The role of neuroscience in the remediation of students with dyslexia

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Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition, spelling and decoding abilities. Research findings agree that these and other observed behavioral manifestations largely result from a deficit in the phonological component of language. However, conflicting theories on the exact nature of the phonological deficit have given rise to divergent treatment approaches. Recent advances in functional brain imaging and genetics have allowed these theories to be examined more closely. If implemented appropriately, commercial programs can be effective in identifying dyslexia. Treatment of dyslexia has been advanced through neuroscience, yet further study is needed to provide rigorous, reproducible findings that will sustain commercial approaches.

Reading and reading failure

Unlike oral language, which is learned naturally from infancy, reading is a skill that is acquired at an older age, through instruction and with effort. The numerous and complex processes that are required for skilled reading were recognized as early as 1917: "the perception and discrimination of forms and sounds; associations of sounds with the visual appearance of letters; linkage of names with clusters of letters, and meaning with groups of words; memory, motor, visual and auditory factors; and motor processes as subsumed under processes of inner speech and reading aloud"[1].

In our long-standing search for the causes of reading disability, each of these constituent processes has been studied and evaluated for susceptibility to failure. In recent decades, neuroscience research has been centrally involved in characterizing both the neurobiology and the genetics involved in reading; in particular, these findings have advanced the identification and treatment of the reading disorder developmental dyslexia. Today, dyslexia research efforts primarily address (i) the definition of developmental dyslexia; (ii) its biological basis; (iii) its early identification and (iv) the most effective treatment approaches. The ultimate goals for current research are better and earlier diagnosis (before reading failure ensues), as well as affordable and practical treatments.

When a child is unable to learn by traditional education, parents often invest in costly alternatives with questionable effectiveness. As with any treatment program, before investing time and money, parents should be asking questions: Is it helpful to dyslexic students? Do reading accuracy, fluency and comprehension improve? Is it a cost-effective solution? Has it been rigorously evaluated through scientific research studies that use standard reading assessment measures? Although the results from neuroscience research can help to provide this information, they are often inaccessible to the nonscientist. To ensure that families get the help they need, independent groups have emerged to assist in identifying a dyslexic child (an important first step in successful treatment), to evaluate the efficacies of reading remediation, and to clarify and summarize information from research. These services are typically provided by parent-supported philanthropic organizations, such as the International Dyslexia Association (IDA)[2].

What is developmental dyslexia?

The definition of dyslexia itself has been the subject of much study, as selection criteria for dyslexics influence research findings and estimates of prevalence (currently 5–10% in the U.S. and the U.K.). In 1969, a formal definition of reading failure was put forward by Critchley[3] with a neurobiological etiology in mind: "Specific Developmental Dyslexia: A disorder manifest by difficulty in learning to read despite conventional instruction, adequate intelligence, and socio-cultural opportunity. It is dependant upon fundamental cognitive disabilities which are frequently of constitutional origin". A definition currently supported by the National Institutes of Health states that dyslexia is inaccurate and/or slow, effortful reading that typically originates with weaknesses in the phonological processing system of language, although weaknesses in many other language functions may be observed[4]. For example, text reading fluency, vocabulary acquisition and reading comprehension are adversely affected by this impairment[5].

Today's neuroscientific approaches typically regard dyslexia as an unexpected reading problem that occurs despite normal intelligence, and that is often accompanied by a family history of similar reading, spelling or language problems. Policies that

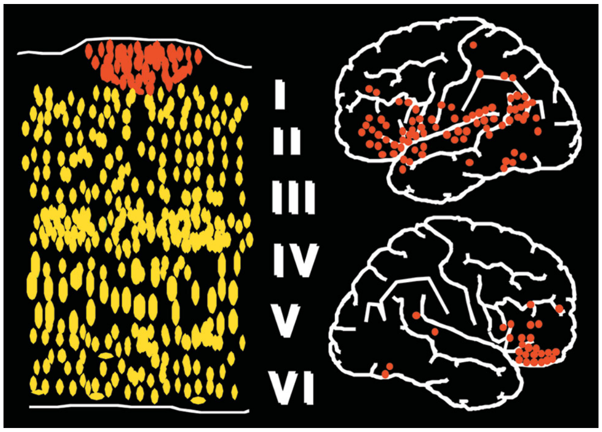

Fig. 1. An example of a brain examined at postmortem. The individual was diagnosed as having had dyslexia. Developmental anomalies consist of neuronal ectopias and architectonic dysplasias as reported by Galaburda and colleagues[10].

require a discrepancy between a child's IQ and his or her reading achievement in order to qualify for special education services are seen as invalid, however. Poor readers of all levels of intelligence have similar reading-related deficits, and most benefit from similar approaches to instruction. Although the neurobiological underpinnings of dyslexia and their interaction with environmental events continue to merit study, the focus of education leaders is now on widespread implementation of research-validated treatments. These treatment approaches predominantly evolved on the basis of behavioral deficits seen in dyslexics. Not surprisingly then, different accounts of the etiology of dyslexia have led to different treatment approaches.

The neurobiological basis of dyslexia

Physicians (frequently ophthalmologists) offered the earliest published accounts of dyslexia. Described as 'word blindness', dyslexia was frequently regarded as a visual dysfunction. The neurolopathologist Samuel Orton (1937) described it as a failure to represent print appropriately in the two occipital poles[6]. Although anomalies of posterior brain regions, specifically in the region of BA 37 in the left hemisphere[7–9], are commonly reported in today's functional brain imaging studies, the underlying pathophysiology is now known to be more complex. Anatomical studies show that anomalies pervade both left- and right-hemisphere regions throughout the dyslexic brain[10,11] (**Fig. 1**). Physiological differences have been reported during the performance of sensorimotor[11,12] as well as reading-related cognitive tasks[7–9]. Although the areas that have been identified in dyslexia are diffuse, the anomalous activity patterns observed in dyslexia (**Fig. 2**) are remarkably consistent across different cultures[13]. This suggests that the basic pathophysiology of dyslexia is universal, despite some variations found in the phonological structure of diverse languages and in societal attitudes toward learning disabilities[14]. Similarly, genetic evidence suggests the involvement of multiple genes: specific regions of the genome have been shown to be involved in a number of reading-related processes, and linkages have been replicated at independent laboratories across the world. The multigenetic nature of dyslexia is likely to be one explanation for its observed heterogeneity and its coexistence with disorders of attention[14].

Brain imaging studies are driven by observations of behavioral manifestations of dyslexia. In the last 30 years, classroom- and laboratory-based studies have converged on the critical role of phonological processing in successful reading acquisition[15]. Phonological awareness (PA), the ability to identify and mentally manipulate the constituent speech sounds, has been found to predict much of the variance in reading skills at any age, even in kindergarteners who are just learning the alphabetic principle (how sounds are represented by letter symbols). PA can be tested by asking a subject to repeat a word after omitting one of its sounds (for example, 'cat' without the /k/ or 'Germany' without the /m/).

Because explicit instruction in speech sound awareness and sound–symbol association helps to prevent reading failure[16], concerted research efforts have attempted to elucidate the functional neuroanatomy of phonological processing. Although initial studies gave inconsistent results[17], persistence and advances in brain imaging technology have brought us closer to under-

Table 1. Summary of current dyslexia theories that have fueled commercial approaches to diagnosis and treatment

	Behavioral differences in dyslexia	Physiological differences in dyslexia	Commercial approaches to identification	Commercial approaches to treatment	Evaluated through research
Cognitive/Linguistic Theories:					
Phonological processing deficits: phonological segmentation, decoding from working memory and rapid phonological retrieval; non-word reading	(ref. 22) (ref. 24)	(ref. 7) (ref. 33) (ref. 8)	Comprehensive Test of Phonological Processing Fox in a Box Phonological Awareness Literacy Screening Phonological Awareness Test Test of Phonological Awareness Test of Word Reading Efficiency Texas Primary Reading Inventory	Lindamood-Bell, Phono-Graphix, Orton-Gillingham Wilson, Slingerland Language!	(ref. 24)
Sensorimotor Theories:					
Anomalous processing in the auditory system: rapid temporal processing deficit	(ref. 21)	(ref. 26)	—	Fast ForWord (modified speech)	(ref. 27)
Anomalous processing in the visual system: magnocellular deficit (ref. 32)	(ref. 31)	(ref. 34)	—	—	—
Anomalous processing in the motor system: rapid bimanual control deficit (ref. 12)	(ref. 12)		—	—	—

standing the functional neuroanatomy for phonological processing. Significant challenges remain, however: psychological models provide few clues about the underlying physiology, and this research does not benefit from animal models in the way that sensorimotor research does. Connectionist approaches have influenced reading models, moving the field away from assumptions that independent routes underlie the reading process[18]. It has now become clear that PA shares attributes with other perceptual and cognitive skills and, not surprisingly, is widely distributed across the brain. It has also been established that throughout reading acquisition, PA and reading itself have a relationship of reciprocal causation: learning how letters represent sounds (phonology) and seeing words in print (orthography) helps novice readers to attend to speech sounds. Consistent with this observation, functional brain imaging studies in Portuguese illiterates have shown that the neural representation of phoneme processing is modified by a person's print experience[19]. Similarly, genetic studies have shown that although much of one's PA skills can be accounted for by hereditary factors[14], significant variance also stems from one's environment. A low heritability for orthographic coding suggests significant environmental influences, including instruction[14].

The exact mechanisms by which the brain recovers phonemes and associates them with visually presented orthography remain elusive. It has been suggested that this process relies on a linguistic process such as the 'articulatory gesture' rather than the speech sound[20], whereas others have argued for a very tangible link between the ability to process auditory input and the ability to perceive phonemes[21]. These contrasting theories—a metalinguistic deficit hypothesis versus a temporal processing deficit in the auditory system—epitomize divergent research approaches that both seek to understand the etiology of reading difficulties and to eventually offer solutions (for discussion, see ref. 5).

Identification of dyslexia with commercial programs

Several validated tests are now available to locate children with phonological and orthographic processing weaknesses (**Table 1**). These tests' validity rests largely on the recurrent research finding that kindergarten and first grade children with poorer abilities in PA and timed letter naming are likely to experience reading failure unless appropriate instruction ensues[22]. If at-risk children are taught in kindergarten and first grade, outcomes are significantly better than if treatment is withheld until later. First-grade intervention takes less time, has more benefit in the long term, and is likely to prevent secondary emotional problems, in comparison to programs implemented at third grade or later. These research findings stipulate that valid screening tools should be used in all elementary schools to identify and promptly treat children with signs of incipient reading problems.

Effective classroom-based programs that minimize reading failure in all but 2–5% of children include several components: structured phonemic awareness (orally identifying and manipulating syllables and speech sounds), phonics (making associations between sounds and letters), fluency (developing speed and automaticity in accurate letter, word and text reading), vocabulary expansion and text comprehension. When this is not sufficient, teachers and clinicians have at their disposal many commercial programs for dyslexic students[23]. Examples of commercial programs include the Orton-Gillingham Approach, Alphabetic Phonics, Slingerland Approach, Spaulding Approach, Project Read, Wilson Language, LANGUAGE!, the Sonday System, Lindamood-Bell and many others. These are systematic, cumulative, explicit and sequential approaches that allow professionals to teach language structure at many levels (sounds, syllables, meaningful parts of words, sentence structure, paragraph and discourse organization). All emphasize the importance of multi-sensory engagement of the learner and teach the phonological features of spoken language using motor, visual, auditory and kinesthetic feedback combined with extensive, controlled practice in word recognition. One of the Lindamood-Bell techniques addresses concepts of the motor theory of speech perception[20] by emphasizing oral–motor feedback and explicit, detailed instruction in labeling speech sounds. Phono-Graphix, on the other hand, minimizes the multisensory mediation techniques of Orton-Gillingham approaches.

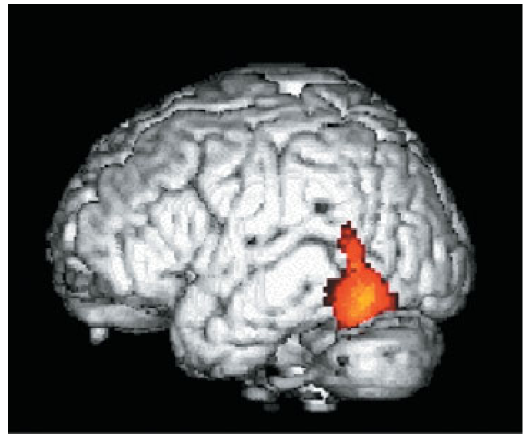

Fig. 2. During word processing, dyslexics in French, Italian and English speaking countries, despite their inherent differences in language systems, all show less activity than controls at the occipito-temporal junction of the left hemisphere. Reprinted with permission from E. Paulesu *et al.* Dyslexia: cultural diversity and biological unity. *Science* **291**, 2165 (2001) Figure 3. Copyright 2001, American Association for the Advancement of Science.

The majority of these programs, however, have undergone only simple, quasi-scientific efficacy studies showing that if the program is implemented by a skilled teacher, students make significant progress[23]. Another approach to intervention takes advantage of technical advances in computer animation and presentation. Earobics and Fast ForWord are examples of software programs that tap phonological and auditory processing skills through interactive computer games. Unlike many of the commercial programs listed above, Fast ForWord has emerged from a systematic, scientifically based study of the relationship between auditory processing and language[21]. This and other more evidence-backed treatment approaches are described below.

Studies of phonologically-based approaches

In its annual review of reading instruction (2000), the National Reading Panel (NRP) screened 1,962 citations on PA studies and reviewed 52 that satisfied research methodology criteria[15]. These showed that PA-based instruction significantly improved the reading performance of poor readers in first grade. Most intensive instructional approaches for students with dyslexia include the same strategies as recommended by the NRP for the general classroom. They differ, however, in the way in which phonology and other language structures are explicitly and systematically taught, the amount of practice given, the mode of delivery (small group or one-on-one) and the use of multi-sensory enhancing techniques that link listening, speaking, reading and writing. The efficacy of these different approaches has been assessed, and findings show that reading accuracy can be significantly improved in younger and older poor readers using several phonologically based methods[24,25]. However, reading rate and, to some extent, reading comprehension have proven to be more difficult to treat, and research is needed to understand why reading fluency is difficult to achieve. Although intensive, structured, explicit, phonologically based reading instruction has been validated, the neurobiological mechanisms by which this approach operates are largely unknown.

Studies of perceptual training

One prevailing approach in neuroscience research has involved the study of the relationship between early sensory processing of verbal and non-verbal sounds and its effects on phonological processing. Studies of individuals with specific language impairment (defined by poor oral language and frequently accompanied by reading problems) show that these individuals require longer time intervals between successive auditory inputs to discriminate or sequence them, as would be required to discriminate between phonemes[21]. As these children may be limited in their ability to segment speech into small time 'chunks' for fine analysis at the phonetic level, computer-based training exercises were devised. The aim of these exercises is two-fold: to drive processing of rapidly successive acoustic stimuli to faster rates and to temporarily extend acoustic speech stimuli to improve speech perception. Consistent with single-unit recording studies in nonhuman primates after perceptual training, functional brain imaging studies in children undergoing this type of training have demonstrated physiological changes[26]. This laboratory evidence for improved language processing[21], however, has yet to be validated by independent findings of positive long-term outcomes with the commercial product Fast ForWord. Further, the link between poor rapid temporal processing in the auditory domain and poor reading has not been solidified by evidence that Fast ForWord improves reading ability.

Treatment methods devised under the influence of Orton in the 1940s are widely practiced, yet their effect on the neurobiological substrate for reading has not been studied. Although basic research has characterized the relationship between sensory perception and reading disability, evidence for effective treatment protocols is sparse. For example, a direct comparison between an approach using structured, multisensory language lessons (Orton-Gillingham) and an approach using structured language teaching plus Fast ForWord showed improved phonological processing in both groups. On long-term follow up, the group receiving instruction enhanced with Fast ForWord showed no advantages in their reading or language skills compared with the group receiving traditional instruction and with a non-intervention developmental control group[27]. The results of these studies highlight the difficulties of putting scientific theories into practice, challenge the basic hypothesis of a link between low-level sensory processing and reading ability[28] and open the possibility that the remediation of sensory systems may not translate into successful reading recovery. These issues all merit further investigation.

Conclusions and future goals

Both positive and negative outcomes of interventions serve to advance research, as they both lead to a better understanding of the etiology of dyslexia. Neuroscience research has contributed to our understanding of the biological basis of reading and reading disability. Regarding treatment, future work promises the advantages of technology, but also requires the integration of information that has been accumulated from long-term clinical and educational practices that dominate the more successful commercial efforts in reading remediation. Functional brain imaging studies of skill acquisition and practice-induced plasticity have paved the way toward a better understanding of the neural mechanisms of normal reading development[29] and reading remediation[30]. Neuroscientists can evaluate the efficacy and mechanisms of intervention programs and thereby determine their suitability for wider dissemination through commercial avenues. For example, future studies can systematically evaluate the efficacy of instructional components and sequences (such as multisensory techniques in structured language programs). As such, scientific-based approaches have the potential for commercialization as effective reading remediation programs, enriching the partnership between science, industry and special education and providing help to families with reading disability.

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