

Neural Mechanisms in Dyslexia

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ABSTRACT—*Within the last two decades, evidence from many laboratories has converged to indicate the cognitive basis for dyslexia: Dyslexia is a disorder within the language system and, more specifically, within a particular subcomponent of that system, phonological processing. Converging evidence from a number of laboratories using functional brain imaging indicates that there is a disruption of left-hemisphere posterior neural systems in child and adult dyslexic readers when they perform reading tasks. The discovery of a disruption in the neural systems serving reading has significant implications for the acceptance of dyslexia as a valid disorder—a necessary condition for its identification and treatment. Brain-imaging findings provide, for the first time, convincing, irrefutable evidence that what has been considered a hidden disability is “real,” and these findings have practical implications for the provision of accommodations, a critical component of management for older children and young adults attending postsecondary and graduate programs. The utilization of advances in neuroscience to inform educational policy and practices provides an exciting example of translational science being used for the public good.*

KEYWORDS—*dyslexia; reading; fMRI; neural systems; accommodations; translational science*

Developmental dyslexia is defined as an unexpected difficulty in reading in children and adults who otherwise possess the intelligence and motivation considered necessary for accurate and fluent reading and who also have had reasonable reading instruction. Dyslexia may be contrasted with other reading difficulties that are not unexpected—for example, in children with low intelligence or with very limited or inadequate reading instruction. In contrast to dyslexia or specific reading retardation,

such reading difficulties have been referred to as general reading backwardness.

Though dyslexia was first described over a century ago, it has only been in the last two decades that neuroscientists have determined the neural systems influencing reading and dyslexia. To a significant extent, this explosion in understanding the neural bases of reading and dyslexia has been driven by the development of functional neuroimaging—technologies such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) that measure changes in metabolic activity and blood flow in specific brain regions while subjects are engaged in cognitive tasks (Frackowiak et al., 2004).

To a large degree, these advances in understanding the neurobiological underpinnings of reading and dyslexia have been informed by progress in understanding the cognitive basis of reading and dyslexia. Though a number of theories of dyslexia have been proposed, there is now a strong consensus supporting the phonological theory, a theory recognizing that speech is natural whereas reading is acquired and must be taught. In order to read, a child has to acquire the alphabetic principle. This is the insight that spoken words can be pulled apart into smaller units of speech—for example, syllables, and the smallest particles of speech, phonemes—and that the letters in a written word represent these sounds. Results from large and well-studied populations confirm that a deficit in phonology is the most robust and specific correlate of dyslexia and form the basis for the most successful and evidence-based interventions designed to improve reading (summarized in S. Shaywitz, 2003).

Languages vary in the consistency and predictability of letter-sound linkages, with some such as Finnish and Italian having highly predictable mappings and others, for example English and Danish, having much more inconsistency (Ziegler & Goswami, 2005). Such differences in consistency have many consequences, including developmental differences in the size of word segments (e.g., syllables, rimes, phonemes) represented in the mental lexicon, the ease of and preferred strategies in learning to read, and manifestations of dyslexia. However, what is uniform across languages is that learning to read depends on the development of phonological awareness, the sensitivity to the sound structure of spoken words.

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NEUROBIOLOGICAL STUDIES OF DISABLED READERS

Though brain-imaging studies of dyslexia are relatively recent, neural systems influencing reading were first proposed over a century ago, based on studies of adults who had suffered strokes with subsequent acquired alexia, the sudden loss of the ability to read. These neuropathological studies, which implicated left-hemisphere posterior regions, have now been confirmed using functional brain imaging. Such imaging studies have begun to describe the brain organization for reading—specifically, the identification and localization of specific neural systems serving reading and their differences in typical and dyslexic readers; a neural system for skilled, fluent reading; plasticity in the systems, that is, that they are malleable and able to respond to an effective reading intervention; and the existence of two types of reading disability, one hypothesized as primarily genetic in origin, the other as primarily influenced by environmental factors.

A range of studies converge to demonstrate three left-hemisphere neural systems for reading (see Fig. 1; reviewed in Price & Mechelli, 2005; S. Shaywitz & B. Shaywitz, 2005). Brain-imaging investigations further demonstrate differences in activation patterns between good and struggling readers at all ages. Nonimpaired younger children demonstrate significantly greater activation in the three left-hemisphere neural systems than do dyslexic children. With maturation, there appears to be compensation in anterior regions around the inferior frontal gyrus, so that differences between older nonimpaired and dyslexic children are confined to two posterior regions, the parieto-temporal and occipito-temporal systems (B. Shaywitz et al., 2002).

These data converge with reports from many investigators showing what has been referred to as a neural signature of dyslexia: a failure of left-hemisphere posterior brain systems to function properly during reading (reviewed in Price & Mechelli,

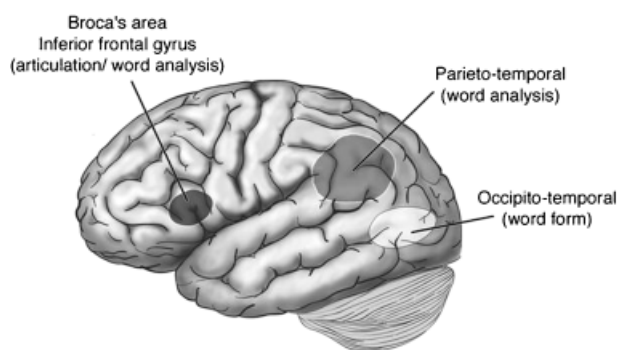


Fig. 1. Neural systems for reading in the brain's left hemisphere. An anterior system in the region of the inferior frontal gyrus (Broca's area) is believed to serve articulation and word analysis. A system in the parieto-temporal region is believed to serve word analysis, and a second in the occipito-temporal region (termed the word-form area) is believed to be responsible for the rapid, automatic, fluent identification of words. Reprinted from *Overcoming Dyslexia: A New and Complete Science-Based Program for Reading Problems at Any Level*, by Sally E. Shaywitz, 2003, p. 78, New York: Alfred A. Knopf. Copyright 2003 by Alfred A. Knopf. Reprinted with permission.

2005; S. Shaywitz & B. Shaywitz, 2005). One of these systems, in the left occipito-temporal (LOT) region, has increasingly attracted the attention of reading researchers and is our focus in this article. Considerable research in the last 5 years has converged to indicate a computational role for this system in influencing skilled, fluent reading, with neurons in this region coding for words and letter strings; not surprisingly, the LOT region has been labeled the "visual word-form area." Specialization of a population of neurons within this area results in the rapid extraction of linguistic information from strings of letters so that, within 250 milliseconds of being viewed, they are integrated and perceived as words—a process resulting in the rapid, effortless recognition of familiar words (for discussion, see Dehaene, Cohen, Sigman, & Vinckier, 2005). Recent evidence indicates that disruption of this region in dyslexic individuals is found not only for reading words but for naming the pictures of the words, suggesting that the disruption in this region "may underlie the reading and naming deficits observed in developmental dyslexia" (McCrory, Mechelli, Frith, & Price, 2005, p. 265).

fMRI has been helpful in clarifying potentially different types of reading disability. Shaywitz et al. (2003) studied men and women from the Connecticut Longitudinal Study, a representative sample prospectively followed since 1983 when they were 5 years old and who have had their reading performance assessed yearly throughout their primary and secondary schooling. Within this population, three groups of young adults, ages 18 to 22.5 years, were identified and imaged: (a) nonimpaired readers, who had no evidence of reading problems; (b) accuracy-improved readers, who were inaccurate readers in third grade but by ninth grade had compensated to some degree so that they were accurate (but not fluent); and (c) persistently poor readers, who were inaccurate readers in third grade and remained inaccurate and not fluent in ninth grade.

A common goal of functional imaging studies of reading is to activate those neural systems used in phonological analysis; to accomplish this, one of the most useful tasks asks subjects to determine if two pseudowords rhyme—for example, "lete" and "jeat" (which do rhyme) or "mobe" and "hail" (which do not). Since pseudowords are novel and could neither have been seen before nor memorized, subjects must use phonologic analysis to perform the task. Brain-activation patterns during this task demonstrated the typical pattern of disruption of posterior neural system in both accuracy-improved and persistently poor readers. However, during a task using real words, brain-activation patterns in the two groups of disabled readers diverged. In this semantic-category task, subjects are asked to judge, for example, if *corn* and *rice* are in the same category (yes, they are both foods) or if *lion* and *tree* are in the same category (they are not). During this task, accuracy-improved readers demonstrated the typical disruption of left-hemisphere posterior systems. In contrast, similar to nonimpaired readers, persistently poor readers activated these posterior systems even though their reading performance was significantly poorer than that of nonimpaired readers on every reading task administered.

Connectivity analysis, an imaging technique assessing the correlations of activity in a source region to activity in other brain areas, showed that when the LOT area was selected as the source region, activity in LOT in nonimpaired readers was correlated with activity in the left inferior frontal gyrus, a component of the neural systems for reading. However, the same analysis in persistently poor readers demonstrated functional connectivity between LOT and right prefrontal regions often associated with memory, suggesting that in these individuals the LOT functions as part of a memory network. Further support for the hypothesis that persistently poor readers rely on memory networks was provided by results of an out-of-magnet oral reading task. Results indicated that persistently poor readers, but not accuracy-improved or nonimpaired readers, identified significantly fewer low-frequency than high-frequency words; this suggests that persistently poor readers have not learned to use phonologic strategies to analyze unfamiliar words and that they appear to rely more on memory-based strategies.

Demonstration of neurobiological differences between the groups led to the examination of the longitudinal data in an attempt to sort out other potential differences between accuracy-improved and persistently poor readers. Both groups began school with comparable reading scores, but compared to accuracy-improved readers, persistently poor readers had poorer cognitive (primarily verbal) ability; attended more disadvantaged schools; and tended to come from lower-socioeconomic-status homes. Thus, persistently poor readers resemble those with what is termed general reading backwardness, who tend to have lower cognitive ability and to come from more disadvantaged circumstances, while accuracy-improved readers appear to relate best to dyslexia, where the reading difficulties are unexpected.

Genetic studies, too, provide support for the notion that accuracy-improved and persistently poor readers may represent different etiologies. Twin studies report that subjects with relatively higher IQs, as is true of accuracy-improved readers or those with dyslexia, tend to have stronger genetic influence, whereas shared environment is a stronger influence for those with lower IQs, comparable to that found in persistently poor readers or those with general reading backwardness. Here, the investigators postulate that “poor home and educational environment could be jointly responsible for the concurrent expression of low IQ” and poor reading (Olson, 1999, p.13). In contrast, in accuracy-improved readers or those with dyslexia, reading difficulties are more likely to be unexpected and to reflect stronger genetic influences.

There is good evidence of differences in exposure to language among children growing up in less, compared to more, advantaged homes—a factor that may place some children at risk for later language and reading difficulties. This supposition is supported, in part, by brain-imaging findings indicating that persistently poor readers read real words using memory systems, suggesting brain systems for analyzing and reading words have not developed. An intriguing suggestion is that with more lan-

guage experience at home and more effective reading instruction at school, persistently poor readers’ phonologically based reading system would have developed.

Alternatively, accuracy-improved and persistently poor readers may both be genetically vulnerable but the higher cognitive ability, better verbal ability, and, perhaps, exposure to more effective reading instruction may serve as protective factors to help compensate for accuracy-improved readers’ decoding difficulties. Thus, a larger vocabulary and strong reasoning abilities may help a struggling reader to use the context around an unknown word to figure out its meaning. Obviously, other factors may be operating as well. At this juncture, the notion of accuracy-improved and persistently poor readers as representing primarily genetic and environmental influences, respectively, is a hypothesis. At least four prominent candidate genes have been related to dyslexia (Fisher & Francks, 2006) and ongoing genetic studies of accuracy-improved and persistently poor readers may help confirm or refute this hypothesis.

Functional imaging studies, too, indicate that the neural systems for reading are malleable and respond to an effective reading intervention. Struggling readers, ages 6.1 years to 9.4 years, who received an intervention based on application of the alphabetic principle (focusing on, for example, teaching sound-symbol associations and practicing segmenting and blending phonemes in words) not only improved their reading but, compared to preintervention brain imaging, demonstrated increased activation in the neural systems for reading (B. Shaywitz et al., 2004). Other investigators, too, have found that an effective reading intervention influences neural systems in the brain (reviewed in S. Shaywitz & B. Shaywitz, 2005).

It is important to note that, from a practical perspective, it is neither necessary nor appropriate to use brain imaging as an assessment tool for the diagnosis of dyslexia in school-age children. Here, the history and diagnostic tools are both effective and economical. In the future, brain imaging may be helpful in the assessment of two very specific groups in whom diagnosis is often difficult: very young children and bright young adults. Newer methods in structural imaging (Sowell et al., 2003)—including diffusion tensor imaging, which shows connectivity of white-matter tracts and does not require the child to perform a task (such as reading) requiring cooperation of the subject during imaging—may be useful in very young at-risk children (Deutsch et al., 2005). Functional brain imaging, when perfected to allow reliable measures in *individual* subjects with dyslexia (it is only reliable currently at the group level), may prove useful in clarifying the diagnosis in bright, highly accomplished young adults who have compensated to some degree for their dyslexia and for whom current testing is often inadequate.

FUTURE DIRECTIONS AND IMPLICATIONS

Where do we go from here? With the elucidation of the neural systems for reading in typical and dyslexic readers and, in

particular, the demonstration of the key role of the LOT in skilled or fluent readers, a next question is to begin to understand the specific mechanisms underlying LOT function in reading—in particular, how important information about orthography, semantics, and phonology is integrated. Brain imaging allows examination of competing hypotheses: for example, whether visual word recognition takes place serially, in a progressive, step-by-step approach (Dehaene et al., 2005), or conversely, whether the LOT functions as an interface between basic visual-form information and linguistic (semantic and phonologic) properties in a dynamic integrative process. Studies using functional imaging combined with priming are beginning to help resolve this question (Devlin, Jamison, Gonnerman, & Matthews, 2006).

To date, most studies have focused on word-level reading; an important next question concerns elucidating and understanding the more complex and distributed neural organization for comprehending connected text. Here, studies using sentence-level tasks engaging semantic or syntactic neural systems are beginning to tease apart the components of a cohesive operational system for reading comprehension.

Findings from laboratories around the world, in every language tested, indicate a neural signature for dyslexia, and these findings have implications for the acceptance of dyslexia as a valid disorder—a necessary condition for its identification and treatment. Simply put, such studies provide, for the first time, convincing, irrefutable evidence that what has been considered a hidden disability is “real.”

This demonstration also has implications for the provision of accommodations for people with dyslexia, a critical component of management for older children attending postsecondary and graduate programs. Such findings should make policymakers more willing to allow children and adolescents with dyslexia to receive accommodations (such as extra time) on high-stakes tests. That would allow dyslexic readers with a disruption in the word-form area (influencing skilled, fluent reading) to be on a level playing field with their peers who do not have a reading disability. The utilization of advances in neuroscience to inform educational policy and practices provides an exciting example of translational science being used for the public good.

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