspects of language acquisition influence the facility with which the different aspects of reading are acquired. If such influences were identified, this would have implications for educational policy and practice regarding the timeframe for teaching different literacy skills, and could well reinforce the importance of developing pre-literacy skills in early childhood.

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 and Tzourio-Mazoyer, 2003). The dual route theory 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. Then, pre-lexical processing occurs at the left occipito-temporal junction. The dual route theory posits that processing then follows one of two complementary pathways. The *assembled* pathway involves an intermediate step of grapho-phonological conversion – converting letters/words into sounds – which occurs in certain left temporal and frontal areas, including Broca's area. The *addressed* pathway consists of a direct transfer of information from pre-lexical processing to meaning (semantic access). Both pathways terminate in the left basal temporal area, the left interior frontal gyrus, and the left posterior middle gyrus, or Wernicke's area. The pathway involving direct access to meaning has led to the proposal of a "visual word form area" (VWFA) at the ventral junction between the occipital and temporal lobes. This area was first proposed to contain a visual lexicon or collection of words which functions to immediately identify whole words when they are seen. Recent research has suggested a modified conclusion that this region may actually consist of constellations of adjacent areas sensitive to various aspects of letter strings, such as length or order of words. The entire process from visual processing (seeing) to semantic retrieval (understanding) occurs very rapidly, all within about 600 ms.

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 the direct processing of semantics or meanings, on the other, can inform the classic debate between top-down and bottom-up approaches – "whole language" text immersion and the development of phonetic skills, respectively. The dual importance of both processes in the brain suggests:

A balanced approach to literacy instruction that targets both phonetics and "whole language" learning may be the most effective.[4]

To support this statement, reports by the United States' National Reading Panel (2000) and National Research Council (Snow, Burns and Griffin, 1998) confirm the educational benefits of a balanced approach to reading instruction. The more studies on reading will be relevant, the less the debates around reading instruction (teaching/learning models of literacy acquisition) will be based on ideologies, beliefs or statistical results. The discussion will become more and more anchored to scientific evidence.

Neuroscientists are only beginning to investigate reading at the level of whole sentences. Preliminary results suggest that the operations which go into sentence construction, how these operations are used to determine meanings, and the working memory systems that support these operations share common neural circuits/substrates involving both hearing and seeing (Caplan, 2004). This implies that reading sentences recruits the structures responsible for these functions in language.

Linguistically-mediated literacy development

While much of the neural circuitry underlying reading is the same across different languages, there are also some important differences. A central theme concerning the brain and reading is the way that literacy is created though the colonisation of brain structures, including those specialised for language and those best suited to serve other functions. The operations that are common to speech and printed word, such as semantics, syntax, and working memory recruit brain structures which are specialised for language and which are biologically-based and common across languages. There are biological constraints determining which brain structures are best suited to take on other functions supporting literacy. Therefore, much reading circuitry is shared across languages. Even so, 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.

4. This statement must be qualified as brain research supporting the dual route theory of reading 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. Interestingly, most Anglo-Saxon research, working (unconsciously) on an extreme case, does not seem to have considered this crucial aspect. Only recently some researchers became aware of this issue.

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Therefore, the dual route theory of reading, which was developed mainly based on research with English speakers, may require modification to describe reading in languages with less complex spelling and orthographic features and it is only partially relevant to non-alphabetic languages. The direct addressed route for accessing meaning without sounding words 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" (occipital-temporal VWFA) implicated in identifying word meaning based on non-phonological proprieties in English speakers appears to be less critical for Italian speakers (Paulesu *et al.*, 2001a). Indeed, preliminary results suggest that the brain of Italian native speakers employs a more efficient strategy when reading text than that of 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.

The recent psycholinguistic "grain-sized" theory describes differences in reading strategies as a function of the orthographic complexity of a language.[5] It proposes that there is a continuum of strategies from the pure decoding of single sounds (phonemes), which have a small grain size, to mixed decoding of involving units with a larger grain size, including the beginnings of words, rhymes, syllables, up to whole words, as well as phonemes. The theory posits that the orthographic complexity of a language determines the reading strategy that develops in the brain, such that the more shallow the language, the smaller the average grain size – for example, letter sounds instead of whole words – used for decoding. This theory is relevant to behavioural data indicating that the delay in reading acquisition is roughly proportional to the degree of orthographic complexity of the language. It suggests that given instructional methods are differentially effective depending on the orthographic structure of the language, which would mean that:

The most effective balance of phonetic and "whole language" instruction will 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 left middle frontal and posterior parietal gyri, areas of the brain often associated with spatial information processing and the co-ordination of cognitive resources. It is likely that these areas come into play because of the spatial representation of Chinese language characters (ideograms) and their connection to a syllable-level phonological representation. While much of the neural circuitry underlying reading is shared across alphabetic and non-alphabetic languages, there are distinct structures which could correspond to the extent of reliance in any language on either the assembled or addressed processing described in dual route theory,

5. Usha Goswami and Johannes Ziegler (2005), "Learning to Read Workshop", co-organised by CERI and University of Cambridge, 29-30 September 2005, Cambrige, UK.

referred to above (Yiping, Shimin and Iversen, 2002). Together with the results on orthographic complexity (deep *vs.* shallow) 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.

All this underscores the importance of considering reading from a developmental perspective. The neural circuitry underlying reading changes as children learn to read. For example, Pugh[6] demonstrated a shift in functional neuroanatomy underlying initial aspects of reading as the developing English reader matures from multiple temporal, frontal, and right hemisphere sites towards a more consolidated response in the left hemisphere occipito-temporal region.

Multi-variate analyses of such brain patterns examining both age and reading skill revealed that the crucial predictor was the reading skill level, suggesting that the development of literacy is guided by experience rather than merely brain maturation. Since literacy is created in the brain through gradual developmental progression, it would be most useful for teaching and learning to involve ongoing assessments which support reading development. From this, the pedagogical implication is:

Reading is most suitably assessed using formative assessment.

Formative assessment, which involves using ongoing assessment to identify and respond to students' learning needs, is highly effective in raising student achievement, increasing equity of student outcomes, and improving students' ability to learn (OECD, 2005).

As research increasingly delineates the relationships between specific experiences and their consequences for the development of reading circuitry in the brain, its interest for education will grow. For example, if early experience with print from a language with a shallow orthography is confirmed to develop more efficient reading strategies in the brain, it might be useful to explore options of building this circuitry in children who speak languages with deep orthographies. Children could, for example, first be taught to read with books containing selected words from a pool with consistent letter-sound combinations. A more radical alternative would be the actual reform of languages with "deep" orthographies so that letter-sound combinations are made more consistent.[7]

Developmental dyslexia

Although experience plays a crucial role in the development of literacy in the brain, biology also has an important part to play. Consider how biologically-based differences in language structures could affect reading given that literacy is built "on top of" these structures. Many children with access to adequate reading instruction struggle to learn to read because of biologically atypical cortical features. These children are said to have developmental dyslexia. Developmental dyslexia is a neurobiological language impairment

6. First joint meeting of the CERI "Literacy" and "Numeracy" Networks meeting, 30-31 January 2003, Brockton, MA, United States.
7. The fact that the most recent initiatives in terms of orthographic reforms did not fully succeed (German) or even did not succeed at all (French) does not mean it is impossible. Spanish and Turkish have shown that it is possible.

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defined as a reading difficulty which does not result from global intellectual deficits or a chronic problem of motivation.[8] It has formally been defined as:

> Dyslexia is a specific learning disability that is neurobiological in origin. It is characterised by difficulties with accurate and/or fluent word recognition and by poor spelling and encoding abilities. Their difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction (Lyon, Shaywitz and Shaywitz, 2003, p. 2).

Dyslexia is both prevalent and widespread.[9] It is the most common subtype of learning difficulty and occurs across cultural, socioeconomic, and to some extent linguistic boundaries. While the phonological deficit underlying dyslexia seems common across alphabetic languages, the degree to which it is manifest, and thus its consequence for reading, may vary as a function of the orthographic structure of a language (Paulesu *et al.*, 2001). And since reading in non-alphabetic languages calls on distinct neural circuitry compared with reading alphabetic languages, dyslexia in non-alphabetic languages may be manifest in a qualitatively different way. The implications of research on dyslexia in alphabetic languages may thus not be transferable to non-alphabetic languages.

Dyslexia is multi-faceted and has variable manifestations, but these variations notwithstanding it frequently is found with atypical cortical features localised in the left posterior parieto-temporal region and the left posterior occipito-temporal region for those native speakers in alphabetic languages (Shaywitz and Shaywitz, 2005; Shaywitz *et al.*, 2001). The functional consequence of the atypical structures is impairment in processing the sound elements of language. Children with developmental dyslexia register sound imprecisely, with

8. A first impulse upon discovering that a learning difficulty is due to a "brain problem" is to consider it beyond remediation by purely educational means. However, one can also turn this around and consider that when the breakdown of a skill into its separate information processing steps and functional modules is sufficiently understood, thanks to the tools of cognitive neuroscience, that is when efficient remediation programmes can be devised. This is precisely what Bruce McCandliss and Isabelle Beck did in the case of dyslexia, building on the intact components of reading skills in dyslexic children to come up with a new method for teaching word pronounciation. And of course, such deep understanding of how a skill is decomposed into separate cognitive processes may also help design better methods for teaching unimpaired children. Using their "Word Building Method", McCandliss and Beck showed that dyslexic children are capable of learning to read. Helping children to generalise from their reading experience enables them to transfer what they had learned about specific words to new vocabulary words. These skills involve alphabetical decoding and word building and enable reading impaired children to progressively pronounce a larger and larger amount of words. This method teaches them that with a small set of letters, a large number of words can be made. As many of school aged children have difficulty in reading, attending to this problem allows this substantial portion of learners to engage in the most fundamental linguistic exchange and lessens their potential marginalisation from society. Others, most notably Drs. Paula Tallal and Michael Merzenich, have reported similar findings with a different technique. Although these results are somewhat controversial, their method does appear to help at least some children. The key point, however, is not whether one particular available method works better than others. Rather, we note that the theoretical and methodological machinery exists to attack the problem, and progress is clearly being made. Many, like for instance Emile Servan-Schreiber, predict that the study and treatment of dyslexia will be one of the major "success stories" of cognitive neuroscience in the relatively near future.
9. It is difficult to assess the relative incidence of dyslexia across countries because its definition (mostly based on economic factors more than anything else) varies from one country to another. As recommended from 2004 (2nd meeting of the CERI "Literacy" and "Numeracy" networks, El Escorial, Spain, 3-4 March 2004), and as confirmed by Kayoko Ishii's work in 2005, a scientific definition of learning disorders, such as dyslexia or dyscalculia, would help researchers (and policy makers) to create internationally agreed-upon definitions, which would, among other things, allow for international comparisons.

difficulties in retrieving and manipulating phonemes (sounds). The *linguistic* consequences of these difficulties are relatively minor, and cover such things as experiencing difficulties with pronunciation, insensitivity to rhyme, and confusing words which sound alike. However, the consequences of the impairment for *literacy* can be much more significant as mapping phonetic sounds to orthographic symbols is the crux of reading in alphabetic languages.

The recent identification of the specific atypical cortical features responsible for the deficits in processing sounds has enabled the development of targeted interventions. Intervention studies have revealed an encouraging adaptability (plasticity) of these neural circuits. The targeted treatment can enable young individuals to develop neural circuitry in left hemisphere posterior brain systems sufficiently so as to read with accuracy and fluency (Shaywitz *et al.*, 2004). It is also possible for the dyslexic brain to construct alternative, compensatory right hemispheric circuitry, sufficient so as to enable accurate, but slow, reading (Shaywitz, 2003). There seems to be a sensitive period for developing phonetic competence in children with atypical left posterior parieto-temporal and occipito-temporal gyri, as early intervention is most effective (Lyytinen *et al.*, 2005; Shaywitz, 2003; Torgesen, 1998). These results suggest that:

Interventions targeted at developing phonological skills are often effective for helping children with dyslexia to learn to read.[10]

The early identification of dyslexia is important as early interventions are usually more successful than later interventions.

Beyond specific interventions, neuroscience can radically alter the way dyslexia is conceptualised. Now that the neurobiological basis of dyslexia has begun to be identified and confirmed as open to change, educators can design effective, targeted reading interventions and start to transform dyslexia from a disability that seriously hinders learning to an alternative developmental pathway to achieving the same end goal – the literate brain. This conception of dyslexia could have many positive consequences in the classroom, including the preservation of children's self-efficacy for literacy, which is tightly linked to achievement (Bandura, 1993).

Dyslexia is more accurately conceptualised as an alternative developmental pathway than as an insurmountable learning disability.

The value of neuroscience to help design targeted interventions for children with phonological deficits suggests the need for further research aimed at tackling other deficits resulting from atypical cortical features. Neuroscience is allowing educators to differentiate among different causes of learning problems even when outcomes appear to be similar and it can therefore be used to examine confounding or alternative neural manifestations of dyslexia, such as that associated with naming-speed deficits (Wolf, 2007). And since interventions may differ in effectiveness with age and reading experience, research should continue to develop a neurobiological understanding of the developmental trajectories of dyslexia. Future research should also investigate differences in these

10. Not systematically, however. The most stunning results to date, in terms of early diagnosis and remediation of dyslexia, are probably those of Heikki Lyytinen at University of Jyvaskyla (Finland). But Lyytinen and his team work on an extremely shallow language. Transferability of these results remains to be measured.

trajectories across languages, as the complexity of the orthographic structure of a language or the representation of words or letters, for example, could well influence the manifestation of dyslexia.[11]

Conclusions

Neurobiological research alters conceptions of literacy in two important ways. First, it promotes a more precise understanding of literacy. Neuroscience facilitates the delineation of the different processes involved in reading in terms of underlying neural circuits. This differentiated understanding can usefully inform the design of effective instruction. For example, the dual importance of phonological and semantic processing suggests that instruction targeting both of these processes may be most effective, at least for children who speak alphabetic languages with deep orthographic structures and follow normative developmental pathways of learning to read. The differentiated conception of literacy allows the different causes of reading difficulties to be pinpointed in the neural subcomponents of literacy, thereby increasing the probability of targeted interventions being effective.

Second, an important contribution to be made by neuroscience is in a more inclusive conception of literacy development. The neural circuitry underlying literacy consists of plastic networks that are open to change and development and are constructed over a period of time. The creation of literacy in the brain is not limited to one single pathway. As reflected by cross-linguistic research and on dyslexia, there are many possible developmental pathways to achieve the end goal of a literate brain. Environmental or biological constraints may render particular pathways more effective than others for certain children. As neuroscience uncovers relationships between specific interventions and neurobiological development, educators will be able to design instruction for different possible developmental pathways. Neuroscience can thus facilitate differentiated instruction capable of accommodating a wide range of individual differences, bringing nearer a literate society which is inclusive rather than selective, with potentially powerful consequences. The famous *Brown vs. Board of Education* United States Supreme Court case concluded that "a mind is a terrible thing to waste", and greater inclusion will provide more raw material for the cumulative evolution of culture and ultimately of human progress.

11. Though most forms of dyslexia seem to be phonologically-based, it seems that some forms may have alternative or cofounding causes.

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