

Dyslexia

A new model of this reading disorder emphasizes defects in the language-processing rather than the visual system. It explains why some very smart people have trouble learning to read

by Sally E. Shaywitz

One hundred years ago, in November 1896, a doctor in Sussex, England, published the first description of the learning disorder that would come to be known as developmental dyslexia. "Percy F.,... aged 14,... has always been a bright and intelligent boy," wrote W. Pringle Morgan in the *British Medical Journal*, "quick at games, and in no way inferior to others of his age. His great difficulty has been—and is now—his inability to learn to read."

In that brief introduction, Morgan captured the paradox that has intrigued and frustrated scientists for a century since: the profound and persistent difficulties some very bright people face in learning to read. In 1996 as in 1896, reading ability is taken as a proxy for intelligence; most people assume that if someone is smart, motivated and schooled, he or she will learn to read.

But the experience of millions of dyslexics like Percy F. has shown that assumption to be false. In dyslexia, the seemingly invariant relation between intelligence and reading ability breaks down.

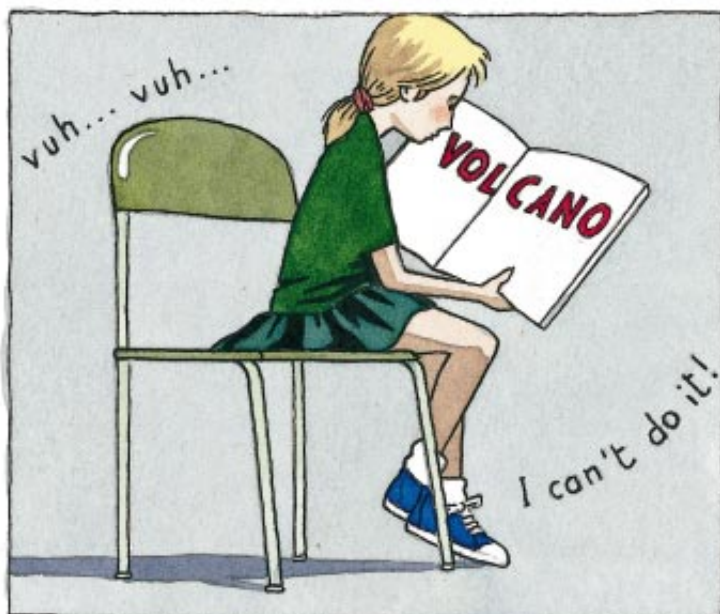
Early explanations of dyslexia, put forth in the 1920s, held that defects in the visual system were to blame for the reversals of letters and words thought to typify dyslexic reading. Eye training was often prescribed to overcome these alleged visual defects. Subsequent research has shown, however, that children with dyslexia are not unusually prone to reversing letters or words and that the cognitive deficit responsible for the disorder is related to the language system. In particular, dyslexia reflects a deficiency in the processing of the distinctive linguistic units, called phonemes, that make up all spoken and written words. Current linguistic models of reading and dyslexia now provide an expla-

nation of why some very intelligent people have trouble learning to read and performing other language-related tasks.

In the course of our work, my colleagues and I at the Yale Center for the Study of Learning and Attention have evaluated hundreds of children and scores of men and women for reading disabilities. Many are students and faculty at our university's undergraduate, graduate and professional schools. One of these, a medical student named Gregory, came to see us after undergoing a series of problems in his first-year courses. He was quite discouraged.

Although he had been diagnosed as dyslexic in grade school, Gregory had also been placed in a program for gifted students. His native intelligence, together with extensive support and tutoring, had allowed him to graduate from high school with honors and gain admission to an Ivy League college. In college,

The Paradox of Dyslexia



Gregory had worked extremely hard and eventually received offers from several top medical schools. Now, however, he was beginning to doubt his own competence. He had no trouble comprehending the intricate relations among physiological systems or the complex mechanisms of disease; indeed, he excelled in those areas requiring reasoning skills. More problematic for him was the simple act of pronouncing long words or novel terms (such as labels used in anatomic descriptions); perhaps his least well-developed skill was rote memorization.

Both Gregory and his professors were perplexed by the inconsistencies in his performance. How could someone who understood difficult concepts so well have trouble with the smaller and simpler details? Could Gregory's dyslexia—he was still a slow reader—account for his inability to name body parts and tissue types in the face of his excellent reasoning skills?

It could, I explained. Gregory's history fit the clinical picture of dyslexia as it has been traditionally defined: an unexpected difficulty learning to read despite intelligence, motivation and education. Furthermore, I was able to reassure Gregory that scientists now understand the basic nature of dyslexia.

Over the past two decades, a coherent model of dyslexia has emerged that is based on phonological processing. The phonological model is consistent both with the clinical symptoms of dyslexia and with what neuroscientists know

about brain organization and function. Investigators from many laboratories, including my colleagues and I at the Yale Center, have had the opportunity to test and refine this model through 10 years of cognitive and, more recently, neurobiological studies.

The Phonological Model

To understand how the phonological model works, one has first to consider the way in which language is processed in the brain. Researchers conceptualize the language system as a hierarchical series of modules or components, each devoted to a particular aspect of language. At the upper levels of the hierarchy are components involved with semantics (vocabulary or word meaning), syntax (grammatical structure) and discourse (connected sentences). At the lowest level of the hierarchy is the phonological module, which is dedicated to processing the distinctive sound elements that constitute language.

The phoneme, defined as the smallest meaningful segment of language, is the fundamental element of the linguistic system. Different combinations of just 44 phonemes produce every word in the English language. The word "cat," for example, consists of three phonemes: "kuh," "aah," and "tuh." (Linguists indicate these sounds as /k/, /æ/ and /t/.) Before words can be identified, understood, stored in memory or retrieved from it, they must first be broken down, or parsed, into their phonetic units by

the phonological module of the brain.

In spoken language, this process occurs automatically, at a preconscious level. As Noam Chomsky and, more recently, Steven Pinker of the Massachusetts Institute of Technology have convincingly argued, language is instinctive—all that is necessary is for humans to be exposed to it. A genetically determined phonological module automatically assembles the phonemes into words for the speaker and parses the spoken word back into its underlying phonological components for the listener.

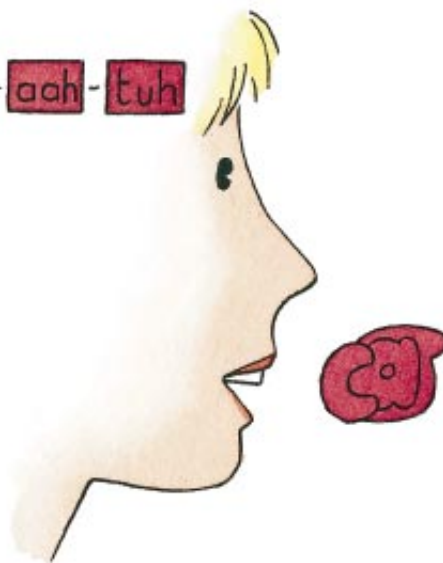
In producing a word, the human speech apparatus—the larynx, palate, tongue and lips—automatically compresses and merges the phonemes. As a result, information from several phonemes is folded into a single unit of sound. Because there is no overt clue to the underlying segmental nature of speech, spoken language appears to be seamless. Hence, an oscilloscope would register the word "cat" as a single burst of sound; only the human language system is capable of distinguishing the three phonemes embedded in the word.

Reading reflects spoken language, as my colleague Alvin M. Liberman of Haskins Laboratories in New Haven, Conn., points out, but it is a much harder skill to master. Why? Although both speaking and reading rely on phonological processing, there is a significant difference: speaking is natural, and reading is not. Reading is an invention and must be learned at a conscious level. The task of the reader is to transform the visual

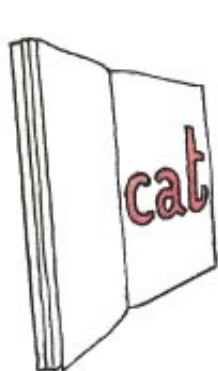


koh	aah	tah
kuh	eh	teh
keh	uh	tuh

— kuh - aah - tuh



SPEAKING is carried out at an automatic and unconscious level by a biologically determined phonological module in the brain. First, the relevant phonemic structures are selected and assembled. These individual phonemes are then coarticulated—that is, overlapped and merged—by the speech apparatus. Coarticulation permits the rapid production of phonetic strings but obscures the underlying segmental nature of speech.



kuh - aah - tuh



READING is not automatic but must be learned. The reader must develop a conscious awareness that the letters on the page represent the sounds of the spoken word. To read the word “cat,” the reader must parse, or segment, the word into its underlying phonological elements. Once the word is in its phonological form, it can be identified and understood. In dyslexia, an inefficient phonological module produces representations that are less clear and hence more difficult to bring to awareness.

percepts of alphabetic script into linguistic ones—that is, to recode graphemes (letters) into their corresponding phonemes. To accomplish this, the beginning reader must first come to a conscious awareness of the internal phonological structure of spoken words. Then he or she must realize that the orthography—the sequence of letters on the page—represents this phonology. That

is precisely what happens when a child learns to read.

In contrast, when a child is dyslexic, a deficit within the language system at the level of the phonological module impairs his or her ability to segment the written word into its underlying phonological components. This explanation of dyslexia is referred to as the phonological model, or sometimes as

the phonological deficit hypothesis.

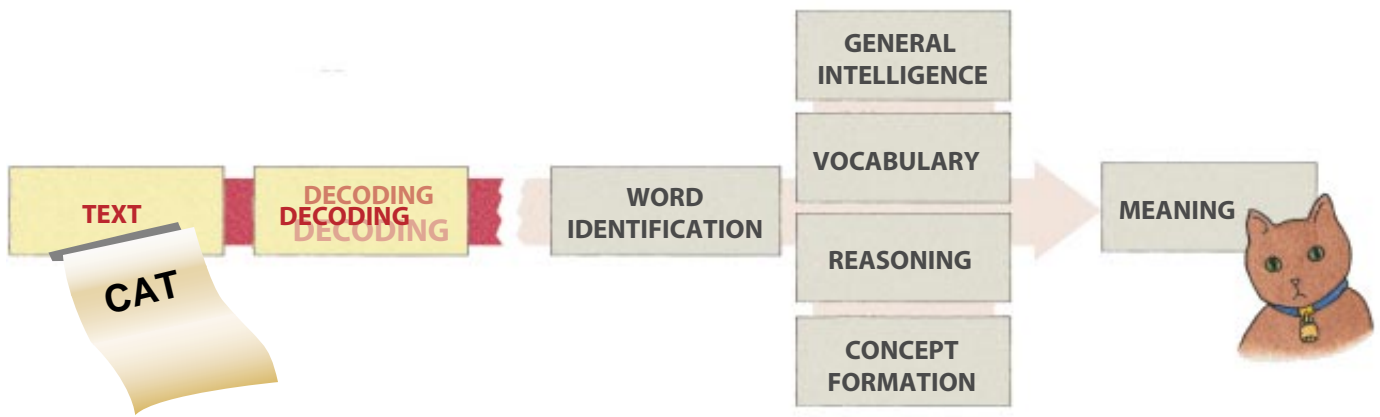
According to this hypothesis, a circumscribed deficit in phonological processing impairs decoding, preventing word identification. This basic deficit in what is essentially a lower-order linguistic function blocks access to higher-order linguistic processes and to gaining meaning from text. Thus, although the language processes involved in comprehension and meaning are intact, they cannot be called into play, because they can be accessed only after a word has been identified. The impact of the phonological deficit is most obvious in reading, but it can also affect speech in predictable ways. Gregory's dilemma with long or novel words, for example, is entirely consistent with the body of evidence that supports a phonological model of dyslexia.

That evidence began accumulating more than two decades ago. One of the earliest experiments, carried out by the late Isabelle Y. Liberman of Haskins Laboratories, showed that young children become aware between four and six years of age of the phonological structure of spoken words. In the experiment, children were asked how many sounds they heard in a series of words. None of the four-year-olds could correctly identify the number of phonemes, but 17 percent of the five-year-olds did, and by age six, 70 percent of the children demonstrated phonological awareness.

By age six, most children have also had at least one full year of schooling, including instruction in reading. The development of phonological awareness, then, parallels the acquisition of reading skills. This correspondence suggested that the two processes are related. These findings also converge with data from the Connecticut Longitudinal Study, a project my colleagues and I began in 1983 with 445 randomly selected kindergartners; the study continues in 1996 when these children are age 19 and out of high school. Testing the youngsters yearly, we found that dyslexia affects a full 20 percent of schoolchildren—a figure that agrees roughly with the proportion of Liberman's six-year-olds who could not identify the phonological structure of words. These data further support a connection between phonological awareness and reading.

During the 1980s, researchers began to address that connection explicitly. The groundbreaking work of Lynette Bradley and Peter E. Bryant of the University of Oxford indicated that a pre-

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IN READING, the word (here, “cat”) is first decoded into its phonological form (“kuh, aah, tuh”) and identified. Once it is identified, higher-level cognitive functions such as intelligence and vocabulary are applied to understand the word’s meaning

(“small furry mammal that purrs”). In people who have dyslexia, a phonological deficit impairs decoding, thus preventing the reader from using his or her intelligence and vocabulary to get to the word’s meaning.

schooler’s phonological aptitude predicts future skill at reading. Bradley and Bryant also found that training in phonological awareness significantly improves a child’s ability to read. In these studies, one group of children received training in phonological processing, while another received language training that did not emphasize the sound structure of words. For example, the first group might work on categorizing words by their sound, and the second group would focus on categorizing words according to their meaning. These studies, together with more recent work by Benita A. Blachman of Syracuse University, Joseph E. Torgesen of Florida State University and Barbara Foorman of the University of Houston, clearly demonstrate that phonological training in particular—rather than general language instruction—is responsible for the improvements in reading.

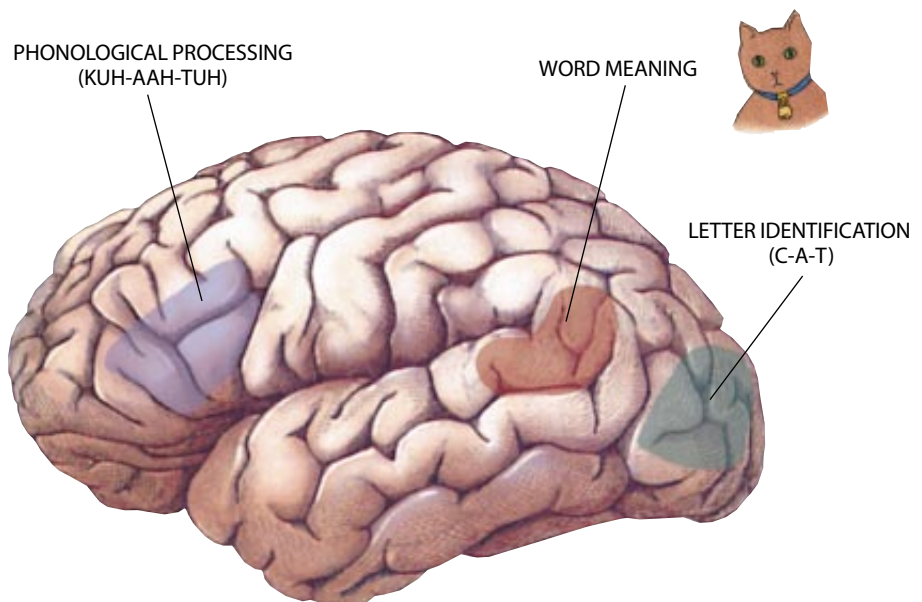
Such findings set the stage for our own study, in the early 1990s, of the cognitive skills of dyslexic and nondyslexic children. Along with Jack M. Fletcher of the University of Texas–Houston and Donald P. Shankweiler and Leon-

ard Katz of Haskins Laboratories, I examined 378 children from seven to nine years old on a battery of tests that assessed both linguistic and nonlinguistic abilities. Our results as well as those of Keith E. Stanovich and Linda S. Siegel of the Ontario Institute for Studies in Education made it clear that phonological deficits are the most significant and consistent cognitive marker of dyslexic children.

One test in particular seemed quite sensitive to dyslexia: the Auditory Analysis Test, which asks a child to segment words into their underlying phonological units and then to delete specific phonemes from the words. For example, the child must say the word “block” without the “buh” sound or say the

word “sour” without the “s” sound. This measure was most related to a child’s ability to decode single words in standardized tests and was independent of his or her intelligence, vocabulary and reasoning skills. When we gave this and other tests of phonemic awareness to a group of 15-year-olds in our Connecticut Longitudinal Study, the results were the same: even in high school students, phonological awareness was the best predictor of reading ability.

If dyslexia is the result of an insufficiently developed phonological specialization, other consequences of impaired phonological functioning should also be apparent—and they are. Ten years ago the work of Robert B. Katz of Haskins Laboratories documented the problems



NEURAL ARCHITECTURE for reading has been suggested by functional magnetic resonance imaging. Letter identification activates the extrastriate cortex in the occipital lobe; phonological processing activates the inferior frontal gyrus (Broca’s area); and accessing meaning activates primarily the superior temporal gyrus and parts of the middle temporal and supramarginal gyri.

poor readers have in naming objects shown in pictures. Katz showed that when dyslexics misname objects, the incorrect responses tend to share phonological characteristics with the correct response. Furthermore, the misnaming is not the result of a lack of knowledge. For example, a girl shown a picture of a volcano calls it a tornado. When given the opportunity to elaborate, she demonstrates that she knows what the pictured object is—she can describe the attributes and activities of a volcano in great detail and point to other pictures related to volcanoes. She simply cannot summon the word “volcano.”

This finding converges with other ev-

idence in suggesting that whereas the phonological component of the language system is impaired in dyslexia, the higher-level components remain intact. Linguistic processes involved in word meaning, grammar and discourse—what, collectively, underlies comprehension—seem to be fully operational, but their activity is blocked by the deficit in the lower-order function of phonological processing. In one of our studies, Jennifer, a very bright young woman with a reading disability, told us all about the word “apocalypse.” She knew its meaning, its connotations and its correct usage; she could not, however, recognize the word on a printed page. Because she could not

decode and identify the written word, she could not access her fund of knowledge about its meaning when she came across it in reading.

Of course, many dyslexics, like Gregory, do learn to read and even to excel in academics despite their disability. These so-called compensated dyslexics perform as well as nondyslexics on tests of word accuracy—they have learned how to decode or identify words, thereby gaining entry to the higher levels of the language system. But they do so at a cost. Timed tests reveal that decoding remains very laborious for compensated dyslexics; they are neither automatic nor fluent in their ability to identify

Playing Past Learning Disabilities

Dyslexia is the most common of the learning disorders, conditions that interfere with a normally intelligent child's ability to acquire speech, reading or other cognitive skills. Children with learning disabilities have become the basis of a thriving industry since 1968, when federal education officials first earmarked funds to help them. The number of children identified as having learning disabilities soared from 780,000 in 1976 to 2.3 million in 1993. An estimated \$15 billion is spent annually on the diagnosis, treatment and study of such disorders.

The definitions and diagnostic criteria for learning disorders are often subjective or ambiguous; their causes are typically obscure or controversial. For example, psychologist Gerald Coles of the University of Rochester challenges the claim that 20 percent of children are dyslexic, and not all researchers and educators accept a phonological (or even biological) explanation for dyslexia. Treatment is another area that has been fraught with controversy and, often, disappointment. Over the years, educators and parents have subscribed to many techniques that promised to help children overcome their learning disabilities, despite the absence of independent research to back up those claims. Nevertheless, ongoing research holds out prospects for some real progress.

One of the most lauded treatments for learning disabilities to emerge in recent years has been developed by a group led by Paula Tallal, co-director of the Center for Molecular and Behavioral Neuroscience at Rutgers University in Newark, N.J., and Michael M. Merzenich of the Keck Center for Integrative Neuroscience at the University of California at San Francisco. Their research has not focused on dyslexics per se but on “language-impaired” children who have difficulty understanding speech. Not all language-impaired children are dyslexic, Tallal notes, and not all dyslexics are language-impaired, but

there is nonetheless broad overlap between the two groups. Studies have suggested that as many as 8 percent of all children may be language-impaired; of this group, more than 85 percent also exhibit dyslexia.

Tallal, who began studying language impairment in the late 1970s, has long suspected that this problem stems from an inability to process auditory information rapidly enough. Whereas most children can process phonemes lasting less than 40 milliseconds, the language-impaired may require as much as 500 milliseconds. To them, the word “bat” may be indistinguishable from “pat.” This hypothesis,

Tallal says, is “compatible” with the phonological-deficit model of dyslexia but places more emphasis on the role of timing in neural processing.

Language impairment, Tallal believes, usually stems from an organic deficit rather than from environmental factors. Magnetic resonance scans and other imaging studies, she states, have turned up distinct neural differences between people with normal language skills and the language-impaired. “But just because something is biologically based doesn't mean it's irremediable,” Tallal adds.

Two years ago she teamed up with Merzenich and several other scientists to develop a com-

puter-based therapy—an animated video game, essentially—for training language-impaired children. The core of the therapy is a speech-processing program that enables the researchers to alter the amplitude and duration of recorded sounds.

In one of the programs, which has a circus motif, a clown utters two closely related phonemes, such as “pa” and “da,” that have been “stretched out” to a length that the children can easily comprehend. When the children correctly distinguish between the sounds, the clown congratulates them; progress is also represented by a bear moving along a tightrope.



FIVE-YEAR-OLD KEILLAN LECKY interacts with a language-learning program at Rutgers University in Newark, N.J.

words. Many dyslexics have told us how tiring reading is for them, reflecting the enormous resources and energy they must expend on the task. In fact, extreme slowness in making phonologically based decisions is typical of the group of compensated dyslexics we have assembled as part of a new approach to understanding dyslexia: our neuroimaging program.

The Neurobiology of Reading

The phonological model incorporates a modular scheme of cognitive processing in which each of the component processes used in word identification is

Once the children have mastered phonemes of a given duration—say, 400 milliseconds—they can move on to more rapid, realistic phonemes. The youngsters also listen to stretched recordings of whole words, sentences and stories, such as *The Cat in the Hat*. Tallal and Merzenich reported in *Science* this past January that 11 children trained with these methods had acquired two years' worth of language skills in only one month. A control group given identical therapy, but without the stretched speech, progressed only one quarter as much.

This year Tallal, Merzenich and two colleagues founded a company called Scientific Learning Principles, based in San Francisco, to develop and market an interactive CD-ROM containing their learning program. They plan to test prototypes in 25 or more special education schools and clinics in the U.S. and Canada over the next year. As many as 500 children are expected to participate.

The studies will include not only language-impaired children but also those diagnosed with dyslexia, attention-deficit disorder and other common learning disabilities. "We want to determine the generalizability of this technique," Tallal notes. If all goes well, she says, the CD-ROMs will be made available to certified learning centers beginning next year.

Since the media first reported on this research a year ago, Tallal and her colleagues have been inundated with queries from the press and parents. In part to satisfy these demands, they have created a World Wide Web site (<http://www.scilearn.com>).

Tallal emphasizes that the questions raised by Coles and other skeptics about the causes and frequency of learning disabilities are important. She nonetheless thinks "it is a mistake to focus on all these differences in definition." Real progress, she says, will come about only through empirical research.

—John Horgan, staff writer

carried out by a specific network of brain cells. Until recently, however, researchers have had no firm indication of how that scheme maps onto the actual functional organization of the human brain. Unlike many other functions, reading cannot be studied in animals; indeed, for many years the cerebral localization of all higher cognitive processes could be inferred only from the effects of brain injuries on the people who survived them. Such an approach offered little to illuminate the phenomena my colleagues and I were interested in. What we needed was a way to identify the regions of the brain that are engaged when healthy subjects are reading or trying to read.

Our group became quite excited, then, with the advent in the late 1980s of functional magnetic resonance imaging (fMRI). Using the same scanning machine that has revolutionized clinical imaging, fMRI can measure changes in the metabolic activity of the brain while an individual performs a cognitive task. Hence, it is ideally suited to mapping the brain's response to stimuli such as reading. Because it is noninvasive and uses no radioisotopes, fMRI is also excellent for work involving children.

Since 1994, I have worked with several Yale colleagues to use fMRI in studying the neurobiology of reading. Bennett A. Shaywitz, Kenneth R. Pugh, R. Todd Constable, Robert K. Fulbright, John C. Gore and I have used the technique with more than 200 dyslexic and nondyslexic children and adults. As a result of this program, we can now suggest a tentative neural architecture for reading a printed word. In particular, the identification of letters activates sites in the extrastriate cortex within the occipital lobe; phonological processing takes place within the inferior frontal gyrus; and access to meaning calls on areas within the middle and superior temporal gyri of the brain.

Our investigation has already revealed a surprising difference between men and women in the locus of phonological representation for reading. It turns out that in men phonological processing engages the left inferior frontal gyrus, whereas in women it activates not only the left but the right inferior frontal gyrus as well. These differences in lateralization had been suggested by behavioral studies, but they had never before been demonstrated unequivocally. Indeed, our findings constitute the first concrete proof of gender differences in

The Myths of Dyslexia

Mirror writing is a symptom of dyslexia.

In fact, backwards writing and reversals of letters and words are common in the early stages of writing development among dyslexic and nondyslexic children alike. Dyslexic children have problems in naming letters but not in copying letters.

Eye training is a treatment for dyslexia.

More than two decades of research have shown that dyslexia reflects a linguistic deficit. There is no evidence that eye training alleviates the disorder.

More boys than girls are dyslexic.

Boys' reading disabilities are indeed identified more often than girls', but studies indicate that such identification is biased. The actual prevalence of the disorder is nearly identical in the two sexes.

Dyslexia can be outgrown.

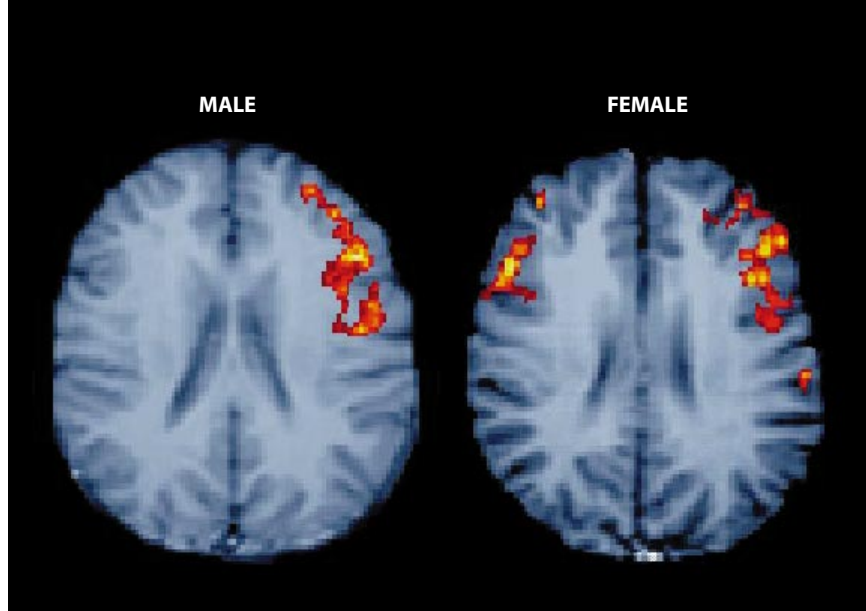
Yearly monitoring of phonological skills from first through 12th grade shows that the disability persists into adulthood. Even though many dyslexics learn to read accurately, they continue to read slowly and not automatically.

Smart people cannot be dyslexic.

Intelligence is in no way related to phonological processing, as scores of brilliant and accomplished dyslexics—among them William Butler Yeats, Albert Einstein, George Patton, John Irving, Charles Schwab and Nicholas Negroponte—attest.

brain organization for any cognitive function. The fact that women's brains tend to have bilateral representation for phonological processing explains several formerly puzzling observations: why, for example, after a stroke involving the left side of the brain, women are less likely than men to have significant decrements in their language skills, and why women tend more often than men to compensate for dyslexia.

As investigators who have spent our entire professional lives trying to understand dyslexia, we find the identification of brain sites dedicated to phonological processing in reading very exciting—it means that we now have a possible neurobiological "signature" for read-



BENNETT A. SHAYWITZ ET AL. / Yale NMR Research

BRAIN ACTIVATION PATTERNS during reading, as revealed in these functional magnetic resonance images, differ in men and women. During phonological processing, men show primarily unilateral activation, in the left inferior frontal gyrus. In women, phonological processing activates both the left and the right inferior frontal gyri.

ing. The isolation of such a signature brings with it the future promise of more precise diagnosis of dyslexia. It is possible, for example, that the neural signature for phonological processing may provide the most sensitive measure of the disorder. Furthermore, the discovery of a biological signature for reading offers an unprecedented opportunity to assess the effects of interventions on the neuroanatomic systems serving the reading process itself.

Putting It in Context

The phonological model crystallizes exactly what we mean by dyslexia: an encapsulated deficit often surrounded by significant strengths in reasoning, problem solving, concept formation,

critical thinking and vocabulary. Indeed, compensated dyslexics such as Gregory may use the “big picture” of theories, models and ideas to help them remember specific details. It is true that when details are not unified by associated ideas or theoretical frameworks—when, for example, Gregory must commit to memory long lists of unfamiliar names—dyslexics can be at a real disadvantage. Even if Gregory succeeds in memorizing such lists, he has trouble producing the names on demand, as he must when he is questioned on rounds by an attending physician. The phonological model predicts, and experimentation has shown, that rote memorization and rapid word retrieval are particularly difficult for dyslexics.

Even when the individual knows the

information, needing to retrieve it rapidly and present it orally often results in calling up a related phoneme or incorrectly ordering the retrieved phonemes. Under such circumstances, dyslexics will pepper their speech with many um’s, ah’s and other hesitations. On the other hand, when not pressured to provide instant responses, the dyslexic can deliver an excellent oral presentation. Similarly, in reading, whereas nonimpaired readers can decode words automatically, individuals such as Gregory frequently need to resort to the use of context to help them identify specific words. This strategy slows them further and is another reason that the provision of extra time is necessary if dyslexics are to show what they actually know. Multiple-choice examinations, too, by their lack of sufficient context, as well as by their wording and response format, excessively penalize dyslexics.

But our experience at the Yale Center suggests that many compensated dyslexics have a distinct advantage over nondyslexics in their ability to reason and conceptualize and that the phonological deficit masks what are often excellent comprehension skills. Many schools and universities now appreciate the circumscribed nature of dyslexia and offer to evaluate the achievement of their dyslexic students with essays and prepared oral presentations rather than tests of rote memorization or multiple choices. Just as researchers have begun to understand the neural substrate of dyslexia, educators are beginning to recognize the practical implications of the disorder. A century after W. Pringle Morgan first described dyslexia in Percy F., society may at last understand the paradox of the disorder. SA

The Author

SALLY E. SHAYWITZ is, along with Bennett A. Shaywitz, co-director of the Yale Center for the Study of Learning and Attention and professor of pediatrics at the Yale University School of Medicine. She received her M.D. from the Albert Einstein College of Medicine in Bronx, N.Y., and has spent her entire professional career at Yale, where, since 1983, she has directed the Connecticut Longitudinal Study. Currently she is using functional magnetic resonance imaging to study the neurobiology of dyslexia in children and young adults. A pediatrician and neuroscientist, she received the impetus to study dyslexia from the many very bright dyslexics she came to know as patients, students and, often, colleagues. She acknowledges the helpful comments of the Shaywitz tribe—Adam, Jon and David—in preparing this article.

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