

Understanding Reading and Reading Difficulties Through Naming Speed Tasks: Bridging the Gaps Among Neuroscience, Cognition, and Education

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Although reading is an important and generative skill, it remains controversial how reading skills and reading difficulties develop. Currently, the fields of neuroscience, cognition, and education each have complex models to describe reading and elucidate where in the reading process deficits occur. We suggest that integrating the neural, cognitive, and educational accounts of reading offers the promise of transformative change in understanding reading development and reading difficulties. As a starting point for bridging the gaps among these fields, we used naming speed tasks as the basis for this review because they provide a “microcosm” of the processes involved during reading. We use naming speed tasks to investigate how incorporating cognitive psychology with neuroimaging techniques, under the guidance of educational theories, can further the understanding of learning and instruction, and may lead to the identification of the neural signatures of reading difficulties that might be hidden from view earlier in development.

Keywords: *reading difficulties, neuroimaging, eye tracking, naming speed, reading performance*

THE ability to read is crucial for children's future academic, economic, and social success (Norton & Wolf, 2012; Olitsky & Nelson, 2003; Snow, Burns, & Griffen, 1998). A majority of children are able to learn to read with ease, and have average reading ability, characterized by fluent word identification and adequate comprehension (Vellutino & Fletcher, 2005). However, 10% to 15% of English-speaking school-aged children have reading difficulties, and 2% to 4% of children are diagnosed with dyslexia (Shaywitz & Shaywitz, 2008; Snow et al., 1998; Vellutino & Fletcher, 2005; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Children with reading difficulties perform poorly on measures of word reading and reading comprehension in ways that cannot be attributed to sensory impairments, lack of intellectual ability, or poor reading instruction (Shaywitz, 2003; Shaywitz, Mody, & Shaywitz, 2006; Vellutino et al., 2004).

Children who struggle to learn to read have been described in many ways. The term *dyslexia* is usually reserved for more severe or persistent word reading

difficulties, but other terms are used such as *low reading ability*, *poor reading*, *reading difficulties*, and *reading problems* often without clear distinctions among them but sometimes carrying implications about the proposed causes and the likelihood of successful remediation. For the purposes of this article, we use the less theoretically laden term *reading difficulties*, making no assumptions about the causes or the potential for remediation.

Epidemiological research has shown that reading ability and reading difficulties occur on a continuum (Gilger, Borecki, Smith, DeFries, & Pennington, 1996; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992; Shaywitz & Shaywitz, 2005). Typically achieving readers and poor readers tend to maintain their relative positions along this continuum over time (Felton, Naylor, & Wood, 1990; Francis, Shaywitz, Stuebing, Shaywitz, & Fletcher, 1996; Kwiatkowska-White, Kirby, & Lee, 2016). Children with severe reading difficulties continue to struggle in reading as they mature, demonstrating that at least some reading difficulties are persistent and chronic conditions (Shaywitz &



Shaywitz, 2005). Children with reading difficulties are less likely to graduate from high school and are at a greater risk for future unemployment, underemployment, and incarceration (Grigorenko, 2006; Humphrey & Mullins, 2002; Norton & Wolf, 2012; Snow et al., 1998; Svensson, Lundberg, & Jacobson, 2001). Therefore, providing appropriate and early interventions to these children is essential to their future outcomes and can change their overall trajectories (Norton & Wolf, 2012; Snow et al., 1998; Vellutino, Scanlon, & Tanzman, 1998). However, developing effective intervention methods requires diagnostic assessment, which in turn requires understanding the underlying nature of these reading difficulties.

Despite generations of research investigating the causes of reading difficulties, it is still unclear how or why some individuals develop them, and whether there are subgroups of children with reading difficulties due to distinct causal factors. Successful reading has many components, ranging from oral language skills to word reading and reading comprehension strategies. Due to this multicomponential nature, deficits in any subsystem may result in reading difficulties, and strengths in some subsystems may compensate for weaknesses in others. Furthermore, individuals may have deficits in single or multiple components or may be unable to integrate information across subprocesses.

Whereas educational practice and theory focus on reading behavior and attempt to explain that behavior in terms of instructional methods, cognitive theories endeavor to explain that behavior in terms of covert psychological processes, and neuroscience aims to provide neurophysiological evidence on the validity of those processes. Each field has investigated reading but usually without paying attention to developments in both these other fields. Education and cognition have strong links, as do cognition and neuroscience, but education and neuroscience make little contact (cf. Bruer, 1997). We suggest that integrating findings *across* fields offers the promise of transformative change in understanding reading development and reading difficulties.

Our goal is not to reduce education to neuroscience, or to eliminate the contributions of any field. Each field makes its contributions: Neuroimaging and lesion studies advance and validate cognitive models, cognitive models provide a foundation for guiding instruction and the investigation of the brain bases of reading, and educational theories identify key aspects of reading and indicate how instruction affects reading acquisition. Bridging the gaps among the neural, cognitive, and educational accounts of reading should lead to a collaborative network among these disciplines that will generate the multidisciplinary research needed to test and integrate the different approaches, with the potential of leading to improved practice.

One of the challenges of bridging the gaps among the fields, and a good illustration of the separation among them, is choosing a task or set of tasks on which to base the

integration. Some educators might resist choosing a single task, or they might choose one that would be impossible to model given all the unconstrained variables (e.g., reading a novel for pleasure). Neuroscience requires a controlled environment if the neural underpinnings are to be investigated. Although word reading is a key central component in most theories of reading development and reading difficulties (Kirby & Savage, 2008; Perfetti & Stafura, 2014), we did not choose it due to the complexity of the processes that are involved. Instead, we chose to focus on naming speed (NS) tasks as the basis for this review. In NS tasks, participants are required to name a set of simple stimuli (letters, digits, colors, or objects) as quickly and accurately as possible. NS performance predicts many aspects of concurrent and future reading ability (word reading and text comprehension, accuracy and fluency) in typically developing readers and those with reading difficulties (Kirby, Georgiou, Martinussen, & Parrila, 2010; Norton & Wolf, 2012). We chose NS tasks for several reasons. First, they provide a better experimental control and a more simplified example of certain processes that are necessary during reading than actual reading tasks. Second, there is continuing disagreement about the mechanism by which NS relates to reading (e.g., Kirby et al., 2010), so examining NS may clarify this. Third, as we argue later, NS tasks activate the neural network involved in reading (and have been described as a “microcosm” of reading; Wolf & Bowers, 1999). We acknowledge that NS is only one of many possible tasks to study and that not all children with reading difficulties demonstrate poor NS performance. We see NS as a starting point, and as a convenient and useful basis for beginning to bridge the gaps among the fields of neuroscience, cognition, and education.

From Neural Function to Educational Practice

Despite advances in understanding the neurodevelopment and neural processes that are involved during reading, they have yet to influence educational practices or be translated into specific applications for educational settings (Bowers, 2016; Goswami, 2006; Stringer & Tommerdahl, 2015). This is because our knowledge and understanding of these neural processes are still in its infancy and currently cannot be linked to educational practice in a direct and meaningful way (Bruer, 1997). More research needs to be conducted to further understand reading processes in typically achieving readers before researchers can determine how these processes differ among children with reading difficulties, and then develop specific interventions and/or educational practices to target these difficulties (Hruby & Goswami, 2011).

It may also be impossible, or at least very difficult, to translate neuroscience findings directly into educational practice (Bowers, 2016). Not only do neuroscientists and educators speak different languages and rely upon very

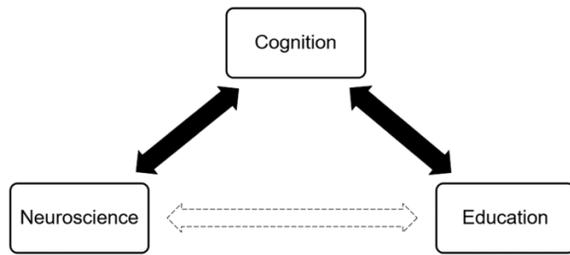


FIGURE 1. *General framework that bridges the current gap among the neural, cognitive, and educational accounts of reading. This figure portrays the current established bridges that cognitive science individually shares with neuroscience and education (black arrows) and the tenuous bridge between neuroscience and education (dotted arrow). This framework will lead to a collaborative network among these disciplines that jointly illuminates processes and problems.*

different knowledge bases, but they also have fundamentally different approaches to studying topics such as reading (e.g., Stanovich, 2003). Whereas educators tend to view reading somewhat holistically, resisting its reduction into a set of subskills, neuroscientists study very explicit and simple subskills. With these differences in mind, two decades ago, Bruer (1997) described the link between neuroscience and education as a “bridge too far.”

Today the link between these two fields is more credible (Goswami, 2006), but still weaker and less traveled than those between cognition and education and between cognition and neuroscience (Figure 1). The bridge between cognition and education has already led to elaborate models of educationally relevant tasks, for instance in literacy and numeracy, and cognitive psychology has already developed and contributed to a number of effective instructional tools and teaching packages (Stringer & Tommerdahl, 2015). These programs range from those that target specific processes, such as temporal auditory processing in children who may be at risk for developing learning disabilities (Merzenich et al., 1996), to programs that help build basic mathematical skills, such as Number Worlds (Griffen, 2003).

Neuroscientists in turn are also well connected with cognitive psychology. They explore the neural structures and neural circuitry that are involved in various cognitive processes, and these increasingly are used to describe models of reading (Hruby & Goswami, 2011; Paulesu, Danelli, & Berlinger, 2014; Shaywitz et al., 2006). For example, neuroimaging has allowed researchers to quantify the neural differences between average readers and readers with dyslexia (Norton, Beach, & Gabrieli, 2015) and examine how NS tasks are related to reading (e.g., Cummine, Chouinard, Szepesvari, & Georgiou, 2015; Misra, Katzir, Wolf, & Poldrack, 2004).

Due to the complexity of reading and the processes that are involved, neuroscience, cognitive psychology, and education

each have mutually supportive roles in further understanding reading and the underlying causes of reading difficulties. For example, cognitive models can (a) help educators cross-reference their theories with subskills that play roles in comprehensive models of reading (Hoeft et al., 2007; Perfetti & Stafura, 2014) and (b) demonstrate to them the importance of basic or lower-level processes (e.g., phonological awareness, NS). Neuroscientists in turn can make use of those cognitive models to select key subskills to investigate. Educators can study the importance of higher-level processes, such as strategies and deeper processing (e.g., McNamara & Magliano, 2009), which may pose interesting challenges for the others to model. Reducing the complexity of these processes to a single level of analysis is inefficient when trying to develop effective and appropriate educational practices (Hruby & Goswami, 2011).

Incorporating cognitive psychology with neuroimaging techniques, under the guidance of educational theories, can further the understanding of learning and instruction, and may lead to the identification of the neural signatures of reading difficulties that may be hidden from view earlier in development (Goswami, 2006). For example, neuroimaging researchers have begun to identify biomarkers that have complemented or enhanced current behavioral measures when predicting future reading outcomes (e.g., Bach, Richardson, Brandeis, Martin, & Brem, 2013; Hoeft et al., 2011; Myers et al., 2014). The integration of research and findings across fields should lead to progress in understanding the underlying nature of reading difficulties and may support the development of personalized intervention programs that target individual reading deficits. In this review, we relate aspects of the neuroscientific, cognitive, and educational accounts of reading by focusing on one subskill of reading, NS. We first discuss the processes that are involved in reading development and the influence of NS on reading outcomes; and then, we examine the link between NS and reading through cognition and neuroscience.

Processes Involved in Reading Development

Reading is undeniably a large topic, covering everything from early letter recognition to the critical analysis and integration of extensive texts. Virtually all reading theories recognize that a key, fundamental component of this process is word reading (Kirby & Savage, 2008), and the basic aspect of most reading difficulties is an inability to read words (Shaywitz & Shaywitz, 2008; Stanovich, 2003). Other reading difficulties are limited specifically to comprehension processes (e.g., Cain & Oakhill, 2007), but these may be general language difficulties and are not our focus here. Without losing sight of the fact that reading goes far beyond word reading, and understanding that word reading is a means to the end of reading comprehension and learning from text, the word reading of typically achieving readers

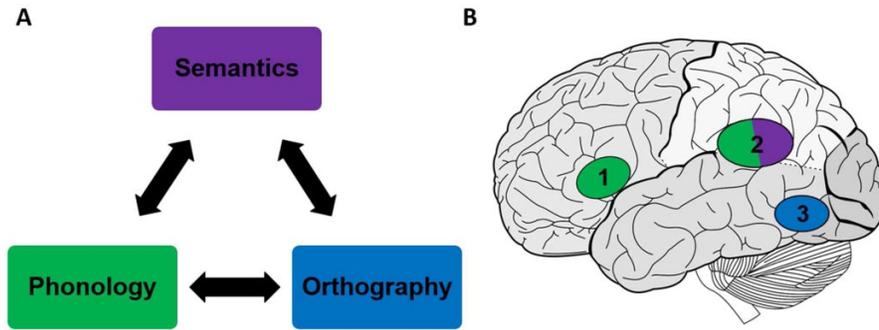


FIGURE 2. *Cognitive and neural models of reading. (A) Connectionist model that serves as a general framework for lexical processing (Seidenberg & McClelland, 1989). (B) The three neural systems of reading in the left hemisphere: (1) anterior system in the left inferior frontal gyrus, or Broca's area; (2) dorsal temporoparietal system involving angular gyrus, supramarginal gyrus, and posterior portions of the superior temporal gyrus; and (3) ventral occipitotemporal system involving portions of the middle temporal gyrus and middle occipital gyrus (Shaywitz, 2003). Brain areas in (B) are colored to indicate the processes in (A).*

and learners with reading difficulties is an important focus of educational and cognitive research. Typically achieving students' word reading is characterized by accurate and fluent word identification (Norton & Wolf, 2012; Vellutino et al., 2004). Accuracy and fluency are important components in the reading process, because inaccurate or disfluent word reading acts as a bottleneck in reading, preventing readers from attaining deeper levels of comprehension (Perfetti & Lesgold, 1979).

Successful word reading development involves the interrelation and integration of phonology (how words sound), orthography (how they appear visually), and semantics (what they mean). This is shown in the connectionist, or triangle, model of reading, illustrated in Figure 2A (Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). Before learning to read, phonology has rich connections with meaning—this is oral language, both expressive and receptive. The fundamental proposal of the connectionist model is that during the initial stages of learning to read a word, the pronunciation of that word is generated by propagating activation from units that process orthographic input to other units that process phonological input, which in turn are connected to units that process meaning. With practice, direct connections develop between orthographic input and meaning units. Therefore, knowledge of words is distributed within this connectionist model and is represented by the connections linking orthography, phonology, and semantics. As this network becomes more automated, word knowledge increases in quality; combined with knowledge of morphology and how to use words in different syntactic and semantic contexts, this automaticity and interconnectedness constitute lexical quality (Kirby & Bowers, in press; Perfetti, 2007). This abstract connectionist model of reading can also be mapped onto the neural systems that are involved during reading (Figure 2B).

Neuroscience has made consistent progress in understanding the neural mechanisms that support reading (Ansari,

De Smedt, & Grabner, 2012), and the neural differences that are associated with reading difficulties (Norton et al., 2015), making use of functional magnetic resonance imaging (fMRI; Shaywitz et al., 2006; Shaywitz & Shaywitz, 2005; Vellutino & Fletcher, 2005) and other imaging techniques. fMRI is a “snapshot” imaging method of the brain that is sensitive to changes in the blood oxygenation level dependent (BOLD) signal that reflects neural activation. During a task such as reading, specific areas of the brain become more activated, leading to an increase in oxygen supplied to these regions. fMRI detects these subtle changes in blood oxygen, providing real-time information about which brain areas are activated or deactivated during task performance (Price & McCrory, 2005). This can then be compared between conditions and/or groups of participants to evaluate the relative magnitudes of their different responses (Frackowiak et al., 2004; Shaywitz et al., 2006).

The majority of the workload for skilled reading in typically achieving readers is performed by a left-hemisphere network of occipitotemporal, temporoparietal, and frontal cortical regions (Figure 2B; Martin, Schurz, Kronbichler, & Richlan, 2015; Norton et al., 2015; Price & Mechelli, 2005; Shaywitz & Shaywitz, 2008). These regions are responsible for translating visual (orthographic) information onto auditory (phonological) and conceptual (semantic) representations (Figure 2A; Pugh et al., 2001; Turkeltaub, Eden, Jones, & Zeffiro, 2002). Visual information is transmitted along the ventral stream occipitotemporal pathway to the mid-fusiform gyrus, also known as the visual word-form area. This region is thought to be responsible for the translation of visual input into orthographic representations. The neural systems that are responsible for translating visual word information into phonological codes and associating meaning with those words are distributed along the dorsal stream pathway that includes the left lateral temporal, inferior parietal, and inferior frontal cortices (Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003).

To become fluent readers, individuals need to be able to move automatically or at least quickly from input to output, that is, from orthography to semantics. This degree of automaticity is reflected in the strengths of each of the linkages in the connectionist model (Figure 2A). These connections become more automatized with increased experience or exposure to words. Automaticity allows developing readers to deal with increasingly large units of text as single units, from individual letters to orthographic and morphological chunks to entire words. This degree of automaticity is reflected in the neurocircuitry of reading; As children become skilled readers, there is an increase in activity in the left-hemisphere network and a gradual decrease in right-hemisphere areas that are involved in visual memory (Turkeltaub et al., 2003). Within this left-hemisphere reading network, more neural activity takes place in the occipitotemporal region of the reading network as children become skilled readers (Figure 2B), which serves for the rapid, automatic, and fluent identification of visually presented words (Norton & Wolf, 2012; Shaywitz et al., 2003). This posterior reading system is functionally disrupted in individuals with reading difficulties and is presumably compensated for by an increased reliance on both inferior frontal regions of the reading network and right-hemisphere posterior regions (Norton et al., 2015; Price & Mechelli, 2005; Pugh et al., 2001; Richlan, 2012; Richlan, Kronbichler, & Wimmer, 2009, 2011; Shaywitz & Shaywitz, 2005). The functional disruption of this posterior system may be one of the key reasons for why readers with severe reading difficulties cannot recognize familiar words rapidly and effortlessly, but the cause of this disruption is not yet clear (Dehaene, Cohen, Sigman, & Vinckier, 2005).

These neuroimaging findings enhance our understanding of an already established psychological model of reading. Therefore, even though these neuroimaging findings do little to directly influence educators in a classroom (Bowers, 2016), this knowledge has expanded our understanding of both the potential underlying etiologies of reading difficulties and the compensatory strategies that are used, and it is making promising advances to help inform current reading research, theories, and policies. As further progress is made by neuroscientists in understanding these underlying processes, this could lead to establishing biomarkers to help identify children who may be at-risk for developing reading difficulties in order to provide them with early assessments and effective interventions.

Deficits in Cognitive Processes Leading to Reading Difficulties

Multiple perceptual, cognitive, and neurological skills have been causally implicated in reading difficulties. The connectionist model of reading proposes that severe word reading difficulties may be due to either poor representations or inefficient connections in any part of the network

connecting orthography, phonology, and semantics (Figure 2A; Rayner & Reichle, 2010). For example, the most widely accepted theory of reading difficulties is the *phonological deficit hypothesis*, which posits a deficit in the consolidation and/or retrieval of phonological or sound-based codes (Snowling, 2000). This phonological deficit is argued to impede the acquisition of alphabetic knowledge and decoding which affects the succession of development in word recognition, fluent reading, and comprehension (Misra et al., 2004). A phonological deficit would interfere with the functioning of the phonology node in Figure 2A.

Another established theory is the *NS deficit hypothesis*: 60% to 75% of individuals with reading difficulties have been found to have impaired timing mechanisms that affect reading fluency (Katzir et al., 2008; Norton & Wolf, 2012; Waber, Wolff, Forbes, & Weiler, 2000; Wolf et al., 2002). NS reflects the automaticity of the entire network in Figure 2A. The following section explains the nature of NS tasks and the ways in which NS is related to reading ability. We focus on NS because it is a network efficiency measure of reading and captures some of the key components of orthographic processing in word recognition, which in turn is the foundation of reading ability.

NS as the Microcosm of Reading

NS tasks were developed based on the hypothesis that rapid naming is both a precursor and concurrent correlate of accurate and efficient reading (Denckla & Rudel, 1976; Kirby, Parrila, & Pfeiffer, 2003). These tasks measure how quickly and accurately participants can name a set of highly familiar stimuli (e.g., letters) randomly presented in a visual array, usually consisting of 50 items in five rows, in a left-to-right, top-to-bottom serial fashion (Figure 3A; Denckla & Rudel, 1976; Kirby et al., 2010; Neuhaus, Foorman, Francis, & Carlson, 2001; Norton & Wolf, 2012; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000).

Studies have found that continuous NS tasks (in which stimuli are presented in a serial list) are stronger and more consistent predictors of reading ability and discriminate task performance between readers with and without reading difficulties compared with discrete NS tasks (in which stimuli are presented individually; Denckla & Cutting, 1999). This indicates that the increased number of processes involved in serial naming tasks, such as visual scanning, saccadic eye movements, and sequencing of multiple items, represent a “microcosm” of the processes required for fluent reading (Wolf & Bowers, 1999). Both tasks require individuals to attend to and identify a stimulus, use the visual information to access stored orthographic and phonological representations, access and retrieve phonological labels, integrate semantic and conceptual information, and then activate the motor regions of the brain to articulate the stimulus (Wolf & Bowers, 1999).

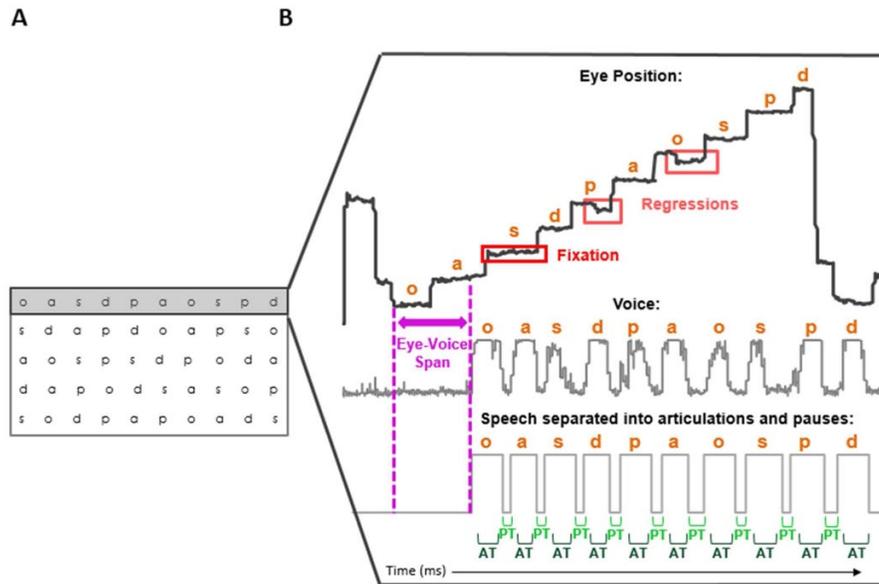


FIGURE 3. (A) Letter naming speed (NS) task (Denckla & Rudel, 1976). During these tasks, participants are instructed to name the letters out loud as quickly and accurately as possible from left to right starting at the top row. (B) Eye movement records and articulations during the first line of a letter NS task for a typically achieving reader in Grade 4. Eye-voice span represents the number of letters that participants' eyes are ahead of the articulation of the first letter in an NS task. AT = articulation time; PT = pause time.

Slow NS performance differentiates between readers with and without reading difficulties (Kirby et al., 2003; Papadopoulos, Georgiou, & Kendeou, 2009). Three hypotheses have been proposed to explain how slow NS contributes to reading difficulties, each of which concerns the orthographic component and its links to the phonological component of the connectionist model (Figure 2A; see Kirby et al., 2010; Norton & Wolf, 2012). First, slow NS prevents the appropriate amalgamation of the connections between phonemes and orthographic patterns in subword and word representations. Second, it limits the quality of orthographic representations in long-term memory, in the sense that lower quality representations are not reliably activated by appropriate input. Third, it increases the amount of practice needed before an orthographic code is learned as a lexical or sublexical unit, and before representations of sufficient quality are achieved. Therefore, if children are slow in identifying individual letters in a NS task, then single letters in a word will not be activated in sufficiently close temporal proximity to allow them to become sensitive to letter patterns that frequently co-occur in print (Wolf et al., 2000).

Wolf and Bowers (1999) proposed that there are multiple subtypes of reading difficulties (dyslexia, in their terms) characterized by the presence or absence of phonological processing deficits, NS deficits, or both. Readers with a double deficit are the most at-risk for developing a reading difficulty and are the most impaired readers (Kirby et al., 2010; Norton & Wolf, 2012; Vellutino et al., 2004; Wolf & Bowers, 1999; Wolf et al., 2002). The independence of phonological

processing and NS is supported by findings that phonological awareness and NS tasks are only moderately correlated in both reading impaired (Cornwall, 1992) and typically achieving samples (Blachman, 1984; about $r = 0.3$), indicating that, even though NS has an influential phonological component needed when retrieving labels of presented items, it is still distinct from phonological awareness and contributes independent variance to reading fluency (Kirby et al., 2003; Kirby et al., 2010; Norton & Wolf, 2012; Swanson, Tainin, Neoechea, & Hammill, 2003). In theory, NS indexes the efficiency of the entire reading network, while phonological awareness assesses the quality of the processing and representations in one node of that network (Figure 2A). This distinction between these two skills has also been found at the neural level in which NS tasks have been found to be related to a distributed network across the four lobes of the brain, whereas phonological decoding tasks have been found to be related to gray matter volume in the left perisylvian cortex (He et al., 2013).

NS has been argued to be an earlier and simpler approximation of the reading process (e.g., Denckla & Cutting, 1999). NS tasks can help identify individuals who may have problems in the future with fluent reading because they assess the foundational subskills needed to develop more complex grapheme-phoneme knowledge (Kirby et al., 2010). However, even though many hypotheses have been proposed, it is still unclear exactly how NS is related to reading and what specific cognitive processes are involved in NS (Georgiou, Parrila, & Kirby, 2006, 2009; Kirby et al., 2010). In the following section, we review recent studies that have

begun to determine which processes tapped by NS tasks are most related to reading.

Studies Linking NS to Reading Through Cognition and Neuroscience

Effects of Stimulus Manipulations

Because NS tasks have both visual and phonological features, several studies have varied the stimulus characteristics to determine if either is more important. Some researchers have argued that NS is fundamentally a phonological task because it assesses how rapidly participants can access phonological codes (Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997), whereas others have argued that NS also assesses the automaticity of recognizing symbolic visual stimuli, thus implicating orthographic processes (Bowers & Newby-Clarke, 2002; Wolf et al., 2000). Increasing the phonological similarity of the stimuli in a letter NS task should negatively affect naming performance if NS is related to reading via phonological processing, and increasing their visual similarity should negatively affect naming performance if NS is related to reading via orthographic processing (Al Dahhan et al., 2014; Al Dahhan, Kirby, Brien, & Munoz, 2016).

Compton (2003) adapted Denckla and Rudel's (1976) letter NS task, which used the letters *a*, *d*, *o*, *p*, and *s*, to test the phonological and orthographic hypotheses among first-grade children with and without reading difficulties (Figure 3A). Compton replaced *o* with *v* in the matrix to make the letters more phonologically similar (because *v* rhymes with *d* and *p*), *o* with *q* in the matrix to make the letters more visually similar (because *q* is visually similar with *d* and *p*), or *o* with *b* in the matrix to make the letters more visually and phonologically similar (because *b* rhymes and is visually similar with *d* and *p*). He found that although the visually similar NS task significantly impaired participants' speed and accuracy, it was the two tasks that increased phonological processing (phonologically similar and visually and phonologically similar tasks) that predicted more unique variance in later word identification skill.

A limitation of these results is that it is not clear whether these differences are due to the fact that most of the participants were at risk of, or already had, a reading disability. Compton's (2003) results may also be affected by the age of the participants. Grade 1 is a period in which phonological processing dominates because children are learning how to read (Georgiou, Parrila, Kirby, & Stephenson, 2008; Kirby et al., 2003), which may explain why Compton found that the phonologically similar task was a better predictor of future reading. However, these results have been supported by studies using other tasks (e.g., Jones, Obregon, Kelly, & Branigan, 2008). English-speaking adults with severe reading difficulties are slower compared with typically achieving readers on NS tasks that increased either visual or

phonological similarity of the letters (Al Dahhan et al., 2014; Jones et al., 2008).

Pause Time and Articulation Time Components of NS

Another series of studies has separated NS times into two components: the articulation times of stimulus names and the pause times between articulations (Figure 3B; Georgiou et al., 2006; Jones et al., 2008; Neuhaus et al., 2001; Norton & Wolf, 2012). Pause times indicate how long individuals need to process a stimulus and prepare a response to name that stimulus (Clarke, Hulme, & Snowling, 2005; Georgiou, et al., 2006; Georgiou, et al., 2009; Kirby et al., 2010), making it a marker for the response preparation aspect of executive control (Li et al., 2009). Articulation times, on the other hand, indicate how automated the pronunciation response is. Pause times, more so than articulation times, have been found to be significantly related to reading ability, and the variability that children show in NS tasks is predominantly due to the average length of pauses and not the average length of articulations (Al Dahhan et al., 2016; Neuhaus et al., 2001). Pause times emphasize the importance of automaticity in the reading network, especially with regard to the activation of the phonological codes from the visual-orthographic areas.

Eye Movements During Letter NS Tasks

Eye movement records are valuable in uncovering the cognitive and perceptual processes of average readers (Hyona & Olson, 1995; Olitsky & Nelson, 2003; Rayner, 1985, 1997; Rayner, Juhasz, & Pollatsek, 2005; Starr & Rayner, 2001). During reading and NS tasks, three primary characteristics occur (Figure 3B). First, there is a series of eye movements, or *saccades*, in which the eyes move very rapidly to fixate from one letter in the display to the next. Second, these saccades are separated by periods in which the eyes are relatively still, called *fixations*, when detailed visual processing occurs. Due to the high velocity of the saccade, no useful visual information is acquired when the eyes are moving; readers only acquire information from text during fixations (Olitsky & Nelson, 2003; Rayner, 1997). Third, 10% to 15% of the time, readers move their eyes backwards in the text to reread material, these are termed *regressions*. Regressions may be due to problems in comprehending the material, hypermetric eye movements, or inference making (Olitsky & Nelson, 2003). For average readers, there is a developmental trend in eye movements: As reading skill increases, fixation duration decreases, average saccade length increases, and the frequency of regressions decreases, all of which are indications of faster information processing (Olitsky & Nelson, 2003). Compared with average readers, readers with reading difficulties make longer and more fixations, saccades with smaller amplitudes, and more regressions (Al Dahhan et al., 2014; Al Dahhan et al., 2016; Olitsky & Nelson, 2003).

Currently, NS tasks are the only assessment tool that directly measures the serial ocular-motor programming required in reading (Kuperman & Van Dyke, 2011). Precise oculomotor control is required in both reading and NS tasks. In both, participants must quickly and accurately inspect and name a series of stimuli arranged in a visual array while repeatedly engaging and disengaging attention from the stimuli as their eyes move through the array. Efficient performance in both requires that the eyes move before naming responses are made, with regressions required if insufficient information has been acquired. Aberrant eye movements and fixations in readers with dyslexia due to visual perceptual and/or oculomotor deficits have been theorized to contribute to reading difficulties (Stein, 2003; Stein & Talcott, 1999; Stein & Walsh, 1997). The magnocellular system is responsible for stabilizing readers' fixations and directing eye movements; thus, impairments to this system lead to unstable fixations and poor control of eye movements. However, this theory has been disputed by researchers who found that magnocellular system abnormalities are a consequence and not a cause of reading difficulties (e.g., Hutzler, Kronbichler, Jacobs, & Wimmer, 2006). Regardless of their ultimate source, deficits in the magnocellular system lead to less-than-optimal information being acquired during fixations, resulting in more regressions that are required to go back and name words that have already been read (Stein, 2003). During NS tasks, this would lead to slower naming times and more errors. Therefore, eye movements during NS tasks could provide clues regarding the relationship between NS and reading. For example, longer fixation durations implicate weaker orthographic processing as the basis of the relationship, whereas an increased number of saccades could implicate difficulties in eye movement control under the speeded conditions of the tasks. A number of studies have analyzed eye movements during NS tasks. Al Dahhan et al. (2014; Al Dahhan et al., 2016) found that typically achieving readers made shorter fixation durations, longer saccades, and fewer fixations and saccades when compared to readers with reading difficulties. Jones, Ashby, and Branigan (2013) found that orthographically similar parafoveal letters increased processing time for participants with reading difficulties, but phonologically similar parafoveal information did not for either typically achieving readers or those with reading difficulties. Similarly, researchers have found that Chinese-speaking children with reading difficulties extracted less parafoveal information than typically achieving readers, indicating that they may allocate more attentional resources mapping visual symbols to orthographic representations during foveal processing (Yan, Pan, Laubrock, Kliegl, & Shu, 2013). This also suggests that translating visual symbols into phonological output may be a less automatic process for those with reading difficulties, reducing their perceptual span and leading to less pre-activation of parafoveal information and more difficulty in processing the next foveal item.

Combining Stimulus Manipulations, NS Components, and Eye Movements

These three approaches of examining NS and the NS-reading relationship were combined by Al Dahhan et al. (2016) using three groups of participants: children with reading difficulties, aged 9–10 years; chronological-age (CA) controls, aged 9–10 years; reading-level (RL) controls, aged 6–7 years, who were reading at the same level as the children with reading difficulties. For all groups, increasing visual similarity of the letters decreased letter naming efficiency and increased naming errors, saccades, regressions, pause times, and fixation durations. Second, children with reading difficulties performed like RL controls and were less efficient, had longer articulation times, pause times, fixation durations, and made more errors and regressions than CA controls. Third, pause time and fixation duration were the most powerful predictors of reading ability and were highly related to each other. The authors concluded that NS is related to reading via fixation durations and pause times, with longer fixation durations and pause times reflecting the greater amount of time needed to acquire visual/orthographic information from stimuli and prepare the correct response.

The finding that children with reading difficulties made longer fixations and pause times and more saccades and regressions than CA controls in NS tasks suggests that they have weaker orthographic processing. This implies that recognizing symbolic visual stimuli (and activating the reading network) may not be an efficient process, and so longer fixations are required to recognize the stimuli in the tasks (Bowers & Newby-Clark, 2002). This would then lead to less fluent naming performance, as shown by the significant negative correlations between pause times and efficiency and between fixation duration and efficiency. However, less fluent naming may also be due to a dispersed allocation of visual attention, which leads to a reduced ability to discriminate a fixated letter from its surrounding information (Whitney & Cornelissen, 2005). This would also be reflected in participants' eye-voice spans (EVS), which evaluate the coordination between eye movements and articulations, during NS tasks. EVS is defined as the distance between the position of the eyes at the beginning of the articulation of a previous letter in an NS task and the position of the letter being named (Figure 3B); typically achieving readers tend to fixate a few words ahead of the word that they are articulating. EVS is an important characteristic of fluent reading, with increases in EVS indicating an increased reliance on parafoveal information, which implies an automatization of reading processes (Buswell, 1922; De Luca, Pontillo, Primativo, Spinelli, & Zoccolotti, 2013).

Pause time and fixation duration during NS tasks may then be capturing important variance associated with rapidly processing serial information, as is required in skilled reading. The multicomponential processes that are required during these tasks may make them more

laborious for readers with reading difficulties, and their poor performance may simply reflect their difficulty in performing tasks simultaneously (Nicolson & Fawcett, 1990). In the same vein, if children with reading difficulties have not automatized the rapid activation and integration of phonological and visual stimuli, then NS tasks may tax limited executive processes to a greater extent compared to typically achieving readers (Wolf & Bowers, 1999). More research is needed to determine the degree to which the ability to integrate the multicomponential processes of reading either causes or contributes to the development of reading difficulties (De Luca et al., 2013).

Studies have also found that participants with reading difficulties have a more parallel distribution of attention in their visual field compared to controls leading to a diffused distribution of attention (Facoetti, Paganoni, & Lorusso, 2000; Geiger, Lettvin, & Fahler, 1994; Lorusso et al., 2004). Both children and adults with reading difficulties have been found to be better at identifying letters presented in their peripheral visual field compared to controls (Geiger et al., 1994), indicating that perceptual analysis of target letters may be disrupted. In other words, they may be less able to suppress peripheral information, leading to a decreased attentional capacity available to process the currently fixated target letter (Figure 3B). Further research is needed to determine to what extent these attentional deficits are driving the difference in performance between CA controls and those with reading difficulties, and how these deficits are related to the longer fixations and more frequent regressions that were found for this latter group (Al Dahhan et al., 2016).

fMRI and NS

These cognitive/behavioral differences between readers with and without reading difficulties leads to the question of whether they are also coupled with differences at the neural level. Researchers have recently begun to use fMRI to investigate both the neural relationship between NS and reading (e.g., Cummine et al., 2015; He et al., 2013; Norton et al., 2014; Turkeltaub et al., 2003) and the neural correlates of NS performance (e.g., Breznitz, 2005; Gonzalez-Gerriod, Gómez-Velázquez, Zarabozo, Ruiz-Villeda, & de la Serna Tuya, 2011; Misra et al., 2004; Wiig et al., 2002). This research has found that neural activation during NS tasks is consistent with areas involved in the reading network (Misra et al., 2004). This network includes regions such as the supramarginal gyrus (grapheme-phoneme mapping; Stoeckel, Gough, Watkins, & Devlin, 2009), cerebellar and motor cortex (motor planning; He et al., 2013), supplementary motor and pre-motor areas (articulation; Alario, Chainay, Lehericy, & Cohen, 2006; Brown et al., 2009), anterior cingulate (speech monitoring; Chang, Kenney, Loucks, Poletto, & Ludlow, 2009; Christoffels, Formisano, & Schiller, 2007; Guenther & Vladusich, 2012), and the

middle temporal gyrus (semantic access; Graves, Desai, Humphries, Seidenberg, & Binder, 2010; Rapsak & Beeson, 2004; Whitney, Kirk, O'Sullivan, Ralph, & Jefferies, 2010). These findings indicate that NS tasks recruit the same network of brain areas that are involved in reading, and target key regions within this network (Figure 2B). However, it is not yet clear whether this pattern of activation is similar or different among readers who have reading difficulties, and whether the activation found in these regions increases or decreases with better NS task performance. This latter point is an important goal for future research because differences in neural activation during a task between typically achieving readers and those with reading difficulties show only a correlation with reading ability, not a causal connection. Linking fMRI with possible reading interventions would be a way to determine a possible causal connection between the improvement of reading ability and neural activation and will lead to further understanding the underlying neurobiological etiology of reading difficulties.

Future Directions

The possibility of using neuroscience findings to influence educational practices or translate into specific applications for educational settings is exciting, but continues to be controversial. On one hand, neuroimaging methods, such as fMRI, allow researchers to analyze the neurodevelopment that occurs during the acquisition of various skills (e.g., reading) that may influence educational practices (Goswami, 2006; Hoeft et al., 2007). On the other, critics argue that neuroscience findings can never replace behavioral data because we care whether a child can read, regardless of what neuroscience data show (Bowers, 2016). We agree that neuroscience data, in the absence of behavioral, (i.e., actual performance) data, can never answer an educational question. However, we see neuroscience and cognitive data and theory playing valuable roles, for example, in the early assessment of risk factors and in the validation of the mechanisms by which remedial interventions are successful. Most importantly, we see neuroscience being able to buttress (or not) conclusions from cognitive and educational studies: Neuroscience's value is not in providing an answer all by itself to an educational question, but rather in supplying different evidence in support of (or against) answers from the other fields. Neuroscience has the potential to help educators understand development, disabilities, and interventions better. For example, Hoeft et al. (2007) found that neuroimaging measures and behavioral tests individually predicted decoding skill after a year of school, but the combination of these measures was a significantly better predictor than either measure alone. This indicates that neuroimaging measures are assessing neural functions and processes that are important for reading but which are not completely captured by behavioral assessments.

However, for neuroscience to be able to contribute to the remediation and/or identification of individuals with or at risk for developing reading difficulties, a number of steps need to be taken. In terms of research, we need more precision about the neural circuits involved, more clarity about the causal sequences, and longitudinal studies of both typically achieving students and those who have received remedial instruction. It is also important to study ways to apply this knowledge. For example, so far, attempts to alleviate the effects of slow NS have not been successful (Kirby et al., 2010). Deeper understanding of the NS-reading relationship may lead to instructional advances, and neuroscientific data may help validate those methods of instruction.

Analyzing the eye movements and neural correlates involved during tasks such as NS will advance the knowledge of the neural circuitry that is involved, and will shed light on how this involvement changes during reading development and following intervention for children with reading difficulties. To further understand the NS-reading relationship, longitudinal studies incorporating eye tracking and neuroimaging should be conducted, starting before formal reading instruction begins. This is important because it is not clear whether the neural differences found between average readers and readers with reading difficulties are due to consequences of the reading difficulty or are merely associated with the underlying etiology of reading difficulties (Norton et al., 2015). Therefore, following children from the pre-literacy stage to the early stages of literacy would allow investigation of the causal relationships of NS with both concurrent and subsequent reading ability (Cobbold, Passenger, & Terrell, 2003) and with the automatization of the reading network. Such longitudinal studies will lead to a more complete understanding of the causal sequence of cognitive processes that are involved in the NS-reading relationship, and how deficits occur within these processes. There are several possible underlying sequences. For example, NS may be only a distal predictor of reading, generally related to cognitive functioning through general cognitive speed but not specific to reading (Breznitz, 2006). Alternatively, the NS-reading relationship may be mediated by orthographic learning or orthographic knowledge (Georgiou, Parrila, & Papadopoulos, in press) and be related to the establishment of an efficient reading network, or it may be mediated by the executive functions needed to coordinate the complex processes of articulating one stimulus while processing another and fixating upon a third. These distinctions are important in designing remediation programs for individuals with NS deficits. If NS is merely a distal predictor of reading, then it may be valuable in identifying only those at risk for reading difficulties. If instead there are mediating factors, and if NS itself is difficult to improve, then remediation may be more productively directed at those mediators (Kirby et al., 2010).

Studies that assess children before and after interventions will help researchers validate specific interventions,

determine their long-term impact, and increase the understanding of what the intervention is accomplishing both cognitively and neurally (Shaywitz & Shaywitz, 2008). This line of research will also further the understanding of how those with reading difficulties compensate for their problems. For typically achieving readers, activation in the left occipitotemporal region correlates with activation in the left inferior frontal gyrus during reading (Figure 2B; Shaywitz et al., 2006). However, for readers with severe reading difficulties, left occipitotemporal activation correlates with right prefrontal activation, which is associated with memory (Shaywitz et al., 2006). This leads to the intriguing hypothesis that those with reading deficits rely on memory to compensate for their reading difficulties, rather than activating the left hemisphere network that supports skilled reading (see Figure 2). It is important to analyze whether this same pattern of activation exists during NS tasks or if there are additional or fewer regions involved. Therefore, such neuroimaging studies could generate hypotheses for future intervention programs targeting specific reading processes and strengthen the current tenuous bridge between neuroscience and education (Figure 1).

Combining neuroimaging and eye movement recordings to assess performance during NS tasks may be a first step in translating current advances in neuroscience into specific applications in educational settings, either by identifying new remedial targets or by helping select among several remedial options. Incorporating these two research tools is important because they allow researchers to understand the underlying neurological bases of reading difficulties. However, fMRI is currently not at a stage in which researchers can identify a specific neural region as a potential problem for individuals with reading difficulties. Furthermore, due to the costs that are involved in using fMRI, it is not a practical tool for literacy assessments (Hruby & Goswami, 2011). Eye tracking, however, can be utilized for assessment and to identify specific biomarkers. The measurement of eye movements is also ideal because the brain regions that are involved in eye movement control are well characterized through numerous lesion, electrophysiology, and fMRI studies. The recent development of computational models of eye movement control also provides rigorous theoretical frameworks for analyzing how the perceptual, cognitive, and oculomotor systems that support skilled reading gives rise to the patterns of eye movements that are observed during reading (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005; Reichle et al., 2013; Reilly & Radach, 2006). Therefore, analyzing eye movements and NS components during NS tasks early in reading acquisition might identify early warning signs in children who are at risk for developing reading difficulties (Goswami, 2009; Rayner, 1997). However, there is not yet a study that tests whether eye tracking by itself or in combination with other behavioral measures improves identification

and diagnosis of children with reading difficulties, i.e., a study equivalent to that of Hoeft et al. (2007) with fMRI.

Combining NS tasks and eye movements to evaluate reading ability is an achievable goal because most children currently have an eye test done before entering school, and in some jurisdictions, this is mandatory. These NS tasks are not very different from the standard eye tests that optometrists use to assess eyesight; They take only a few minutes to administer, and they require only modest training to administer and score. Assessing NS would be important for clinical and educational purposes and for multiple reasons. From a clinical or diagnostic standpoint, multiple longitudinal studies have shown that along with vocabulary, phonological skills, letter name, and letter sound knowledge, NS is one of the most robust early predictors of reading difficulties (Norton & Wolf, 2012). Examiners could determine how children's NS performance compares with age or grade norms, to help identify children who may be at risk for developing a NS deficit which may lead to future problems in fluent reading and comprehension (Wolf et al., 2002).

From an educational standpoint, speed and accuracy are two essential components of reading ability. Typically, English language researchers have only assessed accuracy as a measure for reading, because accuracy by itself yields a great deal of variation. However, many studies have shown that some accurate readers are not fluent readers, and have a hidden speed deficit which is not typically identified until later in school (Breznitz, 2006). This indicates the importance of reading assessments that take into account both speed and accuracy (Norton & Wolf, 2012). Therefore, combining behavioral and neuroimaging measures leads to the possibility of identifying some reading difficulties that may be hidden from view earlier in development.

Conclusion

Interdisciplinary and collaborative research among neuroscience, cognition, and education offers the greatest potential for understanding the underlying causes of reading difficulties and for providing early and efficient interventions. Combining neuroimaging techniques with eye tracking recordings will allow researchers to analyze how learning and instruction alter neural circuitry and neural processes, and how these processes may be different between typically achieving readers and those with reading difficulties. Due to the large number of children and adults who experience reading difficulties, one of the greatest hopes for educational findings from the field of neuroscience is to find more effective ways to screen for individuals who may be at risk for developing reading difficulties, and to develop effective educational support for them (Tommerdahl, 2010). The link between neuroscience and education should not be a unidirectional one in which educators are simply the recipients of information that has been generated by neuroscientists (Figure 1). To the contrary, these links

between disciplines should be bidirectional and inform each other about children's development and learning, and the teaching they require.

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