Rapid Automatized Naming (RAN) and Reading Fluency: Implications for Understanding and Treatment of Reading Disabilities

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Abstract

Fluent reading depends on a complex set of cognitive processes that must work together in perfect concert. Rapid automatized naming (RAN) tasks provide insight into this system, acting as a microcosm of the processes involved in reading. In this review, we examine both RAN and reading fluency and how each has shaped our understanding of reading disabilities. We explore the research that led to our current understanding of the relationships between RAN and reading and what makes RAN unique as a cognitive measure. We explore how the automaticity that supports RAN affects reading across development, reading abilities, and languages, and the biological bases of these processes. Finally, we bring these converging areas of knowledge together by examining what the collective studies of RAN and reading fluency contribute to our goals of creating optimal assessments and interventions that help every child become a fluent, comprehending reader.

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INTRODUCTION AND OVERVIEW

Reading has been compared to rocket science and to conducting a symphony, yet we expect children to have mastered this deeply sophisticated set of skills by the age of seven. Literacy has become so deep-rooted in our culture that we often take for granted the complex cognitive abilities that are required to read effortlessly in so many contexts, from sharing a Dr. Seuss story with a child to enjoying a favorite novel via an e-reader on a busy train. Perhaps the most remarkable thing about reading is that children develop reading skills seemingly in spite of nature. Reading began so recently in the evolutionary history of our species that we have no innate biological processes devoted specifically to reading.

Rather, children are born with a rich neural architecture in place to support the acquisition of oral language, which provides the pre-eminent platform for written language. Certain brain areas are activated in response to the sounds and structure of language from infancy (Minagawa-Kawai et al. 2011, Peña et al. 2003). In sharp contrast, each child must develop reading skills using brain areas that have evolved for other purposes, such as language, vision, and attention (see Dehaene 2009). Psychologist Steven Pinker (1997) famously noted that children are born "wired" for language, "but print is an optional accessory that must be painstakingly bolted on." Indeed, to be a successful reader, one must rapidly integrate a vast circuit of brain areas with both great accuracy and remarkable speed. This "reading circuit" is composed of neural systems that support every level of language—phonology, morphology, syntax, and semantics—as well as visual and orthographic processes, working memory, attention, motor movements, and higher-level comprehension and cognition. As our reading abilities develop, each of these components works smoothly with both accuracy and speed; the reader develops what is called automaticity. As a cognitive process becomes automatic, it demands less conscious effort. Although at first the child experiences a laborious and slow process to decode a simple word or sentence, most adult readers can't help but instantaneously, effortlessly read almost any word they perceive. The development of automaticity at all the lower levels of reading represents the great apex of development that provides us with the bridge to true reading with its capacity to direct cognitive resources to the deepest levels of thought and comprehension.

When a child begins learning to read, many assume that to accurately decode each word of a simple story aloud represents reading. In reality, simply to translate printed words into a stream of speech is but the beginning step, however necessary, of reading. Indeed, even the initial comprehension that comes next is but a second necessary step. Essentially, one must be able to comprehend the meaning of a text in order to go beyond what is on the page: making connections to existing knowledge, analyzing the writer's argument, and predicting the next twist in the story. It is here that the way we define successful reading is important. The term "fluency" has been used to describe the speed and quality of oral reading, often emphasizing prosody, yet this definition does not encompass all the goals of reading or reflect the fact that most of our reading is done silently rather than aloud. We conceptualize fluency in a more comprehensive way. In this review, we examine reading fluency in the sense of what has been called "fluent comprehension": a manner of reading in which all sublexical units, words, and connected text and all the perceptual, linguistic, and cognitive processes involved in each level are processed accurately and automatically so that sufficient time and resources can be allocated to comprehension and deeper thought (Wolf & Katzir-Cohen 2001).

This is a figure-ground shift from conceptualizing fluency based largely on rapid word identification. How did we arrive at this more encompassing conceptualization of fluency, and why is it important that educators and researchers view reading in this way? This multicomponential view of reading is based largely on our understanding of the reading circuit in the brain. Additional research from many sources, including longitudinal, intervention, and cross-linguistic studies, supports this multicomponential model of reading. However, many current approaches to reading instruction, as well as methods for identifying children who are having reading difficulties or for providing intervention struggling readers, do not reflect this more comprehensive view. If our goal is to have children develop fluent comprehension, then our instruction, assessment, and intervention must reflect these ideas.

A closely related aspect of our study that has contributed greatly, albeit unexpectedly, to our understanding of reading fluency involves what is called rapid automatized naming, or RAN (Denckla & Rudel 1976b). The seemingly simple task of naming a series of familiar items as quickly as possible appears to invoke a microcosm of the later developing, more elaborated reading circuit. Our ability to understand the multicomponential structure of RAN, therefore, has helped us to reconceptualize the later development of reading fluency, not as the simple consequence of accurate word recognition processes, but as an equally complex circuitry of multiple components, all of which contribute to the overall reading fluency and comprehension of text.

To be sure, the precise relationship between RAN and reading continues to elude researchers, many of whom have sought to study and single out individual components of RAN, such as visual or phonological processes. We have taken a different view, in which RAN is conceptualized as a microcosm or mini-circuit of the later-developing reading circuitry. There is an extensive body of research (described in this review) that leads us and other researchers to consider RAN tasks as one of the best, perhaps universal, predictors of reading fluency across all known orthographies (Georgiou et al. 2008b, Tan et al. 2005). Within this view, RAN tasks and reading are seen to require many of the same processes, from eye saccades to working memory to the connecting of orthographic and phonological representations. Equally importantly, RAN tasks depend on automaticity within and across each individual component in the naming circuit. It is within this context that Eden, Perfetti, and their colleagues refer to RAN as one of the universal processes that predict the young child's later ability to connect and automatize whole sequences of letters and words with their linguistic information, regardless of writing system (Tan et al. 2005). We consider the ability to automate both the individual linguistic and perceptual components and the connections among them in visually presented serial tasks the major reason why RAN consistently predicts later reading.

The advancement of our knowledge of both RAN and reading fluency has led us to a point where we have the capacity to make great improvements in our ability to identify children with reading difficulties early on and to provide appropriate, effective intervention. Many children develop accurate decoding with basic instruction and then achieve automaticity with time and practice. However, approximately 10% of children in the United States have developmental dyslexia, defined as unexpected difficulty learning to read despite adequate instruction, intelligence, and effort (Lyon et al. 2003). There is no single test and no absolute criteria for diagnosing dyslexia. This is in part due to the fact that there are so many processes in reading that can break down to cause reading failure. Inaccuracy at any level of language or processing or a lack of automaticity in connecting any of these circuits can lead to poor reading. More than 100 years of research into developmental reading difficulties has yet to reveal anything resembling one single explanation for all the symptoms of dyslexia, yet such pursuits continue unabated today.

Given the multicomponential nature of reading, we begin with the premise that dyslexia is not a simple thing. Taking the view that dyslexia is a heterogeneous disorder reflecting difficulty with reading due to any number of sources is essential for successfully identifying and remediating reading disabilities in children. For too many years, schools have waited for children to "grow up a bit" so that the reading troubles will disappear with time, or intervention has been provided that was insensitive to the individual child's profile of strengths and weaknesses. These two mindsets can be deeply detrimental because the consequences of having unremediated reading difficulties can be severe and life-long. Children with dyslexia not only show poorer academic performance, but also socioemotional and behavioral effects such as lower self-esteem and higher rates of entry in to the juvenile justice system (Grigorenko 2006, Humphrey & Mullins 2002, Svensson et al. 2001).

Our potential to ameliorate these outcomes, on the other hand, is significant. Research shows that accurate early identification and appropriate targeted intervention improve reading ability as well as the other potential negative effects associated with dyslexia (Foorman et al. 1997, Vellutino et al. 1998). Thus, it has become crucial to identify dyslexia early and to characterize the precise strengths and vulnerabilities of each child individually so that targeted intervention can be provided to develop accuracy and then automaticity of each aspect of the reading system. If risk for reading difficulties can be determined very early, the chances to improve reading skills are greater. RAN tasks have proven of great potential because children can perform RAN tasks, naming familiar objects or colors, well before they are able to read and because RAN is correlated with reading ability in kindergarten and beyond. Indeed, research on longitudinal predictors of reading has repeatedly shown that RAN is one of the strongest predictors of later reading ability, and particularly for reading fluency.

A BRIEF HISTORY OF RESEARCH ON READING DISABILITIES, RAN, AND FLUENCY

Early Research on Reading Difficulties

Reading difficulties can be classified into two main types: developmental and acquired. Developmental dyslexia affects a person beginning in childhood and makes learning to read and developing reading skills difficult. On the other hand, acquired reading difficulties, usually called alexia, often result from a brain trauma such as an injury or stroke. Although today we recognize these as unique disorders that have different causes, symptoms, and optimal treatments, this was not always the case.

The first medical reports of people with unexpected and specific difficulties with reading were published in Europe in the late 1800s (for a review of this history, see Hallahan & Mercer 2002). Physicians including Jules Dejerine and Adolf Kussmaul described patients who suffered brain injury with subsequent difficulty with reading despite intact language and vision: thus the first term for the condition—"word-blindness." John Hinshelwood and W. Pringle Morgan were among the first to describe "congenital word blindness," that is, difficulty reading beginning in childhood and not due to injury (Hallahan & Mercer 2002).

Subsequent significant work on developmental dyslexia was undertaken by Samuel Orton, a neurologist in the United States. After studying many children with reading difficulties, Orton developed a theory in which inappropriate cerebral dominance accounted for the reversed letters and words sometimes seen in children with reading difficulties (Orton 1925). Orton made several important observations that influence our understanding and treatment of dyslexia today: he noted that many of the struggling readers he saw had average or above-average intellectual abilities; that perhaps as many as 10% of children might suffer from reading difficulties; and that reading difficulties were not likely due to a single brain abnormality. The latter conclusion was based on the premise that the very complexity of reading would require the integration of several brain areas (Orton 1925, 1939). The next major advances in our understanding of reading disabilities would come from two separate theories of the core deficit(s) in dyslexia: rapid automatized naming ability and phonological awareness.

Development of RAN Tasks

In the 1960s, neurologist Norman Geschwind studied various cases of individuals with alexia to determine both what kind of brain damage led to their reading difficulties and exactly what aspects of reading were affected. Based in part on the foundation of Dejerine's earlier findings as well as Wernicke's notions of connections among cerebral areas, Geschwind's (1965) paper "Disconnexion Syndromes in Animals and Man" conceptualized the core deficit in alexia as a disconnection between the visual and verbal processes in the brain. In so doing, like Wernicke before him, Geschwind emphasized the importance of connectivity among brain regions, particularly "association areas," such as the angular gyrus, which act as a switchboard or relay station for different brain regions.

Geschwind also reported the case of a patient with alexia who also experienced great difficulty with naming colors despite the ability to perceive colors accurately (Geschwind & Fusillo 1966). Geschwind was interested in the slow and effortful processing required for this individual to come up with the names of colors, and he devised a timed test of color naming.

This measure was based on an array of 50 colored squares arranged in a grid with five rows, where each of five familiar colors was repeated in random order. Geschwind suggested that the deficit in color naming displayed by this patient might also be due to loss of visual-auditory connections. He further speculated that "congenital dyslexia," what we now call developmental dyslexia, might be due to an impairment in the visual-auditory pathways of the brain, especially in the angular gyrus. Geschwind also suggested that "it is conceivable that even the age of attainment of color naming might be a significant clue to the age at which reading can be acquired" (1965, p. 283). Unlike many of the other theories of developmental dyslexia, which focused on the surface level, this idea suggested that there might be a deeper, more abstract ability that supported reading. Geschwind didn't believe that color naming was an aspect of reading, but rather that the neural processes supporting rapid serial color naming might be similar to those involved in reading.

Neurologist Martha Denckla then explored the idea of a relationship between naming and reading, testing boys with reading difficulties on a speeded naming task. As her mentor Geschwind had done with patients, Denckla used an array of 50 colored squares arranged in five rows. Though color-naming ability wasn't considered to be generally impaired in children with dyslexia, in studying color naming in a large group of kindergarteners, Denckla (1972) discovered five boys who had dyslexia and were particularly slow and inconsistent in serial color naming for their age, despite typical intelligence and color vision.

Together with Rita Rudel, Denckla created three other versions of the speeded serial naming test, using objects, letters, and numbers as stimuli. They coined the term "rapid automatized naming" to describe these tasks that were designed to measure the speed of naming familiar items (1976b). They found that RAN latencies were not related to how early certain stimuli were learned, but instead how "automatized" the naming process was; object names were learned much earlier in development, but elementary school children were faster to name letters and numbers, which were learned later but enjoyed a greater degree of automaticity. They were thoughtful in the design of these tasks, for example, including both the letters "p" and "d," which if not fully automatized were easy to confuse with their mirror-reversed counterparts. They also kept the design and procedure of naming left-to-right across rows, which parallels the motoric and visual processes in reading. These early studies showed that performance on RAN tasks differentiated children with reading difficulties from typical readers of the same age and from children with other, nonlanguage-based learning disabilities (Denckla & Rudel 1976a). In a separate line of research investigating a possible speech-motor encoding deficit in boys with dyslexia, Spring & Capps (1974) had also found similar group differences in serial object, color, and digit naming.

Toward a Multicomponential View of Reading and Reading Disability

Also in the early 1970s, notions of reading fluency were developing in parallel. LaBerge & Samuels (1974) proposed a model of reading that was one of the first to emphasize what we now know as "fluency": the idea that successful reading depends on not only accuracy but automaticity of multiple cognitive and linguistic processes, requiring minimal conscious effort. Similar ideas were presented by Perfetti (1986) in his verbal efficiency theory of reading, where he noted that reading comprehension was associated with accuracy as well as speed of single-word identification.

Another more widely known line of research was unfolding regarding another possible core deficit in dyslexia: difficulty with phonological awareness (PA), which involves the explicit ability to identify and manipulate the sound units that comprise words. Isabelle Liberman promoted the idea that reading development depends on an explicit awareness of the sounds of language and that perhaps the greatest challenge facing young readers is learning to match the phonemes of speech with the graphemes that represent them in print (Liberman 1971). This work was extended to show that children with reading difficulties had trouble with phonological awareness (e.g., Bradley & Bryant 1978, Wagner & Torgesen 1987).

The field generally now agrees that PA is a crucial precursor to reading acquisition in alphabetic languages and that many, if not most, children with dyslexia have PA deficits (Morris et al. 1998, Natl. Inst. Child Health Human Dev. 2000). Though the exact nature of the deficit continues to be specified with some debate about differences across writing systems with more regular orthographies, the fact that phonological deficits can cause reading difficulty has been extensively researched and well accepted. Indeed, many of the most studied and successful reading instruction and intervention programs are centered around this approach.

The fact that a deficit in phonological awareness can cause dyslexia does not mean, however, that a phonological deficit is the single and universal cause of dyslexia, a view espoused by many researchers and clinicians. Many children have difficulty reading despite intact PA and decoding skills. As a result, those children with a reading difficulty not due to phonological awareness and decoding are less likely to be identified as having a reading disability on traditional single-word decoding tests. Further and more importantly, they will be less likely to benefit from standard instruction or intervention that focuses only on phonological deficits. Beginning with research from Orton to Geschwind, and continuing with the increasingly expanding research from neuroimaging, we know that the reading circuit is intrinsically complex and that a lack of accuracy or automaticity at one of any number of levels can cause reading difficulties. Any single-deficit view, however important individually, is at odds with a multicomponential conceptualization of reading.

An understanding of the complexity of the reading circuit and its multiple processes undergirds the efforts by Wolf & Bowers (1999) to move beyond a unidimensional conceptualization of reading disabilities. By studying large samples of children with reading disabilities in the United States and Canada, they found that phonological awareness and RAN contributed separately to reading ability. In an attempt to show the importance of both sets of processes, Wolf & Bowers (1999) proposed the double deficit hypothesis (DDH) as a way to show how children can be characterized in various subgroups according to their performances on each set of processes. According to this hypothesis, a deficit in either phonological awareness or naming speed (as measured by RAN tasks) can cause reading difficulties, with RAN deficits indicating weakness in one or more of the underlying fluency-related processes, not simply a naming speed deficit. In addition, these deficits can co-occur, and children with a double deficit in PA and RAN characterize the most severely impaired readers. Wolf and Bowers developed the DDH as a first step toward a multidimensional understanding of reading difficulties, intending it to promote further research and discussion on the variety of impairments that can cause developmental dyslexia. Researchers around the world have taken up this challenge; both the DDH and the relationship between rapid naming and reading have been studied extensively over the past decade. These studies have suggested that 60% to 75% of individuals with reading or learning disabilities exhibit RAN deficits (Katzir et al. 2008, Waber et al. 2004, Wolf et al. 2002).

DEFINING THE RAN TASKS

Basic Structure of RAN Tasks

Most RAN tasks appear very similar to the original tasks developed nearly 40 years ago by Denckla and Rudel. These tasks have been described in the literature using slightly different terms, such as rapid serial naming, serial visual naming, continuous rapid naming, rapid naming, and naming speed. In this review, we use "RAN" to mean generally any rapid automatized naming task or process. Essentially, a task falls into the broader category of a RAN task if it involves timed naming of familiar stimuli presented repeatedly in random order, in left-to-right serial fashion. In some uses of the RAN task, self-corrections and errors are noted for the purposes of qualitative observations, but the key dependent variable is the total time taken to name the items. It is crucial that the items to be named, whether objects, colors, letters, or numbers, are sufficiently familiar to the examinee. For this reason, as in Denckla and Rudel's original studies, most rapid naming tests begin with practice or pretest trials asking examinees to name each of the stimulus items individually to ensure that they are named accurately in isolation.

Published Standardized Measures of RAN

The two most widely used standardized tests of RAN in the United States are the Rapid Automatized Naming-Rapid Alternating Stimulus (RAN-RAS) Tests developed by Denckla and expanded by Wolf & Denckla (2005; published by Pro-Ed), and the rapid naming subtests of the Comprehensive Test of Phonological Processing (CTOPP), by Wagner and colleagues (1999; published by Pro-Ed). The CTOPP uses a briefer format that is considered by its authors to measure phonological retrieval. Both of these measures are standardized and normed on large, nationally representative samples in the United States and have been used in many research studies. A child's raw score on these tests can be used to derive a standard score and percentile rank, which provides information about how the child performed relative to others of the same age or grade level. Self-corrections and errors can be noted for qualitative interpretation but do not factor into the scores. This is not to say that these do not affect the score at all, as errors and corrections are often related to a lack of fluency and, as a result, increase the time it takes to complete the task.

d s a p o s p d a o

s a o d p a d o p s

d a p o a s p s o d

a p s d o d s a p o

p s o p d o a d s a

Figure 1

Rapid automatized naming (RAN) letters stimulus card, in the same format used by Denckla & Rudel (1976b) and Wolf & Denckla (2005).

RAN-RAS Tests. The published RAN-RAS Tests include the four classic subtests used in Denckla and Rudel's original RAN measures: objects, colors, numbers, and letters, as well as two RAS subtests. Each of the RAN-RAS subtests has 50 items arranged in 5 rows of 10 items each. The five different token items for each subtest are pseudorandomized, with no item appearing consecutively on the same line (**Figure 1**). Age- or grade level–based standard scores and percentiles are calculated based on the total naming time (latency) for each subtest. Norms are available for individuals age 5 through 18.

The RAN-RAS tests are unique in their inclusion of rapid alternating stimulus, or RAS subtests. The RAS was first developed in the 1980s by Wolf as a way to incorporate processes involved in switching and disengaging attention to rapid-naming tests (Wolf 1986). The RAS is structured analogously to the RAN, with two or three types of items repeated alternately throughout the card, reflecting the demands of shifting attention and processing between sets of different stimuli. The RAN-RAS Tests include a two-set RAS composed of alternating letters and numbers and a three-set RAS with alternating letters, numbers, and colors.

CTOPP rapid-naming subtests. The authors of the CTOPP conceptualize rapid naming as one of three subcomponents of phonological processing, along with phonological awareness and phonological memory (Wagner et al. 1999). (This view differs from the theoretical viewpoint of the authors of the RAN-RAS Tests and our viewpoint in this review.) The

CTOPP rapid naming subtests measure rapid object, color, digit, and letter naming. The test is normed for individuals ages 5 through 24. For each subtest, there are six token items, and the task is divided into two parts, with the items arranged in two arrays on separate pages. Each of the two arrays includes 4 rows of 9 items, for a total of 72 items. The examiner determines a score by adding the total number of seconds to complete both arrays, and this raw score can be used to determine age- and grade level–based percentiles and standard scores. The CTOPP raw scores can also be used to derive composite scores based on multiple subtests.

Differences. Though the RAN-RAS Tests and CTOPP rapid naming subtests share many similarities, the two measures differ slightly in their format, reflecting different theoretical viewpoints in the field about the relationship of rapid naming to other cognitive processes. The RAN-RAS tests treat rapid naming as a cognitive ability that includes phonology but also other linguistic and visual processes; furthermore, the collective processes underlying RAN are conceptualized as contributing independent variance to the prediction of reading skills, particularly reading fluency. In contrast, the CTOPP was designed on the basis of a model of overall phonological processing that includes phonological awareness, phonological memory, and rapid naming as related subcomponents. These theoretical differences and evidence for a model where naming speed is separate from phonological processes are discussed below.

Other criterion-based measures of naming speed. Several other psychoeducational assessment tests include RAN subtests, such as the Kaufman Test of Educational Achievement-II, Clinical Evaluation of Language Fundamentals-4, and Process Assessment of the Learner; however, in most cases, the RAN measures are not fully normed, and only criterion scores are given (e.g., performance is categorized only as normal versus nonnormal). The Dynamic Indicators of Basic Literacy Skills (DIBELS) contains several "fluency" subtests, including letter-naming fluency, but this test uses all the upper and lowercase letters in one array and scores the number of letters correctly identified in one minute, a procedure that differs significantly from classic RAN tasks.

Subcomponents of the RAN Task

Like reading, performing a RAN task requires a synchronization and integration across a wide range of processes. Wolf and colleagues (Wolf & Bowers 1999, Wolf & Denckla 2005) enumerated seven related processes that are involved in rapid naming:

> (a) attentional processes to the stimulus; (b) bihemispheric visual processes responsible for initial feature detection, visual discrimination, and pattern identification; (c) integration of visual features and pattern information with stored orthographic representations; (d) integration of visual and orthographic information with stored phonological representations; (e) access and retrieval of phonological labels; (f) activation and integration of semantic and conceptual information with all other input; and (g) motoric activation leading to articulation. (Wolf & Denckla 2005, p. 2)

Several factors, such as the exact items to be named and the precise number of rows and columns, have varied between the many experiments that have investigated RAN. Even with deviations from the traditional RAN, the strong relationship with reading seems to be preserved as long as the factors that underlie the theoretical link between RAN and reading are intact, including naming in a serial, left-to-right fashion, and sufficient familiarity of items to be named. For example, an "alternate" version of the RAN used in the Colorado Learning Disabilities Research Project contained 13 rows of 5 items each, with some consecutively repeated items, and in which examinees are instructed to name as many items as possible in 15 seconds. This RAN task showed relationships to reading ability similar to those of a traditional RAN task and actually predicted more of the variance in reading ability than did traditional RAN in slower namers and children whose naming ability was influenced by attention issues (Compton et al. 2002).

In order to investigate which aspects of rapid naming might drive the relationship with reading, researchers have broken down the RAN task into component parts. At the surface level, one can consider the amount of time taken to articulate each item's name versus the amount of time taken for processing between items (often called pause time). Several studies have found that articulation time itself is not strongly associated with reading in the same manner as are overall RAN scores (Clarke et al. 2005, Cutting & Denckla 2001, Georgiou et al. 2006, Neuhaus et al. 2001, Obregon 1994). Instead, it seems that the interitem processing or pause time may reflect the components of RAN that drive their close association with reading. In considering pause and articulation times, Neuhaus and colleagues (2001) found that the two were not strongly related to each other and that pause time, especially on the RAN letters task, predicted both single-word reading and reading comprehension in first- and second-graders. Georgiou and colleagues (2006) found that pause times at the end of kindergarten were significantly correlated with reading accuracy and fluency in first grade. In contrast, Clarke and colleagues (2005) found that pause time was not correlated with reading single words or nonwords, though their sample was small (n = 30), and their RAN measure included many more different token items (10 digits and 25 different letters) than are typically used. Although these findings give us some insight as to how the component parts of RAN relate to reading, the overall RAN time is much easier to measure than pause time and shows similar patterns of correlation with reading outcomes (Georgiou et al. 2006).

Another dimension of the RAN that has been considered in research is the differences between each row of stimuli. Berninger and colleagues (Amtmann et al. 2007) examined changes in time to name each row of stimuli on a standard 50-item RAN task (as in Denckla & Rudel 1976b and the published RAN-RAS tests, Wolf & Denckla 2005). This allowed them to examine various factors related to initiating the task (e.g., retrieval of item names) versus continuously operating processes (such as executive functioning or sustaining item names in working memory). They found that individuals who were slower namers overall tended to take longer to name subsequent rows, whereas row time was more stable in faster namers. The time for the first row was also slower in the overall slower namers. Children with dyslexia were slower to name the first row of stimuli than were slightly younger typically developing readers, suggesting that the slow naming times seen in dyslexia might be related to automaticity of retrieval or a difficulty sustaining processes needed for retrieval.

RAN Differentiated from Similar Tasks

Single-item naming. It has been thought that timed single-item naming and serial naming would be closely related. However, the added demands of serial naming in RAN render it quite different from single-item naming. Across several studies, single-item and serial naming have been found to be only moderately correlated, with correlation coefficients of about 0.5 (see Logan et al. 2009). The added demands associated with the continuous, serial nature of RAN make it a better predictor of reading than is single-item naming (Bowers & Swanson 1991, Meyer et al. 1998). Logan and colleagues showed that single-item naming does explain any variance in reading beyond that of PA and RAN and may even be a suppressor of serial naming (Logan et al. 2009). Further, in their longitudinal analysis from kindergarten through second grade, single-item naming and serial naming speed grew at different rates as children got older, supporting the notion that RAN is not a simple permutation of single-item naming, nor are both governed by an underlying system (as considered in the global processing speed model of explaining RAN, below).

Stroop tasks. Some characteristics of RAN tasks bear resemblance to the classic Stroop color-word interference task developed in the 1930s, in which participants name the color of the ink rather than the name of a printed color word. The Stroop task is designed to take advantage of the relatively greater automaticity for word reading than color naming, requiring the examinee to inhibit reading the word and instead attend to naming the color. Studies of the Stroop task in relation to reading show several patterns of association similar to the RAN and reading (MacLeod 1991). The RAN has been studied more extensively in relation to reading, however, because it removes the extra executive function demands of the Stroop task.

General processing speed. Researchers including Kail & Hall (1994) have argued that RAN should be considered one facet of general or global processing speed. Global processing speed deficits have been associated with other developmental difficulties, including general learning disabilities and attention deficit hyperactivity disorder (Willcutt et al. 2005). The majority of studies using alphanumeric RAN (that is, rapid naming of letters or numbers) find that processing speed does not account for the RAN–reading relationship (though see Catts et al. 2002, who found that nonalphanumeric RAN did not account for variance in reading beyond the contribution of general processing speed). In a large study using structural equation modeling, Powell et al. (2007) found that although children with slower RAN had slightly slower global processing speed than did matched peers, RAN made a significant contribution to reading after processing speed was controlled for. Similarly, Cutting & Denckla (2001) found that in a path analysis, RAN and other reading-related skills contributed to the understanding of word reading after general processing speed was controlled for. Although general processing speed certainly affects both RAN and reading (especially in terms of speed and fluency), these results underscore the ideas of Wolf & Bowers (1999) that RAN builds on the existing architecture for more general speeded processing. The slow naming speed observed in many individuals with dyslexia might occur at a level higher than simple processing speed; for example, it may occur in the connections between visual and speech circuits in the brain.

Independence of RAN and Phonological Awareness

A crucial question for our understanding of reading is the relationship between RAN and phonological awareness. These two constructs have been perhaps the most widely studied and consistently implicated in predicting reading ability. Some controversy has existed in the field regarding whether rapid naming should be considered a subskill related to phonological processing or whether RAN is a separate process and should be so considered. A major argument that has been made for including RAN as a part of a larger phonological construct is that rapid naming tasks depend on the retrieval of phonological codes (e.g., Torgesen et al. 1997). To subsume rapid naming tasks under phonological processing for this reason alone would, however, be inaccurate. Consider tests of vocabulary, where an examinee is asked to name or provide information about a word. These responses require retrieval of phonological information just as rapid naming does, yet a vocabulary task would never be considered a subcomponent of phonology.

At least three areas of research provide evidence against considering RAN as a subset of phonology. These notions are each reviewed in an earlier paper (Wolf et al. 2000), so we summarize previous findings focusing on more recent data that add to these discussions. First, RAN and phonological processing are not strongly correlated. A comprehensive meta-analysis of the relationship of PA and RAN confirms that these two abilities are only moderately correlated, with an overall correlation coefficient of $r = 0.38$ (Swanson et al.

2003), and that these load on separate factors in an exploratory factor analysis. Based on data from the norming of the Comprehensive Test of Phonological Processing (Wagner et al. 1999), the rapid naming components of the test were moderately correlated with phonological awareness and phonological memory, $r = 0.46$ and 0.45, respectively, for children ages 5–6; $r = 0.38$ and 0.38 for ages 7–24. By comparison, the other aspects of phonological processing, PA and phonological memory, were strongly correlated at $r = 0.88$ for ages 5–6 and $r = 0.85$ for ages 7–24.

Second, regression and structural equation models consistently report that RAN and PA account for unique variance in reading ability (e.g., Cutting & Denckla 2001, Katzir et al. 2006). Models that treated RAN as a separate latent variable from phonological awareness and memory provided a better fit to the data, and confirmatory factor analysis studies suggest that different underlying factors support RAN and PA (Powell et al. 2007). These relationships may change somewhat with age; Wagner and colleagues (1997) found that RAN contributed to the variance in reading skill after PA was controlled for only until third grade (although measures in subsequent grades in their longitudinal study controlled for earlier reading ability, which depends on RAN). Furthermore, RAN varies independently from several potential sources of covariance with phonology. In a recent review, Kirby and colleagues (2010) point out that RAN retains its relationship with reading even after a host of possible explanatory factors have been accounted for. These include verbal and nonverbal IQ, prior reading ability, attention deficit disorder, socioeconomic status, articulation rate, speed of processing, phonological short-term memory, morphological awareness, and orthographic processing (see Kirby et al. 2010 for references).

Third, genetic and neuroimaging studies find different biological bases for RAN and PA abilities. In the past decade, substantial advancements have occurred in this area, allowing us to identify the genetic and neural underpinnings of these abilities. Though research has yet to directly compare RAN with phonological tasks, functional brain imaging studies of the two tasks show some shared regions, as would be expected with their similar task demands, yet also separate areas of processing. These studies are discussed further in the section titled Contributions of Neuroscience and Genetics to Understanding RAN and Fluency.

CHARACTERISTICS AND PREDICTIVE VALUE OF RAN ACROSS DEVELOPMENT

RAN and phonological processing tasks are valuable tools because both are excellent predictors of reading ability that can be assessed before children learn to read and thus can be used as early indicators of risk for reading difficulties. Published measures of RAN are normed to provide standard scores and percentile ranks for children beginning at age 5 years. Importantly, most 5-year-old children in the United States are very familiar with the common objects and colors presented on rapid naming tests, yet many are still learning the numbers and alphabet. As a result, 5- and 6-year-olds often name the color and object stimuli more quickly than letters and numbers. With more practice and exposure to letters and numbers, the alphanumeric stimuli become much more automatic. At this point, alphanumeric stimuli are named faster and alphanumeric RAN becomes more strongly associated with reading ability (Meyer et al. 1998, Wolf et al. 1986). These differences underscore the importance of considering alphanumeric RAN separately from nonalphanumeric RAN stimuli. It is also important to consider the predictive ability of RAN across groups, as research suggests that its predictive value may be different for poor than for typical readers. The study design and type of reading outcome may affect these findings, as research studies have found that RAN–reading relationships are stronger in poor than in typical readers (Frijters et al. 2011, Meyer et al. 1998, Scarborough 1998).

Prediction in Kindergarteners and Prereaders

Several longitudinal studies have examined early predictors of later reading abilities. Understanding these factors is extremely important because our ability to understand which measures predict later reading scores directly informs our ability to identify reading difficulties as early as possible. The overarching goal is to use this information to inform what would be the most effective intervention for a particular profile. To date, our ability to correctly identify which children will go on to have dyslexia based on kindergarten data has been insufficient, lacking both sensitivity and specificity.

Although different studies have used different assessments, the measures that most consistently predict future reading difficulty in English are phonological processing/awareness, letter-name knowledge, and RAN (Pennington & Lefly 2001, Scarborough 1998, Schatschneider et al. 2004). In perhaps the largest study of kindergarten prediction of later reading abilities, Schatschneider and colleagues (2004) assessed typically developing children at four points throughout kindergarten and followed them through second grade. Measures of RAN objects and PA in the fall of kindergarten showed similar correlations with second-grade outcomes on untimed passage comprehension (both $r = 0.36$). However, as seen in earlier work (Bowers & Swanson 1991), RAN was more highly correlated ($r = 0.55$) than PA ($r = 0.35$) to timed measures of single-word and nonword reading in second grade. The authors also performed dominance analysis to see which variables contributed more substantially to explaining variance in the outcomes. Here, RAN letters scores in the fall and spring of kindergarten was a more dominant predictor than was PA of word reading efficiency at the end of first grade and second grade. This suggests that RAN may have a stronger impact on timed reading measures; unfortunately, no timed measures of comprehension or text fluency were included. Despite the importance of RAN and PA in predicting reading outcomes, a more meta-view is important here: Even by putting together these best predictors of reading at kindergarten, the best statistical models only accounted for about half of the variance of second-grade reading ability.

There is additional evidence that RAN may be an important factor in determining risk for dyslexia in young children. In a longitudinal study in Finland, children who were identified as having dyslexia at the end of second grade were slower for an object RAN task in previous testing at age 3.5 (Torppa et al. 2010). In addition, RAN appears to differentiate between English children with and without a history of dyslexia (Raschle et al. 2011). Again, a meta-view of these comparative performances is important. Scores on a number of other variables, including expressive and receptive language and phonological variables, did not differ significantly between the groups, whereas RAN did. Overall, these studies suggest that RAN is one of the best predictors of later reading abilities, yet we are still far from being able to predict reading from our current behavioral assessments.

Prediction of Reading from RAN Through Primary School and Beyond

Given these close relationships between RAN and reading early in the school years, does RAN continue to predict reading scores as children become older and more proficient readers? This issue has been much debated in the literature (e.g., Torgesen et al. 1997).

This relationship can vary depending on the ability of the readers being studied. Scarborough (1998) found that second-grade RAN scores significantly predicted eighth-grade reading and spelling scores, and the predictive value of RAN was much stronger in poor readers than in typical readers. Meyer and colleagues (1998) found that the relationships between RAN and reading were strong and lasting, but only in poor readers. Among poor readers, RAN scores in third grade significantly predicted untimed single word-reading in fifth grade and eighth grade, accounting for as much as 18% of variance in eighth-grade word reading after SES and IQ were controlled for, and 14% when third-grade reading ability was controlled for. Phonological awareness and nonword reading, on the other hand, were not significant predictors. Looking at the broadest lens, RAN was strongly related to decoding, but it did not predict untimed reading comprehension measures in the later grades in typical or disabled readers. Unfortunately, the outcome measures in these studies did not include any timed reading or fluency tasks, which have been shown to be more closely related to RAN by most researchers.

How does RAN change into adolescence and beyond? Published tests of RAN contain norms for people through the late teens to early twenties (age 18 for the RAN-RAS and age 22 for the CTOPP, described previously). Differences in RAN ability persist between young adults with and without dyslexia through age 25 (Vukovic et al. 2004). Van den Bos and his Dutch colleagues (2002) studied how RAN changes with age and its relationship with reading. Their cross-sectional study included groups of Dutch children ages 8, 10, 12, and 16, and a group of adults ages 36 to 65. They found that the developmental trajectory of alphanumeric RAN reached an asymptote after age 16 but that RAN latencies for colors and objects continued to decrease through adolescence and adulthood. The correlations between alphanumeric RAN and reading are also significant through adulthood, at $r = 0.53$ in adults. The adults were considered a single group; it is unclear whether there are slight differences in RAN or its relationship with reading associated with aging.

CROSS-LINGUISTIC STUDIES OF RAN AND FLUENCY

RAN and its relationship to reading have now been studied in many of the world's languages. This growing list includes, to our knowledge, Arabic, Chinese, Dutch, Finnish, French, German, Greek, Hebrew, Hungarian, Italian, Korean, Japanese, Norwegian, Persian, Polish, Portuguese, Spanish, and Swedish. Research findings in these languages follow the general patterns of what we know about RAN in English: that RAN predicts reading, both concurrently and longitudinally, in typically developing and reading-impaired populations (e.g., Georgiou et al. 2008a,b; Ramus et al. 2011; Tan et al. 2005; Vaessen et al. 2010; Ziegler et al. 2003). Studying the subcomponents of reading across languages helps us to understand what factors are universal and which are language- or orthography-specific factors in the reading system. We know from imaging studies that the reading circuit shifts accordingly to accommodate different emphases in different orthographies. That said, we should be better able to understand dyslexia when we know what types of deficits account for reading failure across various languages.

Shallow Orthographies

Much of the research regarding reading is conducted in English, although English is substantially different from many other languages. Alphabetic languages can be considered as falling along a continuum based on the complexity of the mapping between sounds and letters, or phonology and orthography. The orthography of English is considered very deep or opaque because the correspondences from phonemes to graphemes are not consistent. On the other hand, many other alphabetic languages such as German, Spanish, and Greek have what is called a shallow or transparent orthography, where grapheme-phoneme correspondences are highly predictable. As a result, learning sound-to-letter correspondences and decoding is more straightforward in these orthographically shallow languages. Because there are fewer rules to learn, children who speak these languages usually master accurate decoding by the end of first grade (Seymour et al. 2003), whereas children learning deep orthographies take longer at a proportion based on the opacity of the language.

Several recent studies have compared the effects of orthographic depth on reading processes (Vaessen et al. 2010, Ziegler et al. 2003). Overall, it appears that PA is important early in reading acquisition but that as children essentially reach ceiling in their ability to decode words accurately, a shift occurs in which the relationship between RAN and reading becomes much stronger. The orthographic depth of the language dictates when this shift from reliance on phonology to fluency-related skills occurs; children reading more transparent languages shift away from phonology earlier in schooling (Vaessen et al. 2010).

A current project that has exciting potential to answer more questions in this area is the NeuroDys consortium project in Europe. This group is studying the longitudinal course of reading and dyslexia across six languages in eight countries, using a large sample of about 2,000 children with and without dyslexia. The first set of results from their research suggest that orthographic complexity affects the relationship of PA and reading ability but that the relationship of RAN and reading is essentially consistent across languages (Ramus et al. 2011). The measures that are used to define reading ability are also important. Across languages, PA was a stronger predictor than RAN for untimed word-reading measures, but RAN was stronger than PA for timed reading. A study by Georgiou and colleagues (2008b) corroborates these findings. They studied typically developing children who spoke English, Greek, and Chinese and found that the relationships between RAN and reading fluency were similar across languages. Similar to now extensive findings in the field, they reported that the correlation of RAN with fluency measures was stronger than its correlation with reading accuracy measures.

Patterns of fluency and naming speed are also similar in poor readers across languages. Overall, children who are poor readers in shallow orthographies do exhibit lower phonological awareness scores than those of both age-matched and younger reading-matched peers (Landerl et al. 1997, Ziegler et al. 2003). However, there is also evidence that, as in English, multiple deficits can cause dyslexia and that difficulties with PA versus RAN will affect readers differently depending on the orthography of their language. Cross-linguistic research suggests that similar proportions of RAN, PA, and double-deficits exist in other European languages (Ramus et al. under review) and in Hebrew (Shany & Share 2011), which is consistent with the double-deficit hypothesis. Again, these findings underscore that a variety of deficits can cause reading difficulties but that these factors interact depending on language.

Nonalphabetic Orthographies

Whereas English is considered a rather deep orthography, nonalphabetic languages, such as Chinese and Japanese orthographies, are composed of thousands of characters that are essentially unrelated or much less related to phonemes. At the syllable level, Chinese words share many similar syllables, with each syllable represented by many different characters (Tan et al. 2005). Phonological decoding plays a much more minor role in reading standard Chinese and Japanese, although somewhat more phonologically based systems (e.g., Chinese Pin-yin, Japanese Kana) do exist for introducing children to reading in these languages. As one would expect, phonological awareness is a weaker predictor of timed reading in Chinese; in a regression model, PA did not account for significant variance in timed single-word reading when RAN was controlled for (Tan et al. 2005). One might imagine that orthographic knowledge accounts for much of the variance in Chinese reading ability because of the many characters that must be learned and recognized. However, RAN is strongly correlated with reading in Chinese and accounts for additional variance after writing (orthographic) ability is controlled for. In several cases, correlations reported between RAN and reading in Chinese and Japanese are even greater than those reported in Swanson and colleagues' (2003) meta-analysis of English (Georgiou et al. 2008a, Kobayashi et al. 2005, Tan et al. 2005). This may reflect the powerful contribution of visual processes also measured within RAN to reading the logosyllabaries of China and Japan.

Underscoring the fact that some factors may be language specific and others may be more general, McBride-Chang and colleagues (2011) studied Chinese-English bilinguals who had reading difficulties in one language or in both. Individuals who had difficulty reading both Chinese and English were significantly slower namers than were peers who struggled in just one of their languages or who were typical readers. Furthermore, this effect was stable in children who were followed longitudinally from ages 5 through 9. Overall, the differences in RAN across languages and orthographies are small in comparison with the many similarities. We have seen no evidence of a language in which RAN has not been shown to be important for reading.

CONTRIBUTIONS OF NEUROSCIENCE AND GENETICS TO UNDERSTANDING RAN AND FLUENCY

Perhaps the greatest advances in our understanding of reading disabilities over the past decade have come from neuroimaging studies. Developments in magnetic resonance imaging (MRI) technology have progressed such that it can be used easily with children to address questions about the brain structures and associated functions involved in reading. In addition, recent genetic and twin studies have produced results that give first-time insights to the biological mechanisms that underlie brain and behavioral differences in dyslexia.

Functional Brain Networks in Reading and Dyslexia

Brain activation for reading-related tasks has been consistently found in three main areas of the left hemisphere: the inferior frontal gyrus (IFG), temporoparietal area, and occipitotemporal area (see meta-analyses by Maisog et al. 2008, Richlan et al. 2009). The IFG has been implicated in a wide variety of reading and language-related functions, from semantic search to working memory. The temporoparietal aspect of the reading circuit includes areas of posterior temporal cortex as well as the angular gyrus and supramarginal gyrus. These regions are classic "association areas" as described by Geschwind, responsible for the integration of information across visual and auditory modalities. The occipitotemporal region includes the fusiform gyrus and inferior temporal gyrus and is most often implicated in orthographic processing.

In people with dyslexia relative to controls, the most consistent finding is an underrecruitment (hypoactivation) of left temporoparietal and left occipitotemporal areas (Maisog et al. 2008, Richlan et al. 2009). Functional brain differences in both of these areas are thought to be related to the etiology of dyslexia, rather than absolute level of reading ability, because younger children matched for ability to dyslexic readers do not show hypoactivation of these areas (Hoeft et al. 2007). In addition to these areas of the reading circuit that show reduced activation in dyslexia, many individual studies have identified areas of the right frontal and temporal lobes that show greater activation in people with dyslexia relative to controls. These are thought to represent compensatory mechanisms or effortful processing, as they are sometimes engaged in younger relative to older typically developing readers (Hoeft et al. 2007). Several studies have reported cerebellar differences associated with dyslexia, but these have varied widely and were not significant in meta-analyses of imaging studies (Maisog et al. 2008, Richlan et al. 2009).

The tasks used in nearly all brain imaging studies to date have focused on accuracy rather than fluency. One recent study to focus on fluency had typical adult readers read sentences presented at rates slower than, equal to, and faster than their normal reading speed (Benjamin & Gaab 2011). As compared to a letter-reading baseline task, the posterior middle temporal gyrus was engaged at all reading speeds, whereas areas of the left IFG and occipitotemporal region were more active at both slow and fast, but not normal, speeds. These findings suggest that when the automaticity of normal reading is disrupted, activation in reading-related regions changes, consistent with a multicomponential view of fluency.

Several important questions remain to be answered, including whether readers with different subtypes of dyslexia use different areas of the brain in reading and how activation for timed reading might differ from untimed accuracy measures. However, we are starting to gain some insight into the brain processes that support RAN. There is some evidence that phonological and RAN or fluency abilities may have separate neural substrates. Eden and colleagues (Turkeltaub et al. 2003) examined correlations between activation for an fMRI implicit reading task and behavioral measures of RAN, phonological awareness, and working memory. They found that patterns of correlations with brain activation were spatially distinct for each task, suggesting that each of these processes may tap separate aspects of the reading network.

To our knowledge, the brain basis of RAN tasks has been examined in only two studies. Misra and colleagues (2004) and Christodoulou and colleagues (2011, Lymberis et al. 2009) had adults name stimuli, as in a traditional RAN task (5 × 10 matrix), on a screen during fMRI scanning. Both studies found that for letter naming contrasted with fixation, the RAN task engaged the left inferior frontal gyrus, left posterior middle frontal gyrus, and bilateral inferior occipital areas (**Figure 2*a***). Misra et al. (2004) found additional activation in left parietal and right frontal areas, although their statistical thresholds were much more liberal. These areas are consistent with areas involved in the reading network as well as for tasks that require eye saccades.

Christodoulou and colleagues (2011, Lymberis et al. 2009) also compared in-scanner RAN performances of typical adult readers and adults with dyslexia who were matched on age and IQ. The adults with dyslexia had lower standardized RAN scores and lower in-scanner performance. The typical controls engaged several posterior areas in the occipital and parietal regions bilaterally more than did the group with dyslexia (shown in red, **Figure 2*b***), whereas the adults with dyslexia (shown in blue) showed greater activity than did controls in a variety of bilateral temporal, motor, and left supramarginal gyrus (part of the temporoparietal area). These results suggest that readers with dyslexia are employing a more distributed network that may represent compensatory mechanisms for performing RAN tasks.

Timing of Brain Processes in Reading and Dyslexia

Functional MRI studies have provided us with a clearer picture of what happens in the brain while we read, but what do we know at this juncture about the timing aspect of reading that is so important for fluency? Electroencephalography (EEG) allows us to examine the precise timing of neural processes, which can complement information obtained about the location of processes determined by fMRI. EEG records the electrical activity of the brain from the scalp, so researchers can present stimuli and analyze the response, called an event-related potential (ERP), to each type of stimulus. From EEG research we know that different aspects of words are processed along a timeline. For example, initial visual processing occurs within the first 50 milliseconds after a word is presented. Word-specific orthographic processing begins around 150 msec and executive and attention processes at about 200 msec, with phonological processes between 150 and 300 msec, followed by semantic and comprehension processes (Wolf 2007). Ongoing debate, however, concerns whether phonological processing occurs well before other linguistic processes, perhaps in an interactive mode with orthographic processes. As we have noted, a lack of automaticity in any one of these areas can cause a delay that leads to less time available for comprehension. Indeed, research finds that individuals with dyslexia show later peak responses for several of these different components during word reading (see Shaul 2008 for a review). Not surprisingly, the peak of each of the ERP components involved in rapid naming was delayed in adults with dyslexia relative to controls (Breznitz 2005).

Because EEG systems are relatively inexpensive and portable as compared to MRI, EEG research regarding early indicators of reading disability is especially promising. In particular, the mismatch negativity (MMN) ERP component, which is a preattentive response to a difference within a series of auditory stimuli, has been studied as a possible correlate of automatic language processing. The MMN response is a significant predictor of reading outcomes, even better than a combination of behavioral assessments in children (Maurer et al. 2009), and differs among infants with and without a family history of reading disability (Leppänen et al. 2002). Recently, we found that the MMN response in children was significantly correlated with RAN, timed single-word reading, and timed connected text reading, but not with PA or untimed reading (Norton et al. 2011), suggesting that it might reflect processes important for the rapid processing of stimuli necessary for fluent reading. Further research in this area has great potential to help us understand the relationship between automaticity of language processing and reading fluency.

Brain Structure and Connectivity Differences in Dyslexia

Researchers have also used structural MRI to look for an anatomical basis of reading and language disorders. In a series of studies, Leonard, Eckert, Berninger, and colleagues (e.g., Eckert et al. 2003, Leonard et al. 2006) have examined the brain structure differences associated with RAN, single-word reading, and reading comprehension. Children with dyslexia showed smaller volumes of the pars triangularis area of the IFG bilaterally as well as an area of the right cerebellum. On the basis of these anatomical markers, more than 80% of the subjects could be correctly classified as dyslexic or typical readers. These anatomical measurements were also significantly correlated with RAN scores. On the other hand, a separate set of anatomical predictors related to the size and symmetry of the planum temporale (part of the temporoparietal area implicated in successful reading) has been related to word reading and comprehension. However, conflicting results as to the lateralization of the asymmetry have arisen from postmortem anatomy studies and in vivo MRI studies (Leonard et al. 2006). It may be the case that extreme asymmetries of the planum temporale in either direction may induce risk for dyslexia. Pernet and colleagues (2009) also found that structural volumes either much larger or smaller than those of controls were associated with atypical reading. In their sample, 100% of adults could be accurately classified as typical or dyslexic on the basis of the volumes of the right cerebellar declive and left lentiform nucleus (part of the basal ganglia). Their findings also suggested that the concept of a U-shaped curve, in which extreme values on either the high or low end can cause a disorder, could also help explain the conflicting findings of asymmetry noted above. In particular, smaller volumes of the cerebellar declive were associated with more severe phonological deficits. Although the precise role of the cerebellum relating to PA is not entirely clear, notable research has implicated the lentiform nucleus in the automaticity for automatic, serial processing of language, such as is required for rapid naming (Smits-Bandstra & De Nil 2007). Although anatomical differences relating to RAN have been less studied, a few differences have been reported, including greater rightward asymmetry of pars triangularis of left IFG and right cerebellum associated with lower RAN scores (Eckert et al. 2003).

Because RAN and fluency depend on the speed and integration of multiple processes throughout the brain, the extent and quality of white matter pathways may play a substantial role in helping us to understand the biological basis of fluency-related processes. A newer type of MRI scan, called diffusion tensor imaging (DTI), has allowed researchers to look at white matter pathways of the brain. Studies suggest that white matter differences exist between typical and dyslexic readers in reading-related regions including IFG, temporoparietal, and occipitotemporal areas (Rimrodt et al. 2010); white matter characteristics in these areas were also correlated with speeded word-reading ability.

Furthermore, one of the first and most striking insights into the fluency circuits in the brain came from research on a rare genetic brain malformation known as periventricular nodular heterotopia (PNH), in which neurons migrate into the ventricles of the brain to form nodules in various areas both posterior and anterior. Subjects with PNH all demonstrate specific deficits in reading fluency despite intact IQ and single-word reading ability and despite great diversity in where the nodules formed across individuals (Chang et al. 2007). In people with PNH, RAN letters and numbers were strongly correlated ($r = 0.78$ and 0.91, respectively) with a DTI measure of white matter quality called fractional anisotropy (FA). DTI scans also revealed that white matter tracts were disorganized around areas where nodules occurred in each individual. This unique disorder provides further evidence that reading can be disrupted at the fluency level only and that the connectivity of various regions in the brain may play a strong part in determining fluency.

Genetics of RAN and Fluency

Although researchers have long recognized that dyslexia is heritable, the leap from genes to behavior in a process that is not genetically dictated (like vision or language) is likely to be extraordinarily complex. Our relatively recent ability to compare genetic samples from twins or groups of different reading abilities and to scan the genome for markers associated with behavioral variables allows us another window into the processes of the reading circuit and underlying causes of dyslexia.

Heritability estimates for dyslexia range widely, from 0.3 to 0.7 (a trait that was 100% determined by genetics would measure 1.0). The precise level of heritability is difficult to ascertain because of the different reading measures, diagnostic criteria, and methods used, but the concordance of dyslexia is consistently reported to be higher in monozygotic than in dizygotic twins (Scerri & Schulte-Körne 2010). Several studies have examined the relationship between RAN and PA and whether they are based on shared or unique genetic factors. Several researchers have reported that there is a set of common genetic influences that affect PA, RAN, and reading (that is, they are all affected by some common genes) but that there are also separate genetic influences on PA and RAN (Byrne et al. 2005, Compton et al. 2001, Petrill et al. 2006).

At least nine major candidate genes for susceptibility to dyslexia have been identified, located on eight different chromosomes (Scerri & Schulte-Körne 2010). Most of these are related to neuronal migration and axon growth in utero (Galaburda et al. 2006). Indeed, the importance of neuronal migration for dyslexia is echoed in findings of PNH as well as in Galaburda's and Geschwind's earlier studies of postmortem brains that showed abnormal migration, especially between cortical layers. It will be essential in future research to link findings from structural and functional MRI, DTI, EEG, and genetics, to learn how biology and behavior interact to affect reading ability. Researchers including Hoeft, Gaab, and Gabrieli have begun work in this area.

IMPLICATIONS OF RAN AND FLUENCY FOR IDENTIFYING READING DIFFICULTIES, INSTRUCTION, AND INTERVENTION

Identification and Assessment

Although the relationships between rapid naming ability and reading abilities have been studied extensively, there remains insufficient understanding of its clinical uses among some practitioners. It is our assessment that RAN tasks can be best used by educators and psychologists as part of a clinical assessment to identify risk for reading and learning difficulties and as a measure of the development and efficiency of processes related to word retrieval and reading fluency (Wolf & Denckla 2005).

RAN tasks take only a few minutes to administer and require only modest training to administer and score. It is essential that RAN and other fluency measures be included in psychoeducational assessment batteries. For early screening for potential reading difficulties, we presented evidence from multiple longitudinal studies that show that RAN is one of the most robust early indicators of potential reading difficulties, along with phonological skills and letter name and sound knowledge. Using published normed measures, examiners can determine how a child's RAN ability compares with what is typical for a given age or grade. A second important reason for assessing RAN and other fluency issues is that speed and automaticity are essential components of what it means to be a good reader, yet we tend to measure reading too often only in terms of accuracy. Myriad studies have shown that one can be an accurate reader without being a fluent reader (see Breznitz 2006). Often, children who have an "invisible" speed deficit are not identified until later in school, and they may start to suffer the negative effects of having a reading difficulty, such as poorer academic performance in other subjects. For this reason, fluency measures that take into account speed and comprehension should be included in reading assessments.

Interventions for Fluency

A question that naturally follows from these findings is, can we train children to improve their RAN ability and thus impact their reading skills? Children with phonological weaknesses who receive high-quality phonological interventions tend to improve both their PA skills and decoding ability (Torgesen 2004). A host of well-designed, structured, multisensory phonology programs exist, and they are indeed effective in remediating phonological deficits. However, the question of how to improve reading fluency, and whether one can improve RAN ability, is much more difficult. First, the RAN task itself is a surface indicator of the efficiency of the underlying processes shared by naming and reading. There have been no large-scale, well-controlled studies that have tried to explicitly train naming speed. Here, a gap in the literature is not a bad thing—most researchers would agree that training students on a RAN task would not be the optimal way to improve their reading fluency. RAN seems to be related to individual developmental processes; RAN times improve with age, but individuals seem to be relatively consistent in their overall naming ability across time, relative to peers. In terms of assessment, we would expect to see raw scores for RAN change as children develop and become more automatic, but an individual's standard score based on age would be more consistent. Our own studies have shown that although our best interventions can improve most reading and language variables, the RAN changes little from pre- to posttreatment, indicating that RAN taps a more basic index of processing.

How, then, do we promote reading fluency and provide intervention for students who struggle with this skill? How do we train this system that seems inherently untrainable? One technique that has been widely used as a purported way to improve fluency is repeated reading. In this technique, a student reads a passage multiple times, with increasing speed. After repeated reading, students show some generalizible increases in speed and accuracy of decoding (see Meyer & Felton 1999 for a review). However, these results and the entire approach of repeated reading measures yield changes in speed that may not be related to improvements in our sine qua non of reading, fluent comprehension. Whereas we know that fluent comprehension depends on accuracy and automaticity at every level of language, few intervention programs reflect this. There are numerous programs designed to address phonological decoding skills, but few programs explicitly address multiple components of language, such as orthography, morphology, syntax, and semantics, with the goal of improving fluent comprehension.

Few random-assignment treatment-control studies examine the effects of different reading intervention programs. One such study, led by Lovett, Morris, and Wolf, examined the impact of intervention on 279 students with reading difficulties (Morris et al. 2011). Students were randomly assigned to one of four different intervention programs designed to contrast different types of instruction: (*a*) study skills and math instruction (no reading instruction), (*b*) PHAB + study skills, a phonological program plus study skills instruction, (*c*) PHAST, a multicomponential word-identification strategy and phonological program, or (*d*) PHAB+RAVE-O, a multicomponential program designed to address each level of reading (Wolf et al. 2009) and a phonology program. Students were matched for IQ, race, and socioeconomic status among groups, and each group received 70 hours of small-group instruction.

Results showed that children who received multicomponential interventions (PHAST or PHAB+RAVE-O) had significantly greater growth than did other intervention groups on timed and untimed word and nonword reading and passage comprehension. The multicomponential groups also maintained these levels of growth at follow-up one year after intervention. In terms of fluency, which is notoriously difficult to improve, children in the multicomponential groups again outperformed the other interventions, with only the RAVE-O group gaining more than six standard score points on the Gray Oral Reading Quotient (Morris et al. 2011). In sum, the two multicomponential interventions significantly improved children's reading accuracy and fluent comprehension relative to closely matched programs that included phonology-only or general academic instruction, and RAVE-O, which targeted the most components, had the best results for fluent comprehension and also on vocabulary measures, both post-treatment and at one-year follow-up. These results highlight the importance of explicitly addressing the multiple levels of language and multiple cognitive processes involved in reading.

The present review of the fluency research highlights the need for multicomponential interventions, such as PHAST, RAVE-O, and Language!, especially for students with RAN or double deficits whose weaknesses are not adequately addressed by a phonological decoding program. As we better understand each child's ability, we can better tailor instruction to benefit each child. Children whose teachers were trained in individualizing literacy instruction (including more emphasis at the subword and word levels versus connected text comprehension) during first grade had better literacy outcomes than those of matched classrooms without individualized instruction (Connor et al. 2009). Ultimately, our goal should be to understand the abilities of all children and to provide the types of instruction that best addresses their needs.

CONCLUSION

The field of reading research has come a long way toward understanding the complex set of skills that allow fluent comprehension of text. Research across the globe studying individuals' brains and whole classrooms' development has shown that RAN is deeply linked with reading processes. Slowly but surely, the field is moving from narrow, polarized views on the best ways to teach reading and conceptualize dyslexia to multicomponential frameworks for assessment and intervention. Even the long-held ideal that fluency is mostly reflected in the quality of prosody in oral reading is changing (Kuhn et al. 2010), so that fluency is understood as the crux of when many processes at multiple levels integrate seamlessly to promote the comprehension of text.

SUMMARY POINTS

1. Rapid automatized naming (RAN) measures act as a microcosm of the reading system, providing an index of one's abilities to integrate multiple neural processes.
2. RAN and phonological awareness are both robust early predictors of reading ability, and one or both are often impaired in people with dyslexia. Longitudinal, cross-linguistic, genetic, and neuroimaging studies suggest that these two crucial reading-related processes should be considered distinct constructs rather than subcomponents of a single construct.
3. It is advantageous to conceptualize fluent reading as a complex ability that depends on automaticity across all levels of cognitive and linguistic processing that are involved in reading, allowing time and thought to be devoted to comprehension.
4. Successful intervention for reading disabilities depends on accurate assessment of a child's profile in terms of both accuracy and speed across all levels of reading, from the subword to connected text. Multicomponential intervention programs that target phonology as well as multiple levels of language show the greatest promise in improving reading fluency.

FUTURE ISSUES

1. To better understand RAN and fluency as behavioral predictors and outcome measures, based on longitudinal studies incorporating brain imaging and/or genetics (such work is underway among the Neurodys consortium in Europe and by our colleagues Nadine Gaab and John Gabrieli in Boston).
2. To determine the most appropriate instruction and intervention techniques for certain profiles of readers or subtypes of dyslexia, especially those with fluency and naming deficits who may not benefit from traditional phonologically based interventions.
3. To research how reading in new and electronic media (e.g., on the Internet or from an e-reader) affects automaticity and fluent comprehension.

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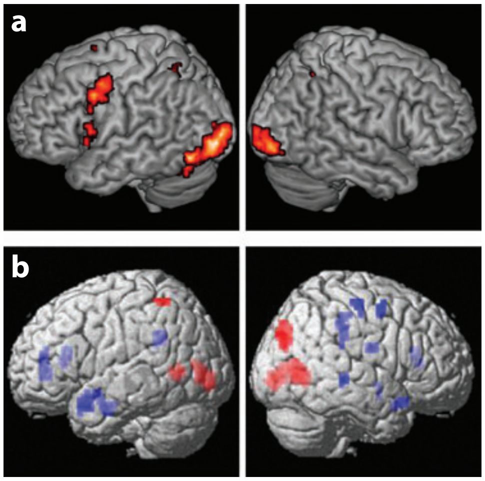

Figure 2

fMRI brain activations for a RAN letters task from Christodoulou et al. (2011). (*a*) Whole-brain activations for RAN letters >visual fixation. N = 18 typical adults. Activations significant at height threshold of $p < 0.05$, FWE (family-wise error) corrected, k > 10 voxels. (*b*) Whole brain differences for RAN letters >visual fixation in typical adult readers (N = 9) versus adults with dyslexia (N = 9). Activations significant at height threshold of $p < 0.05$, FDR (false discovery rate) corrected, k > 10 voxels.

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