Title

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Journal

TEACHING Exceptional Children, 51(3)

ISSN

0040-0599 2163-5684

Authors

Kearns, Devin M
Hancock, Roeland
Hoeft, Fumiko
et al.

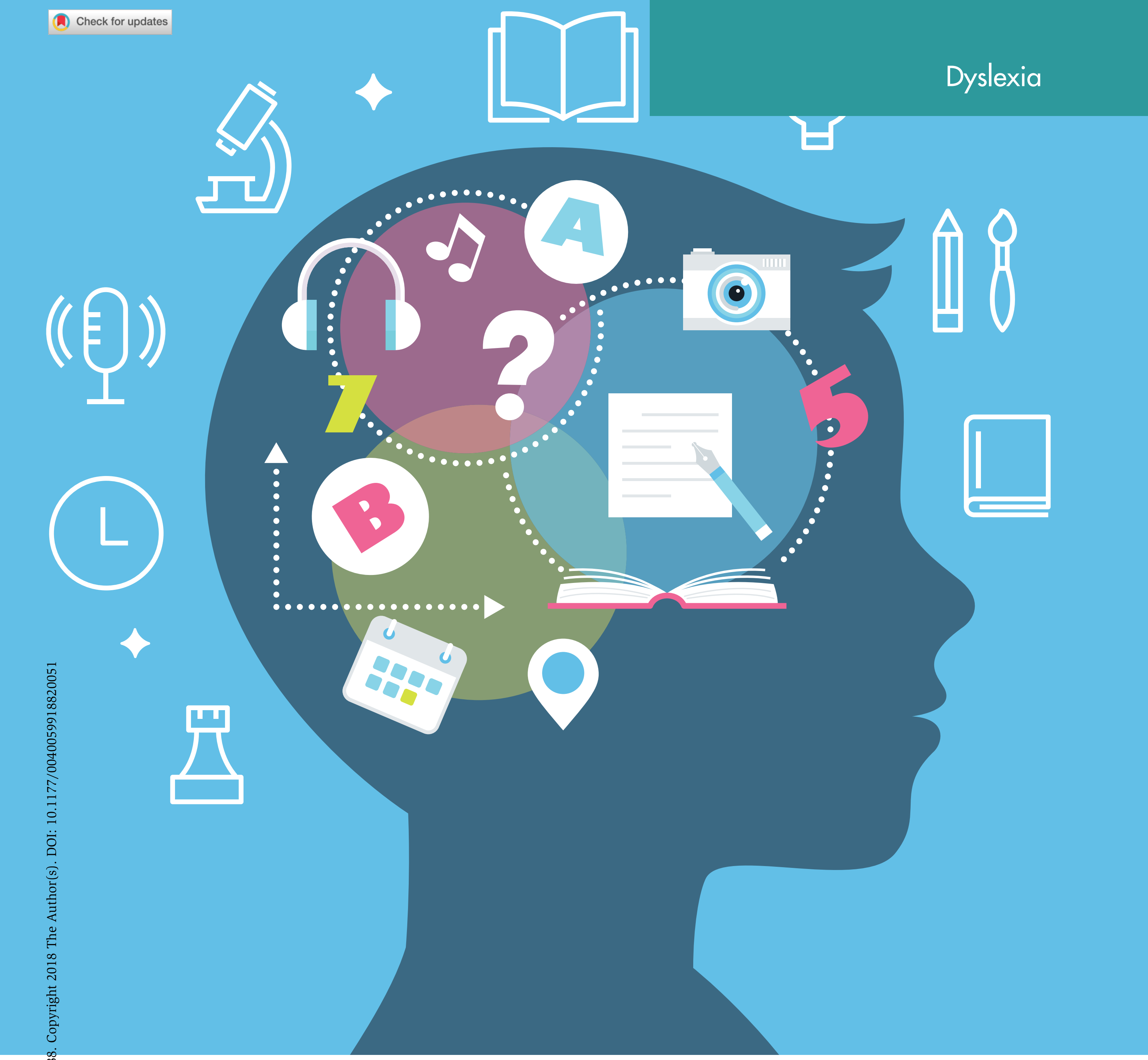
Publication Date

2019-01-11

DOI

10.1177/0040059918820051

Peer reviewed



The Neurobiology of Dyslexia

Devin M. Kearns, Roeland Hancock, Fumiko Hoeft, Kenneth R. Pugh, and Stephen J. Frost

TEACHING Exceptional Children, Vol. 51, No. 3, pp. 175–188. Copyright 2018 The Author(s). DOI: 10.1177/0040059918820051

Advances in neurobiological research have created new opportunities for understanding and exploring dyslexia. The purpose of this article is to (a) provide a straightforward, although not overly simplified, overview of neurological research on dyslexia and (b) make connections between neurological research and classroom interventions for students with dyslexia. Key ideas are that neuroscience confirms the importance of systematic phonics instruction, neuroimaging has led to new ideas about how dyslexia might be treated, and specific brain regions and pathways are involved in reading. Educational neuroscience remains in early stages, but the immediate relevance for the classroom is emerging.

The term *dyslexia* refers to difficulty in reading, a type of specific learning disability, sometimes called a *reading disability* or *disorder*. Dyslexia is complex, and varied definitions exist across educational, medical, and governmental organizations (Table 1). Despite the many differences, most definitions include one common characteristic—difficulty recognizing words. That is, students with dyslexia will encounter difficulty identifying or pronouncing familiar and unfamiliar words accurately and fluently (Hancock, Gabrieli, & Hoeft, 2016; Hulme & Snowling, 2017; Mabchek & Nelson, 2007; Tanaka et al., 2011). Individuals with dyslexia often have other difficulties, as some definitions in Table 1 address (e.g., reading comprehension challenges). However, this is often the result of word-reading difficulty rather than a core aspect of dyslexia.

Word reading is the ability to pronounce real words quickly and accurately and the ability to read unknown words by decoding them. In alphabetic languages such as English, readers link the graphemes (written units that represent sounds; e.g., *c* or *ck*) to the phonemes (sounds of a language; e.g., /k/). This happens in two ways (see Figure 1). One way involves attention to letters and letter patterns—readers link graphemes to phonemes and assemble the phonemes to say a word, as in the top path for *cat*. Mapping letters and letter patterns to phonemes is decoding, also called *phonics* or *sounding out*. The other way that readers connect letters to the sounds in a word is through whole-word or sight recognition. Sight recognition occurs only when a reader has previously encountered a word and memorized the pronunciation of the printed word, as in the bottom path, where the letters are linked directly to the pronunciation. Most developing readers will partly rely on sight memory and partly on decoding for words that they have seen (they may remember some letters but not others). Neuroimaging allows researchers to understand how readers with dyslexia use decoding and sight recognition to read words and how the reading behavior of students with dyslexia differs from that of students with typical reading development.

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Why Study Neurobiology?

In special education, many researchers and practitioners focus on students' observed difficulties when reading, rather than the possible internal processes that cause dyslexia. For example, researchers will examine the effects of specific approaches to word-reading instruction on students' word-reading ability (Reschly, 2005). Examining the relation between specific approaches to reading instruction and changes in the reading ability of students with reading disabilities and those at risk for reading failure has resulted in a strong body of knowledge related to effective reading instruction for students with dyslexia (e.g., Wanzek et al., 2013). Therefore, the benefits of understanding the neuroscience of reading (i.e., the internal processes associated with reading behavior) may not be apparent.

Some special educators are also wary of neuroscience because they associate it (understandably but not correctly) with the "brain based" education of the 1960s and 1970s. At that time, the promoters of the "Doman-Delacato treatment of neurologically handicapped children" (Doman, Spitz, Zucman, Delacato, & Doman, 1960) said that reading difficulties were caused by brain damage that could be reversed with activities such as crawling, breathing through masks, and doing somersaults. Others recommended cognitive interventions based on students' cognitive profiles identified by the Illinois Test of Psycholinguistic Abilities. These "brain based" interventions became very popular, but studies showed that they did not improve students' reading (American Academy of Pediatrics, 1982; Hammill & Larsen, 1974). There are more "brain based" or "cognitively focused" interventions available today, but most do not have supporting evidence (see Burns et al., 2016; Kearns & Fuchs, 2013).

Despite the misuse of the concept of "brain based" approaches, an understanding of the neurobiology of dyslexia can be beneficial to special educators for several reasons. First, examining the brain at a fine-grained level can provide insights about how students are performing in ways that performance (i.e., evaluations of external behaviors) on tests cannot. For example, researchers have shown that data from brain scans can demonstrate whether students will respond to reading instruction even before it begins (Hoeft et al., 2007; Hoeft et al., 2011). In theory, these kinds of data could be used to decide the intensity of intervention needed to help a

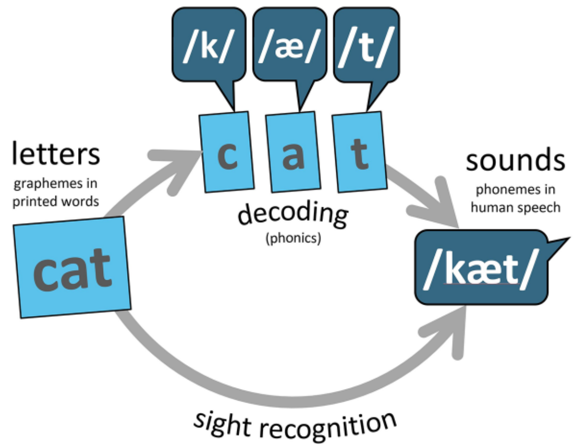
Table 1. Different Definitions of Dyslexia

Source	Definition	Included skills	Identified cognitive processes	Superordinate category
NINDS of the National Institutes of Health (n.d.)	"Dyslexia is a brain-based type of learning disability that specifically impairs a person's ability to read."	Decoding, fluency, reading comprehension, spelling	Phonological processing. Rapid visual-verbal processing	None given
International Dyslexia Association Board of Directors (2012)	"Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities."	Decoding, spelling, word reading. Possible related skills: background knowledge, reading comprehension, vocabulary	"Phonological component of language"	None given
Understood Team of NCLD (n.d.)	"A specific learning disability in reading. Kids with dyslexia have trouble reading accurately and fluently. They may also have trouble with reading comprehension, spelling and writing."	Fluency, word reading. Possible related skills: reading comprehension, spelling, writing	Not addressed	Learning disability
American Psychiatric Association (2013), *DSM-5*	None—given as a type of "specific learning disorder"	Decoding, fluency, spelling. Skills in broader category (specific learning disorder): reading comprehension, spelling, writing, word reading	Not addressed	Specific learning disorder
ICD-10-CM Diagnosis Code F81.0	"Developmental dyslexia is marked by reading achievement that falls substantially below that expected given the individual's chronological age, measured intelligence, and age-appropriate education."	Reading achievement. Skills in broader category (specific reading disorder): reading comprehension, spelling, word recognition, writing	Not addressed	Specific reading disorder
Learning Disabilities Association of America (n.d.)	"A specific learning disability that affects reading and related language-based processing skills. The severity can differ in each individual but can affect reading fluency, decoding, reading comprehension, recall, writing, spelling, and sometimes speech and can exist along with other related disorders. Dyslexia is sometimes referred to as a Language-Based Learning Disability."	Decoding, fluency, reading comprehension, recall, spelling, writing. Possible related skills: speech	Language processing	Learning disability
Individuals with Disabilities Education Act (2004)	None—given as a type of specific learning disability	Not addressed. Skills in broader category (specific learning disability): reading, spelling, speaking, writing	Language processing	Specific learning disability
American Academy of Pediatrics Section on Ophthalmology et al.[a] (2009)	"Dyslexia is a primary reading disorder and results from a written word processing abnormality in the brain. It is characterized by difficulties with accurate and/or fluent sight word recognition and by poor spelling and decoding abilities. These difficulties are unexpected in relation to the child's other cognitive skills" (p. 838).	Word reading, fluency, spelling	Phonological processing. Also in some individuals: rapid visual-verbal processing, working memory, attention	Learning disabilities

Note. DSM-5 = Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition; *ICD-10-CM* = *International Classification of Diseases, Tenth Revision, Clinical Modification*, maintained by the World Health Organization; NCLD = National Council for Learning Disabilities; NINDS = National Institute of Neurological Disorders and Stroke.

[a]Joint statement from the American Academy of Pediatrics Section on Ophthalmology, Council on Children with Disabilities, American Academy of Ophthalmology, American Association for Pediatric Ophthalmology and Strabismus, and American Academy of Certified Orthopedists (2009). Most definitions also implicitly or explicit proscribe the inclusion of students with intellectual disabilities from the category of dyslexia.

Figure 1. Two ways a reader might pronounce the printed word *cat*



struggling reader. Although researchers have yet to make instructional decisions for individual students on this basis, the fact that neuroimaging data can provide information that tests cannot is alone one reason for educators to understand what neuroscientists have learned about how the brain works when students read.

Another benefit of knowing what parts of the brain are activated during reading is that this location-based information is now being used to develop new reading interventions that target the specific brain regions implicated in dyslexia. For example, some researchers found that stimulating certain reading-related regions of the brain with a tiny electrical current (safely and nonsurgically) in adults (Turkeltaub et al., 2012) and school-age students (Costanzo et al., 2016; Costanzo et al., 2018; Costanzo, Menghini, Caltagirone, Oliveri, & Vicari, 2013) during reading leads to more improvement in reading as compared with nonstimulated reading conditions. This promising, albeit unique, technology can work because researchers know what part of the brain to stimulate. Neuroscientific reading research makes that possible.

Finally, a benefit of showing how the brain operates during reading is that it provides an objective understanding of how reading works. If it is known what brain regions are strongly activated during reading and what their general functions are, it is possible to understand how the brain operates when a student tries to read a word. Neuroscience now provides such information. Without neuroimaging data, it might be easy to argue about the processes that readers use to recognize words and the instruction that will help them best—as was the case in the past (e.g., Adams, 1990). With neurological data, however, researchers and educators can know how the brain processes word information with little room for debate. It may not end disagreements about how reading works or what kind of instruction is best, but neuroscience provides an objective biological starting point that can offer some clarity. For these reasons, we think that it is worthwhile for educators to understand the neurobiology of reading among students with and without dyslexia.

It is also important to acknowledge the limitations of the neuroscientific research on dyslexia. Neuroscience has improved our understanding of reading, dyslexia, and the effects of reading intervention, but it has not yet resulted in direct changes to instructional approaches for students with dyslexia (Bowers, 2016; Gabrieli, 2016). There are other limitations and many things still to learn. One goal of this article is to provide a straightforward picture of the state of the art in the neuroscience of dyslexia to provide an understanding of what neuroscience can and cannot presently demonstrate about reading and dyslexia.

Neurobiology and Reading

Neurobiology is a way of describing the organization of the brain and the uses of its various parts. The brain has four main lobes—the frontal, parietal, temporal, and occipital lobes in each hemisphere—as well as the cerebellum, subcortical nuclei, and brainstem that underlie these. Although humans constantly use all of these systems, researchers have long known that different regions within these lobes are more active during some tasks than others. The systems of the brain support many basic human functions, such as movement and communication. However, reading is unique because it is not an innate human ability. Humans invented reading more than 5,000 years ago (Daniels, 2001) primarily to allow efficient, direct communication with others without being in the same place (Seidenberg, 2017). What makes reading remarkable is that humans can learn to do it with such great automaticity despite the fact that our brains are not specifically organized to do this (Dehaene, 2009).

It is also remarkable that—across many people and cultures—readers use the same parts of the brain to accomplish the task of reading. Researchers are still debating whether reading "takes over" a part of the brain (Dehaene & Cohen, 2011) or whether the reading parts still have other functions. For example, researchers are not sure if the part of the brain that recognizes letters also performs other visual processing tasks (Price & Devlin, 2003). Research is clear on one point, though:

Neurobiology is a way of describing the organization of the brain and the uses of its various parts.

Reading does not happen in just one region of the brain. During the reading process, regions from all four lobes work together. Neurobiological research has revealed patterns of coordination among these regions in good readers, demonstrated how the brain scans of students with dyslexia differ, and indicated how reading intervention can change the brain activation patterns of students with dyslexia.

Researchers have studied the neurobiology of reading for more than a century. Early studies examined individuals who had acquired word-reading problems as a result of a lesion (e.g., tissue damage as a result of an injury) on the brain (Hinshelwood, 1900). In these studies, individuals with lesions in different areas of the brain demonstrated different kinds of difficulties with word reading. Some had great difficulty reading nondecodable words, such as *eye* and *who*, but could still perform decoding tasks. Some had the opposite problem: They could not decode but could remember words that they had read before. Researchers then began to theorize what these patterns revealed about how humans use the brain when they read.

Researchers have now developed special techniques to better understand how the parts are being used in people who may not have brain damage—and without surgery. Today, one of the most common technologies used to analyze the reading brain is functional magnetic resonance imaging (fMRI). fMRI allows researchers to see what is happening in the brain using information about how much blood flows to different parts of the brain during the reading process (i.e., while a person is actively decoding). The circulatory system provides oxygen to all parts of the brain at all times, but additional oxygenated blood is provided to some parts of the brain when they are particularly active and have depleted the oxygen. The fMRI machine can detect when there is more oxygenated blood in a part of the brain—the more oxygenated blood, the greater the activation.

When individuals participate in neuroimaging research with fMRI, the "functional" part refers to the fact that they perform tasks in the scanner that involve some kind of reading-related processing. For example, words may flash on the screen in rapid succession (Malins et al., 2016). Because it is virtually impossible not to read a word if one knows how, participants will read the words as they are flashed on the screen. Performance on the word-reading tasks can be compared with nonreading performance tasks, such as looking at a picture, so that researchers can identify differences in location and activation levels during reading and nonreading tasks.

The Reading Brain in Typical Readers

As a result of many fMRI studies, researchers have identified what is now considered the "classical" pattern of activation in the reading brain. Specifically, three regions across the four lobes are involved in decoding or sight recognition reading: the left inferior frontal gyrus in the frontal lobe, the left temporoparietal cortex, and the left occipitotemporal region. fMRI studies of good readers have shown that these regions are more active than other parts of the brain during reading (Price, 2012; Turkeltaub, Eden, Jones, & Zeffiro, 2002). However, the story of the reading brain is a little more complex because researchers have identified areas within these three regions that have a role in reading (Figure 2).

Table 2 provides an overview of the regions of the brain and their functions.

The Inferior Frontal Gyrus in the Frontal Lobe

The inferior frontal gyrus (IFG, in particular the posterior IFG), which overlaps with what some call Broca's area, has several language-related functions. In reading, the IFG stores information about the sounds that words contain, and it links this information to other representations of the word in the brain and motor regions, even during silent reading (Richlan, Kronbichler, & Wimmer, 2011). The IFG also has a more general role in sequencing information, and researchers think that this may help readers put the sounds in the correct order when they are ready to say a word aloud. The IFG is used regardless of whether the reader decodes the word or recognizes it by sight.

Temporoparietal Region

The primary areas of focus within the temporoparietal region are the superior temporal gyrus (which overlaps with what some call Wernicke's area), supramarginal gyrus, and angular gyrus. The superior temporal gyrus is the main speech-processing region and helps extract phonemes from the speech that we hear. The supramarginal gyrus serves as a link between phonemes and graphemes. The angular gyrus may be involved in processing word meanings (Seghier, Fagan, & Price, 2010). The temporoparietal region serves as the decoding center of the reading brain.

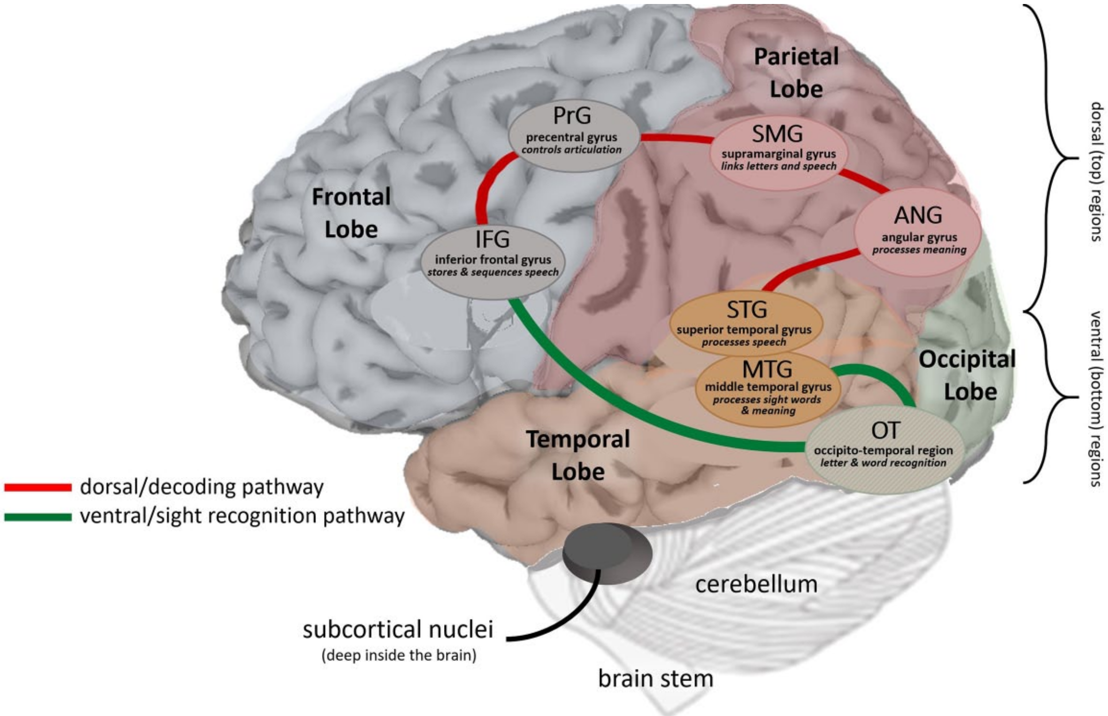
Occipitotemporal Region

The occipitotemporal region includes the fusiform gyrus and the inferior temporal gyrus. This region is very close to the parts of the brain that process visual information. Researchers believe that this region is used to process familiar visual information, such as letters and words (Kronbichler et al., 2004; Schlaggar & McCandliss, 2007). A portion of the fusiform gyrus is sometimes called the visual word form area (McCandliss, Cohen, & Dehaene, 2003). However, not all researchers use this term, because it implies that the region is specialized for words. To the contrary, researchers have shown activation in this area when readers process other types of familiar visual information (e.g., images of objects; Devlin, Jamison, Gonnerman, & Matthews, 2006).

The Reading Network

The IFG, temporoparietal, and occipitotemporal regions interact to link printed words to sound and meaning. The *dorsal pathway* uses systems on the top half of the brain (the parts linked by the red line in Figure 2) and is used by

Figure 2. Regions of the reading brain



good readers to decode unknown words. Researchers think that readers use the systems in the parietal lobe to link letters to sounds and activate their pronunciations in the IFG. The *ventral pathway* (shown by the green lines in Figure 2) is used by good readers to read familiar words, likely because known words are recognized in the fusiform gyrus and linked to pronunciation in the IFG (Levy et al., 2009).

Finally, the brain has a subcortical system that lies underneath the four regions and above the cerebellum. Its components, the striatum (a region including the caudate nucleus, putamen, and basal ganglia) and the thalamus are thought to have a role in reading as well. However, their contributions are less well understood.

The Reading Brain in Readers With Dyslexia

The primary difference between developing readers with dyslexia and their peers with typical reading skills is that those with dyslexia show less increase in brain activation in the temporoparietal regions and the occipitotemporal regions during reading and rhyming tasks (Martin, Schurz, Kronbichler, & Richlan, 2015). Some studies showed that readers with dyslexia even have less gray matter (brain tissue) in the temporoparietal regions that involve decoding and the occipitotemporal regions involved in sight word reading (Richlan, Kronbichler, & Wimmer, 2013). The lower activation and smaller amount of gray matter in these areas align with the fact that students with reading difficulty have weaker decoding skills and more difficulty recognizing words by sight than do their peers with typical reading skills.

However, a few studies found that students with dyslexia show some areas of greater activation as compared with their peers with typical achievement. The left precentral gyrus—a region involved in articulation (i.e., the production of speech sounds)—shows more activation in children and adults with dyslexia than that of their typical peers (Richlan et al., 2011). Currently, researchers have hypothesized that readers use articulation to compensate for their weakness in the temporoparietal system that involves decoding (Hancock, Richlan, & Hoeft, 2017). For example, a reader might try to pronounce an unknown word using the visual information without trying to link letters to sounds. This could explain why some readers with dyslexia appear to be guessing when they read—it may be an adaptation that the brain makes due to difficulties in the decoding system.

Finally, there is evidence that students with dyslexia activate

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Table 2. Left Hemisphere Regions of the Cerebral Cortex Involved In Reading

Region	Involved Areas	(Near) Synonyms	Function	Pathway
Posterior inferior frontal gyrus	Pars opercularis Pars triangularis	Broca's area	Storing and sequencing speech	Dorsal and ventral
Precentral gyrus			Controlling articulation of speech sounds	Dorsal[a]
Temporo-parietal region	Parietal • Supramarginal gyrus • Angular gyrus Temporal • Superior temporal gyrus	Perisylvian regions Wernicke's area	Linking letters and speech sounds Processing meaning Processes speech	Dorsal Dorsal Dorsal
Occipito-temporal cortex	Temporal • Middle temporal • gyrus Occipital • Fusiform gyrus • Inferior temporal gyrus	 Visual word form area[b] Extrastriate cortex	Processing sight words and meanings Letter and word recognition	Ventral Ventral

Note. The dorsal pathway is often called the *decoding pathway*. The ventral pathway is the often called the *sight recognition pathway*.
[a]Activation in the precentral gyrus is particularly associated with a potentially compensatory mechanism for students with dyslexia.
[b]This refers to the fusiform gyrus specifically. Many researchers prefer not to use the term *visual word form area* because activation in this area is not exclusive to words.

subcortical regions (parts of the brain covered by gray and white matter), including the striatum and thalamus, more than their typical peers do (Richlan et al., 2011). These regions interact with many other parts of the brain and are involved in motor control (Alexander & Crutcher, 1990), learning (Packard & Knowlton, 2003), and cognitive control (Aron et al., 2007). Parts of the thalamus are involved in attention. The diverse functions of these regions make it difficult to make inferences about their role in dyslexia. Some researchers have suggested that the striatum and thalamus may be important in developing the ability to learn without being taught directly (Ullman, 2004), which is impaired in some individuals with dyslexia (Lum, Ullman, & Conti-Ramsden, 2013) and thought to be important for learning phoneme-grapheme correspondences (Deacon, Conrad, & Pacton, 2008). Others have suggested that these circuits have a direct role in phonological processing (Booth, Wood, Lu, Houk, & Bitan, 2007; Crosson et al., 2013). It is not simple to derive an overall finding from these results, but these areas of overactivation indicate that readers with dyslexia are using other systems to read words rather than relying on the process of mapping graphemes to phonemes as other readers do. In terms of the reading network, poor readers do not always use the pathways in the same way as good readers. For example, they may activate the ventral pathway even when reading nonwords. This is one possible reason why readers with dyslexia try to read nonsense words as real words (Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012). Taken together, these data suggest that readers with dyslexia activate different regions and use different pathways when reading as compared with peers with typical reading.

The Reading Brain and Reading Intervention

Although neurobiological research has yielded a clearer picture of the reading brain in typical readers and individuals with dyslexia, one of the most promising outcomes relates to findings associated with neurocognitive flexibility. That is, researchers have demonstrated that students' patterns of brain activation can change as a result of reading intervention (for a review, see Barquero, Davis, & Cutting, 2014). In an increasing number of studies, researchers have placed students with dyslexia in reading interventions designed to improve their word-reading skills—namely, interventions that focus on building their decoding skills. As a result of these interventions, students read words more accurately and fluently. These studies demonstrated that (internal) neurological change was evident as were changes in (external) reading behaviors.

The ways in which the brain changes are not completely understood, in part because of the few studies that involve reading intervention and neuroimaging. For this article, we reviewed recent studies of the effect of intervention on neurobiological processing and Barquero and colleagues' (2014) analysis of earlier studies. Unfortunately, there are still not enough studies to draw specific conclusions about exactly how intervention changes brain activity. However, the studies almost all included approaches that will not surprise; they are the same kinds of word feature–focused strategies contained in many programs designed for students with dyslexia.

Changes in Activation: Different From Typical Readers

Neuroimaging data now appear to indicate something that typical intervention studies have not. Successful intervention changes the patterns of activation of students with dyslexia, but the patterns are still different from those of students with typical achievement (Peck, Leong, Zekelman, & Hoeft, 2018). One important finding is that readers who respond to intervention increase their activation in the precentral gyrus, the region that activates the articulation (physical formation) of sounds in the mouth (Hancock et al., 2017). Students who benefit from reading intervention also appear to rely more on meaning than do their peers with typical achievement. The subcortical systems play a role in processing meaning (Yeatman et al., 2012), so students who respond may be using meaning information to support their reading. Finally, increased activation in the left thalamus in the subcortical region could also indicate improvement involving language and memory; increased right IFG could indicate improvement related to attention; and middle occipital gyrus could indicate a role for visual processing.

Changes in Activation: Implications for Intervention

The data on these unique patterns among students with dyslexia have led to questions about whether students should learn compensatory strategies—that is, strategies that focus on using the parts of the brain that students with dyslexia appear to use after intervention anyway (e.g., meaning-focused approaches). However, the data are not yet conclusive about the efficacy of targeting compensatory areas only. There are, though, evidence-based approaches that align with a focus on meaning and articulation—areas of higher activation among readers with dyslexia.

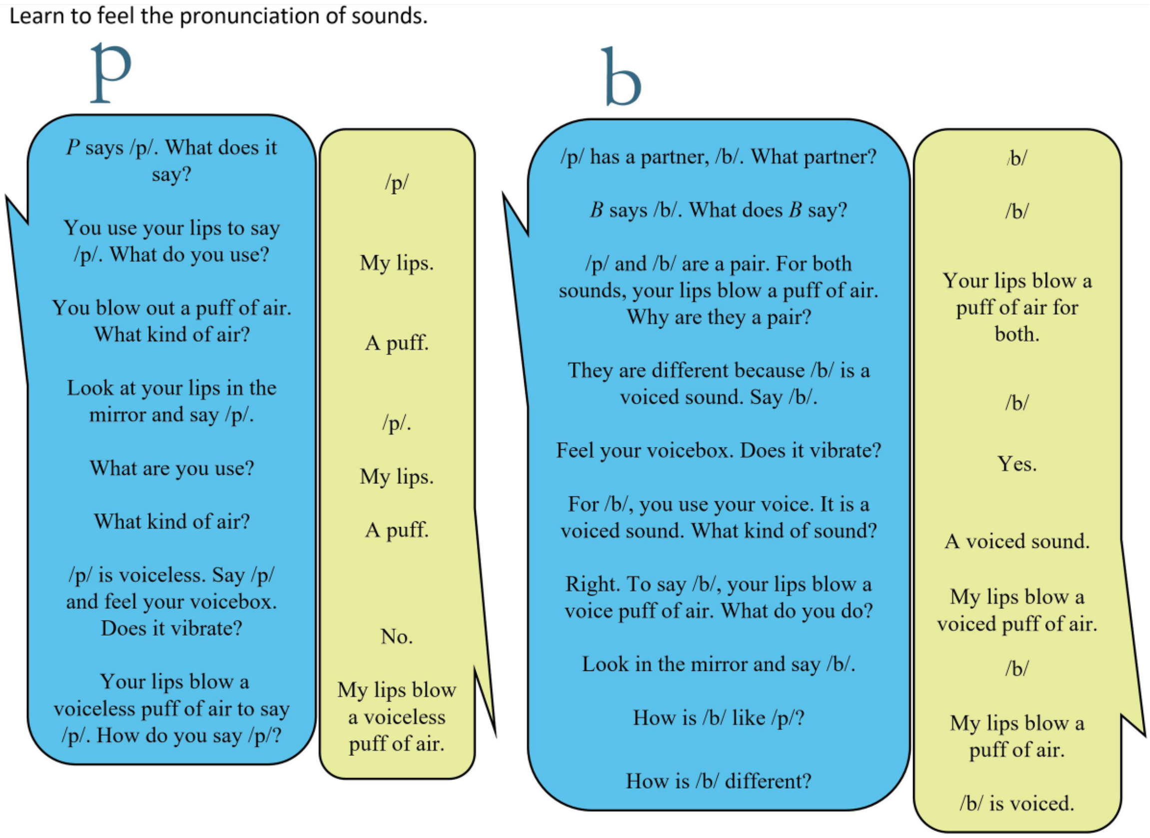
Meaning-Based Approaches. In terms of meaning, it is possible that students with dyslexia might receive benefits from learning about the meaning parts within words—that is, morphemes such as *re-*, *-ment*, and *-s* in *replacements.* Given the possibility that readers with dyslexia are using some meaning information, it may be beneficial to teach students how morphemes affect meaning and how they are used to change the part of speech of base words, as suggested by Ullman and Pullman (2015). Morpheme units are also valuable even within the typical reading system because they are recognizable units that might be processed similarly to familiar words in the occipitotemporal region, and data suggest that students benefit from instruction on morphemes—regardless of the neurobiological data. See Kearns and Whaley (2019; this issue) for further details on how to teach morphological units.

Researchers have demonstrated that students' patterns of brain activation can change as a result of reading intervention.

Articulation-Based Approaches. For the data showing that readers use information about speech sound formation, one way to help students compensate might be to teach them about how sounds are produced. At least one program, the Lindamood-Bell Phoneme Sequencing Program (Lindamood & Lindamood, 1998), includes instruction on how sounds are formed in the mouth, including the parts of the mouth that are used (e.g., lips, teeth, tongue), whether the sound is a stop sound (e.g., /p/) or a continuous sound (e.g., /f/), and whether the sound is produced with or without activating the voice. Figure 3 provides a dialogue that a teacher might use to teach a student with dyslexia about the pronunciation of the /p/ and /b/ sounds for the letters *p* and *b*. Even though it is not yet clear whether increased activation in the precentral gyrus indicates compensation, the Lindamood-Bell Phoneme Sequencing Program has evidence of increasing reading achievement (e.g., Kennedy & Backman, 1993). As a result, teaching about speech sound formation may help readers even if research has not empirically demonstrated that this approach reflects compensation.

It is important to be clear that the word-reading strategies described in Figures 4 and 5 are still essential, even if there are potential benefits of morphological and speech-production instruction. In addition, some researchers have found that instruction does produce a more typical pattern of activation, similar to students without difficulty (Peterson & Pennington, 2015). In short, teachers should use evidence-based phonological strategies for word-reading instruction, but they might consider some supplemental instruction on morphemes or speech production for *some* students. The phrase "for some students" is important. Students with dyslexia begin intervention with unique patterns of brain activity during reading, so they will not all respond exactly the same way to instruction. Phonological word-reading strategies should be used for teaching all students (National Institutes of Child Health and Human Development, 2000; Stuebing, Barth, Cirino, Francis, & Fletcher, 2008), but educators can

Figure 3. A dialogue between a teacher (wider boxes) and student designed to teach the production of the speech sounds /p/ and /b/ associated with the letters *p* and *b*



optimize instruction by considering additional strategies when students do not respond.

Complexities Associated With Neurobiological Reading Research

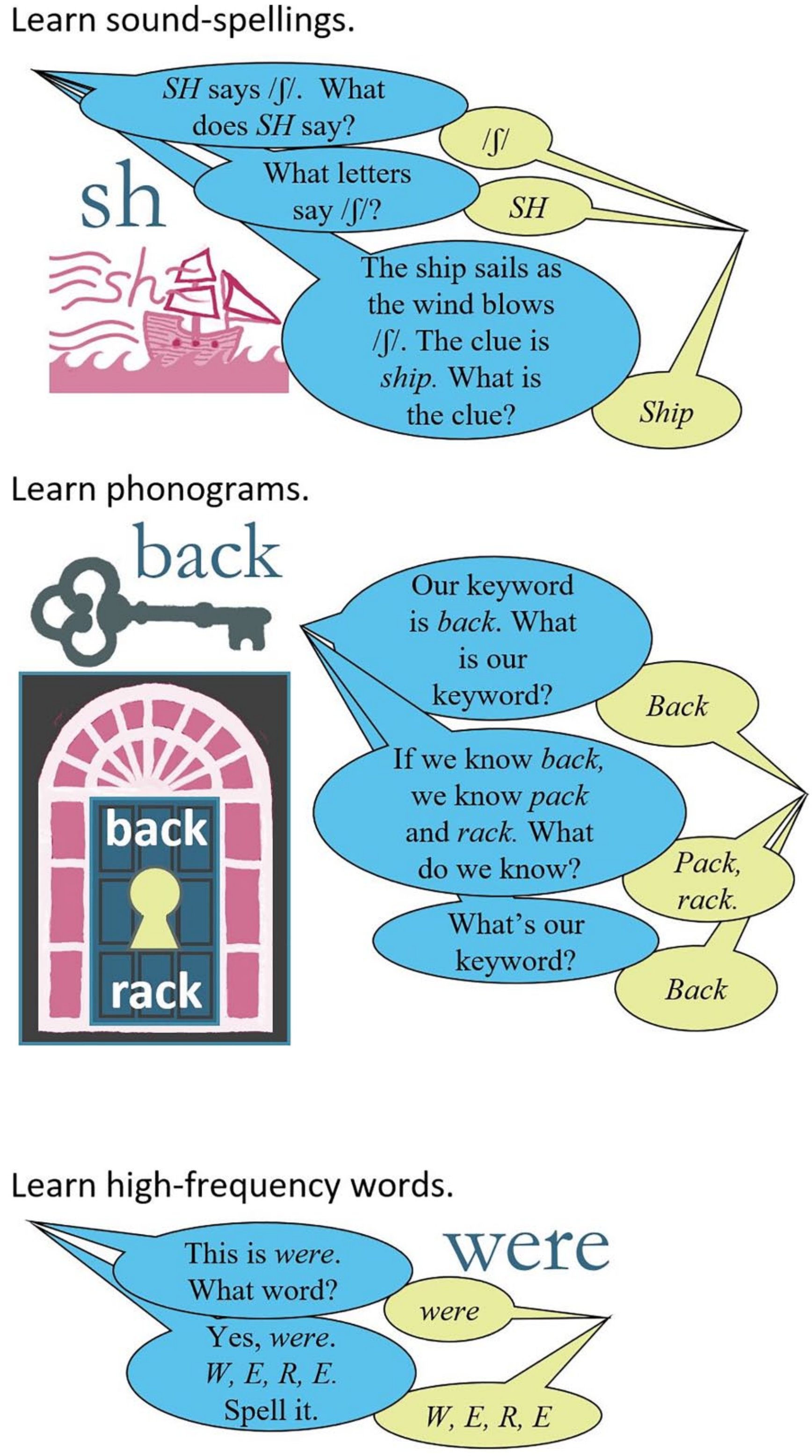
At the outset of this article, we described that students are typically identified with dyslexia because they have poor word-reading skills. The problem for reading researchers and educators is that there are many reasons why students might exhibit poor reading skills (see Table 3). Difficulty linking letters to speech characterizes most cases of dyslexia, but there are other factors related to reading difficulty that could result in a diagnosis of dyslexia.

Some students have difficulty in all academic areas, not just reading. Others may have attention, emotional, or behavioral difficulties that make it hard for them to stay focused during reading instruction. Another group may struggle due to an inadequate amount of evidence-based word-reading instruction. In the early elementary grades, students require extensive instruction and practice to help them learn grapheme-phoneme connections and recognize many words by sight. Some kinds of instruction—especially explicit, systematic phonics instruction—are especially effective in helping students acquire word-reading skills. In its absence, some students will not develop good word-reading skills. In short, there are many possible reasons why students may experience difficulty learning to read.

It is tempting to think that the effects of attention, inadequate instruction, and inherent problems processing graphemes and phonemes can be separated by analyzing fMRI data, but they cannot. It can be hard to separate students with dyslexia from those with attention difficulty because children often have both problems and it is difficult to separate issues of attention from those related to dyslexia. In terms of inadequate instruction, individuals with reading problems often have patterns of activation similar to those of students with dyslexia before they receive instruction (Dehaene et al., 2010). Thus, researchers cannot identify the source of reading problems, even using advanced neuroimaging techniques.

Therefore, although neurobiological research has yielded new insights about the reading brain of students with dyslexia in general, the research

Figure 4. Words and sound-spelling units that students with dyslexia need to learn



has not resulted in the identification of unique groups of students to target instruction. We are also still unable to scan students, determine their patterns of activation during reading, and decide on appropriate instruction. However, researchers think that this may be possible, and they have made some progress in this direction (Hoeft et al., 2011). The data presented in this article reflect studies where performance has been combined across many students. This body of research has resulted in a deeper understanding of components and related areas of the reading brain, but fMRI data cannot yet be used to diagnose and identify interventions for individual students.

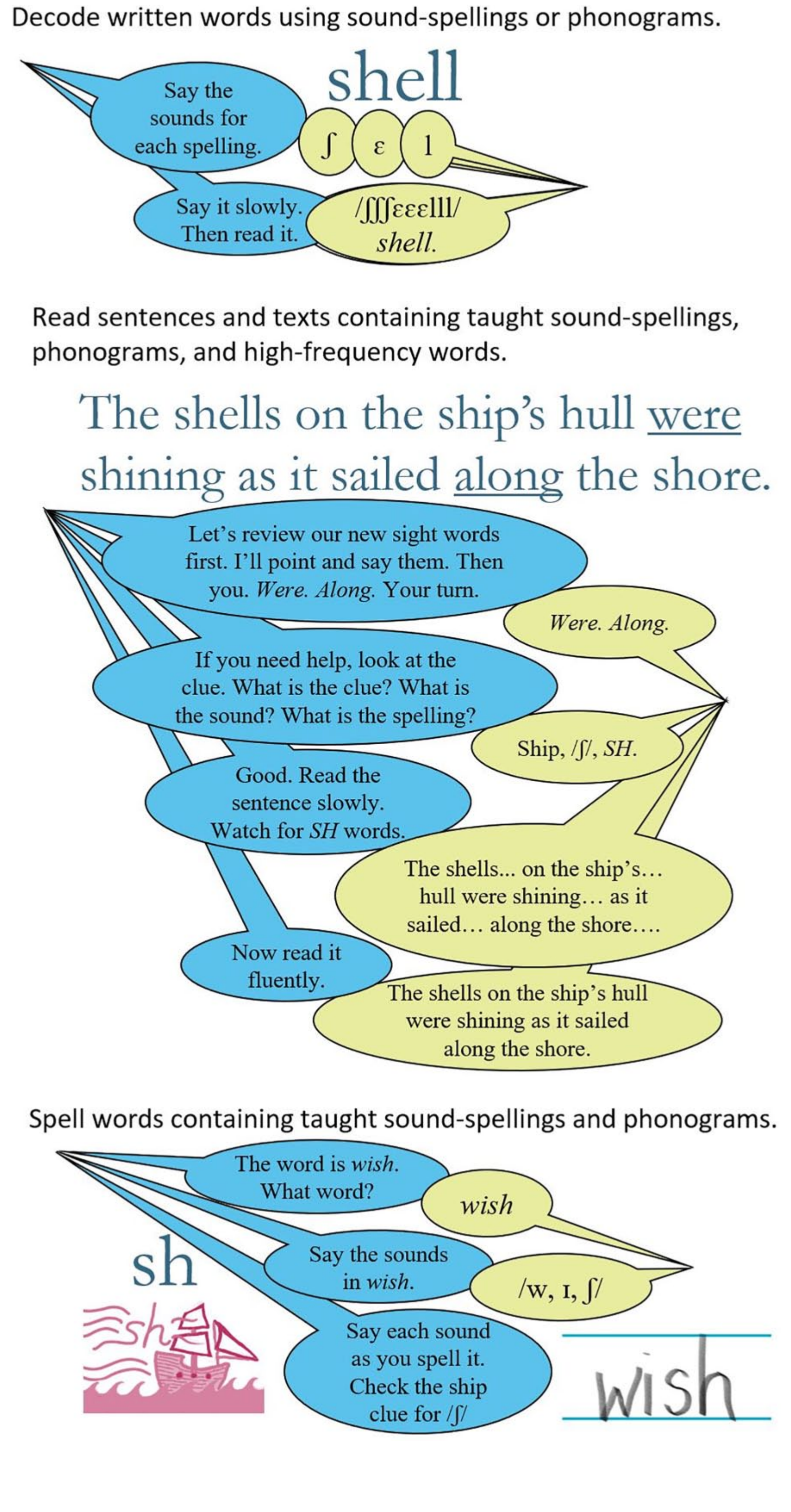
Conclusion

As we have made clear, researchers have a strong understanding of how readers use their brains to read and how the patterns of activation differ between students with and without dyslexia. In addition, researchers' understanding of the relation between intervention and neurobiological change continues to improve—although there is much more work to do in this area.

Overall, there are several key findings about the neurobiology of reading among students with dyslexia. First, individuals with good and poor reading differ in their patterns of activation, in terms of the degree to which they activate parts of the brain associated with reading, such as recognizing familiar print (the occipitotemporal region), linking letters and sounds (the temporoparietal area), and processing phonemes (the inferior frontal gyrus). Importantly, readers with dyslexia are not just showing less activation overall; they show a different pattern of activation. In other words, their brains are not working more slowly—they are working differently.

The second important finding is that when students with dyslexia successfully participate in reading interventions, their patterns of brain activation do not always end up the same as those of students with typical reading achievement. These differences occur even when students with dyslexia participate in phonics-focused, word-reading interventions. This means that a foundational word-reading intervention will help students with dyslexia, but there are still differences in the brain. The data showing differences may also suggest

Figure 5. Activities to practice decoding skills



that students with dyslexia might benefit from different kinds of instruction—but the data on this are not conclusive.

Third, neuroimaging data appear to provide support for using the word-recognition programs upon which many educators have long relied. Although this is obvious, we think that it is important given the continued debate about the value of foundational word-recognition instruction. There are decades of data demonstrating the efficacy of these programs (Scammacca, Roberts, Vaughn, & Stuebing, 2015; Stuebing et al., 2008). We think that it is helpful to illustrate the same effect via a very different approach—differences in patterns of neurological activation before and after instruction of this kind.

A fourth point is that educators should continue to stay tuned. Researchers are working on new ways to do intervention based on some of these preliminary neuroimaging data and to continue refining understanding of the activation patterns associated with response to intervention. We also expect that revolutionary approaches such as the one by Costanzo and colleagues (2018) and Turkeltaub and colleagues (2012) will continue to emerge as more is learned about the reading brain. Compared with 10 years ago, there is much more known about the impact of intervention on the way that readers use their brains, and we expect that there will be much more to say in the next few years.

Finally, in this article, we present current scientific understandings of the neurobiology of reading and dyslexia. There are many unfounded claims about the "brain science." Therefore, separating fact from fiction is important. We are aware that educators, advocates for students with dyslexia, and students with dyslexia themselves have turned to neuroscience to understand this serious difficulty. All of us are likely to hear more frequent discussions of the neurobiology of dyslexia in the next few years, and we think that this article may facilitate engagement in these conversations. We also hope that the educators reading this article consider researchers like ourselves as partners in the future of this work. Some of the authors are education researchers and others are neuroscientists, and we are—like many whose work bridges education

Table 3. Possible Causes of Reading Difficulty and Their Relationships With Dyslexia

Cause	Description	Relationship with dyslexia
Phonological deficit	A core deficit associated with dyslexia	In neuroimaging, students with reading difficulty always show this difficulty. This type of difficulty is at the core of the cognitive and neurobiological understanding of dyslexia.
General difficulty	A level of cognitive functioning that is below average for all academic areas, not just reading	Many students have difficulty in multiple academic areas. If dyslexia is a deficit related to reading specifically, it is unclear whether this fits into the definition of dyslexia.
Attention, behavioral, or emotional difficulty	Challenges that affect a student's ability to focus on reading instruction, even if one does not have dyslexia	If students have not paid attention to reading instruction, their brain activity will look the same as the activity of a student with only a phonological deficit. In this case, the neurobiological origin of the problem is very different than it is for those with a phonological deficit.
Limited evidence-based word-reading instruction	A school-based reason why a student may not have developed good word-reading skills, including (a) limited word-reading instruction altogether or (b) word-reading instruction that does not include evidence-based practices	Some students start to improve their word reading as soon as they receive evidence-based instruction. This could mean that these students did not have a phonological deficit but had not received the instruction that they needed to start to use the brain for reading.

and neuroscience—strongly committed to working with educators in schools to conduct research that will have meaningful benefits for students with dyslexia.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported in part by the Eunice Kennedy Shriver National Institute of Child Health and Human Development Grants R01HD090153 to Kenneth Pugh (KP), R01HD086168 to KP and Fumiko Hoeft (FH), R01HD094834 to FH and Roeland Hancock, and R01HD078351, R01HD096261 and P50HD052120 to FH.

ORCID iD

Devin Kearns https://orcid.org/0000-0001-9703-0932

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Devin M. Kearns, Assistant Professor, and **Roeland Hancock**, Assistant Research Professor, *Department of Psychological Sciences, University of Connecticut, Storrs;* **Fumiko Hoeft,** *Professor and Director of Laboratory for Learning and Engineering and Neural Systems, Department of Psychiatry, University of California, San Francisco, and Professor and Director of Brain Imaging Research Center, Department of Psychological Sciences, University of Connecticut, Storrs;* **Kenneth R. Pugh,** *Professor, Department of Psychological Sciences, University of Connecticut, Storrs, and President and Director of Research, Haskins Laboratory, New Haven, Connecticut; and* **Stephen J. Frost**, *Senior Scientist, Haskins Laboratory, New Haven, Connecticut, USA.*

Address correspondence concerning this article to Devin Kearns, Department of Educational Psychology, University of Connecticut, 249 Glenbrook Road, Unit 3064, Storrs, CT 06269, USA (e-mail: devin.kearns@uconn.edu).

TEACHING Exceptional Children,
Vol. 51, No. 3, pp. 175–188.