Special Article

Using Our Current Understanding of Dyslexia to Support Early Identification and Intervention

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ABSTRACT

One of the major risk factors for reading disability is difficulty learning to read words in text in an accurate and fluent manner. This is apparent when a child at risk of dyslexia first starts to attempt to read. Dyslexic children struggle to grasp and automate the alphabetic principle (ie, they cannot "sound out" words or use phonemic decoding strategies) and therefore have difficulty deciphering unfamiliar words that they have not encountered before. Even though many of these words are part of the child's oral vocabulary, the child cannot recognize them in printed form. As a result, reading can be extremely laborious and time-consuming, fraught with errors, and altogether an unrewarding, aversive experience. To be an efficient reader, one must be able to rapidly and effortlessly recognize many words by sight, and for a child to acquire this facility requires multiple exposures to these words. The difficulty that dyslexic children have in developing reliable and efficient phonemic decoding ability makes the acquisition of a lexicon of sight words a much slower process than it is for the average reader. Several other factors can affect a child's ability to read, which are reviewed herein. However, early recognition and treatment of deficient phonologic awareness are an extremely important step in the prevention of a reading problem in the child who is at risk of dyslexia. (*J Child Neurol* 2004;19:759–765).

A recent comprehensive summary of research on reading and reading instruction published by the National Research Council identified three broad reasons why children can have difficulties in learning to read even when they receive reasonably effective instruction.[1] First, they can experience difficulties in learning to read words in text accurately and fluently. Second, they can fail to acquire the verbal knowledge and thinking skills that are required to understand the meaning of text. Finally, they can be poorly motivated to learn to read or fail to develop a mature appreciation of the rewards of reading. Although a simple trichotomy such as this undoubtedly oversimplifies the range of difficulties that children have in learning to read, it provides an appropriate context within which to understand the modern concept of dyslexia.

The primary difficulty experienced by children with dyslexia involves problems in learning to accurately and fluently identify words in their printed form. This problem is identified in a recent definition of dyslexia that is based on outcomes from the last 20 years of intensive research on this condition:

> Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities. These difficulties typically result from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction.[2]

WHAT ARE THE DEVELOPMENTAL MANIFESTATIONS OF DYSLEXIA?

When children with dyslexia have been in school for 3 or 4 years and have not had sufficiently strong reading instruction, they will show two obvious difficulties when asked to read text at their grade level. First, they will not be able to instantly, or automatically, recognize as many of the words in the text as average readers. They will stumble on, guess at, or attempt to "sound out" many words. This is the problem in fluent word recognition identified in the definition. The second problem is that their attempts to identify words that they do not immediately recognize will produce many errors. They will not be efficient in using letter-sound relationships (phonics) in combination with context to identify unknown words. This is what is referred to in the definition as difficulty in decod-

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ing. Because the broad verbal abilities of these children are substantially higher than their word reading abilities, usually, the word reading difficulties of these children present the most immediate barrier to good reading comprehension.

The struggle that children with dyslexia face in learning to read words accurately and fluently is apparent from the very earliest stages of reading instruction. First, they invariably do not grasp the alphabetic principle (learning to "sound out" words) and cannot apply it when deciphering unfamiliar words. The early development of accurate and fluent phonemic decoding skills (alphabetic reading skills) is critical because learning to read involves everyday encounters with words that have never been seen before in print. These words are typically present in the child's oral vocabulary, but their printed form is unfamiliar. The systematic relationships between the phonemes in spoken words and the letters in their printed form are the single most reliable clue to the identity of words when they are encountered for the first time in print.[3] Children can use a variety of strategies to identify unknown words,[4] but if they do not become skillful at using letter-sound cues early in development, they almost invariably remain inaccurate readers.[5]

The difficulty that children with dyslexia have in developing reliable phonemic decoding ability makes it hard and unrewarding for them to read independently, and it also produces far too many word reading errors. Unfortunately, both of these consequences of weak phonemic decoding skills affect the development of fluent word reading ability.[3] Because words do not become "sight words" until they are read accurately a number of times,[6] inaccurate reading and diminished reading practice both cause a slow growth in the number of words that can be recognized at a single glance. Although many factors contribute to the overall development of the ability to read text fluently,[7] the single most important factor is the ability to recognize a large number of words effortlessly or automatically.[8] As mentioned earlier, a common characteristic of children with dyslexia who have not received powerful preventive instruction is that they have a restricted "sight word vocabulary,"[9,10] which limits their ability to read text fluently.

WHY DO CHILDREN WITH DYSLEXIA EXPERIENCE DIFFICULTIES MASTERING THE ALPHABETIC PRINCIPLE?

As stated previously, the most powerful current explanation of the word-level reading difficulties of children with dyslexia involves a deficiency "in the phonological component of their natural capacity for language."[11] Children with dyslexia have deficiencies in the set of linguistic processing abilities that make humans sensitive to the complex array of phonologic, or acoustic, information in speech. This disability does not necessarily affect their ability to speak or to understand speech, but it does interfere with their ability to take advantage of the alphabetic principle in reading. In their original thinking about children who have specific problems in learning to read words accurately and fluently, Liberman and her colleagues began by asking the question, "What is required of the child in reading a language but not in speaking or listening to it?"[11] Their answer was that the child must master the alphabetic principle:

> This entails an awareness of the internal phonological structure of words of the language, an awareness that must be more explicit than is ever demanded in the ordinary course of listening and responding to speech. If this is so, it should follow that beginning learners with a weakness in phonological awareness would be at risk.[11]

Empiric research on this hypothesis has, indeed, amply verified that children who experience difficulties acquiring alphabetic reading skills are, as a group, substantially impaired in their performance on tasks that assess awareness of the phonologic structure of words using oral language tasks.[12–14] Tasks used to assess phonologic awareness do not involve printed letters; they assess a child's ability to notice, think about, or manipulate the sounds in words that are presented orally. They involve operations such as indicating similarities or dissimilarities among words on the basis of their first, last, or middle sounds; telling how many different sounds a word contains; or blending separately presented sounds to form a word.

In addition to the pervasive evidence that children who struggle in learning to read words accurately and fluently also experience delays in the development of phonemic awareness, there is strong evidence that the relationship between these two variables is causal. Limited evidence comes from longitudinal, causal modeling studies,[15,16] but the strongest evidence comes from experiments that employ random assignment of children to conditions.[17] In these studies, groups of children who receive more powerful instruction in phonemic awareness show stronger subsequent growth in reading accuracy than children who do not.[18] Current conceptualizations identify at least three ways in which phonemic awareness supports the growth of accurate and fluent word reading skill:

1. *It helps children understand the alphabetic principle.* To understand the way in which letters are used to represent words in English, children must have at least emergent levels of phonemic awareness. Without some ability to identify the individual sounds in spoken words, it is difficult to capitalize on the fact, or even understand, that there are systematic relationships between the letters in print and the individual phonemes in spoken words.
2. *It facilitates the generation of possible words in context that are only partially "sounded out."* For example, consider the child who comes to a sentence such as "Sam ____ his dog in the woods" and does not recognize the second word. If the child must guess the word from the context of the sentence or passage, many words would fit, such *as walked*, *found*, *saw*, *left*, or *chased*. However, if the child knows the sound that is represented by the first two letters in the word, *ch*, then he or she will be much more likely to guess the right word, *chased*. An early level of phonemic awareness supports the ability to search one's mental dictionary for words that begin with a given sound. That is, in addition to being categorized by their meanings, words can be categorized by their beginning, middle, or ending sounds. If children are able to use information about the phonemes in an unknown word that they obtain from even a partial phonemic analysis to constrain their search for words

that also fit the meaning of the sentence or paragraph, they will significantly increase the accuracy of their first guesses about the identity of unknown words in text.

3. *It helps children notice the regular ways in which letters represent sounds in words.* If children can "hear" four sounds in the word "clap," it helps them notice the way in which the letters correspond to the sounds. The ability to perceive the correspondence between the sounds in a word and the way it is spelled has two potential benefits. First, it reinforces knowledge of individual sound-letter correspondences, and, second, it helps in forming mental representations of words so that they can be recognized by sight. Ehri has shown how developing readers use their awareness of the phonemes in words as a mnemonic to help them remember the words' spellings so that they can eventually recognize words by simply glancing at them while reading.[4,19]

In addition to the delays seen in the development of phonemic awareness, the core phonologic processing deficits of children with dyslexia have also been linked theoretically and empirically to problems in verbal short-term memory.[20] Verbal short-term memory is usually measured with tasks that require verbatim repetition of short sequences of digits or letters, but more recently developed tasks require children to repeat single nonwords that vary in length from 2 or 3 phonemes to ones containing 8 to 10 phonemes.[16,21]

Performance on measures of verbal short-term memory is affected in children with phonologic processing difficulties because, on short-term memory tasks, verbal items are briefly stored using phonologic representations.[22] That is, when a child is asked to remember a string of digits or a nonword such as "bliget" or "enstrectormamble," the most common strategy is to remember how the string of digits or phonemes sounds, not how it looks. If the child's phonologic representations of letters, digits, or phonemes are degraded or indistinct, then the memory for strings of these items will be affected.

Severely impaired digit span performance has been a characteristic of all of the subjects who have been examined in detailed case studies of developmental dyslexia.[23–25] In these cases, the subjects had severely curtailed abilities to repeat strings of digits, often performing like children 3 or 4 years younger. In addition, early reviews of the literature on the cognitive characteristics of children with severe reading disabilities reported that poor performance on digit span tasks was one of the most common characteristics of these children.[26,27] Torgesen and colleagues also reported a systematic series of studies in which severe problems in verbal short-term memory were linked to weaknesses in phonologic processing and development of alphabetic reading skills.[28,29]

The primary way in which weaknesses in verbal short-term memory might affect the growth of accurate and fluent word reading ability is through their impact on children's ability to use letter-sound correspondences to "sound out" words. To efficiently use phonemic decoding strategies for unknown words in text, children must be able to identify the sounds associated with several of the letters and then blend these sounds together to produce an approximate pronunciation of the word. Although an example provided earlier in this article indicated that just knowing even the first sound of an unknown word can be helpful in improving the accuracy of the child's first attempt at reading the word, the more complete the phonemic decoding is, the more accurate the first attempt will be.[3] Children with deficient verbal short-term memory can find it difficult to perform the simultaneous or rapidly sequential identification, comparison, and blending processes that are required for efficient identification of words by phonologic or analytic strategies.

Although there is a plausible theoretic relationship between phonologic representation (coding) problems and difficulties in applying phonemic decoding skills to unknown words, the empiric evidence for a causal relationship between these two variables is relatively weak.[20] Further, when measures of verbal short-term memory have been included in the same study with measures of phonemic awareness, measures of the latter construct seem to be the most sensitive to the phonologic processing problems of children with dyslexia. For example, several longitudinal studies that have included both measures of phonemic awareness and verbal short-term memory found that individual differences in memory did not add anything to the prediction of growth in reading accuracy if phonemic awareness was already in the predictive equation.[30–32] In contrast, phonemic awareness always improved the power of the prediction, even if short-term memory was entered first into the predictive equation. In our own work, we have shown that it is best to conceptualize phonologic awareness and verbal short-term memory as correlated but distinct abilities, with phonemic awareness consistently being the most predictive factor in the acquisition of accurate and fluent word reading skills.[33]

DO WE NEED A DOUBLE DEFICIT TO EXPLAIN DEVELOPMENTAL DYSLEXIA?

Apart from being a nicely alliterative phrase, this question is currently one of the most intriguing in the scientific study of dyslexia. The question arises primarily from the work of Wolf and Bowers and colleagues, who investigated the relationship between performance on rapid automatic naming tasks and the growth of fluent word reading skills and reading comprehension.[34–37] Wolf and Bowers have shown that rapid automatic naming tasks, in which children are typically asked to name a visual array of 50 items displayed 10 to a row for 5 rows as rapidly as possible, are consistently and strongly predictive of word-level reading difficulties and reading comprehension. Although it is possible to argue that rapid automatic naming tasks should be conceptualized, along with phonemic awareness tasks and measures of verbal short-term memory, as measures of a different form of phonologic skill (ie, rapid access to phonologic representations),[38,39] Wolf, Bowers, and other researchers have argued against this idea. Rather than viewing rapid automatic naming tasks as primarily phonologic in nature, they emphasize the numerous nonphonologic requirements of these tasks, such as attention,[40] executive functioning,[41] general speed of processing,[42] and the complex interplay of all of these mechanisms necessary to perform this task.[35]

In Wolf and Bowers' conceptualization of the primary processes involved in both rapid naming and fluent word reading, they focus on the need for a "precise timing mechanism" that is important in the formation of the visually based representations of words that allow them to be recognized as whole units in text.[35] They hypothesize "that slow letter (or digit) naming speed may sig-

nal disruption of the automatic processes which support induction of orthographic patterns, which, in turn, result in quick word recognition."[35] Orthographic patterns are patterns of letter combinations that frequently occur in words. According to this explanation, if children are sufficiently slow at visual recognition of letters, it interferes with their ability to construct a mental representation of a word's spelling that will allow the word to be recognized automatically.

Answers to the question of whether we will eventually end up with a fully developed double-deficit explanation of dyslexia or whether current explanations that emphasize phonologic processing disabilities will prevail ultimately hinge on the answers to two related questions. First, do the components of naming speed that are predictive of reading outcomes lie outside of the domain of phonologic processing? The research is clear that naming speed is an important predictor of reading above and beyond phonologic awareness.[43] However, this finding does not necessarily imply that the important components of naming speed lie outside the phonologic domain, just that they measure some dimension of ability (phonologic or otherwise) that contributes to the prediction of reading, independently of measures of phonologic awareness, which is only one type of phonologic measure. Two recent studies reported evidence that seems, at least initially, to provide different answers to this question.

First, Compton created multiple versions of the rapid automatic naming of letters task (the one most predictive of reading), contrasting tasks that required increased phonologic processing to those that involved increased visual processing.[44] The phonologically challenging tasks contained letters that sounded alike, whereas the tasks requiring increased visual processing contained letters that looked alike but did not sound alike. Compton found that the rapid automatic naming task containing the phonologically confusing information was significantly more predictive of word reading skills than the rapid automatic naming task that increased the amount of visually confusing information but decreased the phonologically confusing information. That is, when the naming speed task increased the demands on phonologic processing, it became even more predictive of word reading. This finding indicates that at least part of the predictive relationships between rapid automatic naming tasks and reading arises from the fact that it requires some form of phonologic processing.

In the second study, Misra and colleagues examined patterns of brain activation using functional magnetic resonance imaging technology in adults performing rapid automatic naming tasks involving either objects or letters.[45] Rapid automatic letters naming tasks are more consistently predictive of word-level reading difficulties than those that require students to rapidly name series of objects.[44,46–48] In this study, adult average readers covertly named objects or letters or passively viewed a fixation matrix of plus signs. Both tasks produced activation in areas associated with eye movement control, attention, and phonologic processing. However, the key finding was that letter naming resulted in greater activation in the angular gyrus, superior parietal lobule, and medial extrastriate areas—areas of the brain associated with phonologic processing. These areas are part of the "reading network" and are likely involved in the processing of word forms and the interpretation of orthographic information. In contrast, object naming only differentially activated an area of the fusiform gyrus. The authors discussed this finding as consistent with the idea that the rapid naming of letters uniquely measures processing skills beyond those in the phonologic domain, and they pointed to a processing dimension (recognition of orthographic forms) that is clearly involved in reading.

This finding is actually not inconsistent with Compton's demonstration that increasing the phonologic processing load of rapid automatic naming tasks also increases the strength of their relationship to reading.[44] Given that Misra et al showed that rapid automatic naming tasks activate areas of the brain associated with phonologic processing, it is logical that a manipulation that increased the phonologic processing demands of the task would strengthen its relationship to reading.[45]

The other side of the same question is whether phonologic deficits alone are a sufficient explanation for the problems with fluent word recognition experienced by almost all children with dyslexia. Our earlier discussion of the role of phonemic decoding skills suggested that they are necessary, but not entirely sufficient, for the development of fluent word recognition skills. For example, a child might be able to accurately identify words by using a combination of phonologic reading skills and context, but if these skills are not practiced in extensive exposure to print, the child will not develop a sufficiently large vocabulary of words that can be recognized by sight. We also know that variation among children in fluent reading skills cannot be fully explained empirically by a combination of general verbal ability, phonologic abilities, and exposure to print.[49–51] That is, when the influence of these factors on fluent reading skills is controlled, children and adults still show variation in their fluent word recognition skills. Although it is quite possible that this unexplained variability in fluent word recognition is due to unreliable or incomplete measurement of phonologic reading skills or only partial assessment of reading experience, it might also be due to another disability, such as the one proposed by Wolf and Bowers.[35]

To summarize, the idea that a complete explanation for the word-level reading problems of children with dyslexia involves two distinct kinds of core processing difficulties must be regarded as an intriguing and increasingly well-supported hypothesis. However, the evidence for a causal relationship with word-level reading difficulties is clearly strongest for phonemic awareness, next strongest for rapid naming ability, and weakest for verbal-short term memory.[39] We turn now to a consideration of the usefulness of our knowledge about these constructs to the early identification of students who are at risk of experiencing difficulty in reading.

USING OUR UNDERSTANDING OF DYSLEXIA TO AID IN EARLY IDENTIFICATION AND INTERVENTION

There can be no question that it is critically important to intervene early with students who have the processing weaknesses characteristic of children with dyslexia. Students who are allowed to persist with significant phonemic decoding difficulties for too long miss out on enormous amounts of reading practice that has important effects on the growth of reading fluency,[8] vocabulary,[50] and reading comprehension skills.[1] In fact, it is very difficult to make up for

the large amounts of reading practice that are missed by children with dyslexia if appropriate instruction is postponed until they have failed in reading for a number of years. Several different remedial studies with older children have now shown that it is possible to significantly "close the gap" in phonemic decoding ability, text reading accuracy, and reading comprehension if older children are provided with interventions that are appropriate and sufficiently intensive, but the fluency gap remains relatively unaffected even by such powerful interventions.[52]

So what is currently known about the utility of measures of phonemic awareness, rapid automatic naming ability, and verbal short-term memory to aid in identifying children with dyslexia so that they can receive powerful interventions before they experience a prolonged period of reading failure? The major points regarding our knowledge in this area can be summarized thus:

1. Among the three constructs discussed in this article, phonemic awareness and rapid automatic naming are the most accurate predictors of early word reading difficulties. In constructing a predictive battery, measures of verbal short-term memory do not need to be included as long as measures of either phonemic awareness or rapid automatic naming are included.[32]
2. Measures of letter-name knowledge (early kindergarten) or letter-sound knowledge (later kindergarten) are equal or better predictors of early word reading difficulties than either phonemic awareness or rapid automatic naming ability and should always be included in a battery to identify children who are likely to experience difficulties in early reading growth.[46,53] Rapid automatic naming tasks do not substantially add predictive power to a battery that already contains a measure of letter knowledge and phonemic awareness, nor do phonemic awareness tasks usually improve predictive accuracy when added to a battery containing a good measure of letter knowledge plus a rapid automatic naming task involving letters or digits.
3. Although measuring phonemic awareness or rapid automatic naming ability in children before they begin to learn to read can clearly increase the accuracy of identification of "at-risk" students beyond chance levels, predictive accuracy from a single administration of rapid automatic naming or phonemic awareness tasks (even when the battery includes a measure of letter knowledge) is still not as strong as we would like it to be. The basic problem is that to ensure that most children who will actually develop word-level reading difficulties are identified in the screening, cutpoints for performance must be set that produce an unacceptably high number of false-positives.[54,55] One general rule is that to ensure that almost all of the students at a given level of risk are identified, at least double that number of students must be included in the at-risk group. So if a school district wanted to identify almost all of the students who were destined to be in the bottom 10% in word reading ability at the end of first grade, they would end up identifying approximately 20% of the children as being at risk.

   One solution to the problems inherent in single screening assessments of phonemic awareness and letter knowledge (both of which are responsive to instruction) is to monitor progress in the growth of these skills several times during kindergarten and first grade. The advantage of multiple assessments is that they can provide an indication of children's response to the instruction they are receiving, and they can be used to identify children who are not keeping pace with expected levels of growth before the learning failure has become too severe.[56,57]
4. The advantage of frequent progress monitoring in the development of phonemic awareness, letter knowledge, and eventually phonemic decoding skills themselves is that predictive accuracy improves as the children become older.[35,55] If there is a system in place within schools that assesses performance several times a year, then predictive accuracy will be continually updated, and at-risk students who might have been missed in an earlier assessment will be identified as soon as their difficulties begin to emerge.
5. Once children actually begin to learn to read (around the second semester of first grade), the best diagnostic indicators of dyslexia are measures of phonemic decoding efficiency and text reading fluency, not measures of phonemic awareness and rapid automatic naming.[58] Once information is obtained about children's actual progress in learning to read words accurately and fluently, the more distal measures of phonemic awareness and rapid automatic naming actually add very little to the diagnostic accuracy of identifying children with dyslexia.

SUMMARY AND CONCLUSION

The last 20 to 30 years of research on children with dyslexia have produced an amazingly convergent and powerful theoretic understanding of the nature of their reading difficulties and the underlying cognitive or linguistic deficits that cause them.[59] These children experience early difficulties mastering the alphabetic principle, which leads directly to both inaccurate and dysfluent text-reading skills. The inability to read the words in text accurately and fluently is the primary impediment to reading comprehension in children with dyslexia. We also know that problems in the phonologic language domain are primarily responsible for the difficulties that these children experience in mastering the alphabetic principle. These processing difficulties have an effect on the development of children's phonologic processing skills even before they begin to learn to read words. There is also a clear possibility that many children have an additional type of disability that is measured by naming speed tasks but that disability is not clearly specified at present, nor are its specific effects on the development of accurate and fluent word reading skills well understood. The current best solution to the problem of early identification of children with dyslexia involves frequent progress monitoring of the development of children's phonemic awareness and letter knowledge during the earliest phases of reading instruction.

References

1. Snow CE: *Reading for Understanding: Toward an R&D Program in Reading Comprehension. Report of the RAND Reading Study Group.* Arlington, VA, RAND Education, 1998.
2. Lyon GR, Shaywitz SE, Shaywitz BA: A definition of dyslexia. *Ann Dyslexia* 2003;53:1–14.
3. Share DL, Stanovich KE: Cognitive processes in early reading development: Accommodating individual differences into a model of acquisition. *Issues in Education: Contributions from Educational Psychology* 1995;1:1–57.

4. Ehri L: Phases of acquisition in learning to read words and implications for teaching, in Stainthorp R, Tomlinson P (eds): *Learning and Teaching Reading.* London, British Journal of Educational Psychology Monograph Series II, 2002.
5. Foorman BR, Francis DJ, Shaywitz SE, et al: The case for early intervention, in Blachman B (ed): *Foundations of Reading Acquisition and Dyslexia.* Mahwah, NJ, Lawrence Erlbaum Associates, 1997, 243–264.
6. Reitsma P: Printed word learning in beginning readers. *J Exp Child Psychol* 1983;36:321–339.
7. Allington RL: *What Really Matters for Struggling Readers.* New York, Longman, 2001.
8. Torgesen JK, Rashotte CA, Alexander A: Principles of fluency instruction in reading: Relationships with established empirical outcomes, in Wolf M (ed): *Dyslexia, Fluency, and the Brain.* Parkton, MD, York Press, 2001, 333–355.
9. Manis F, Custodio R, Szeszulski P: Development of phonological and orthographic skill: A 2-year longitudinal study of dyslexic children. *J Exp Child Psychol* 1993;56:64–86.
10. Torgesen JK, Alexander AW, Wagner RK, et al: Intensive remedial instruction for children with severe reading disabilities: Immediate and long-term outcomes from two instructional approaches. *J Learn Disabil* 2001;34:33–58.
11. Liberman IY, Shankweiler D, Liberman AM: The alphabetic principle and learning to read, in Shankweiler D, Liberman IY (eds): *Phonology and Reading Disability: Solving the Reading Puzzle.* Research Monograph Series. Ann Arbor, MI, University of Michigan Press, 1989, 1–33.
12. Fletcher JM, Shaywitz SE, Shankweiler DP, et al: Cognitive profiles of reading disability: Comparisons of discrepancy and low achievement definitions. *J Educ Psychol* 1994;85:1–18.
13. Shatil E, Share DL: Cognitive antecedents of early reading ability: A test of the modularity hypothesis. *J Exp Child Psychol* 2003;86:1–31.
14. Wagner RK, Torgesen JK, Rashotte CA, et al: Changing causal relations between phonological processing abilities and word-level reading as children develop from beginning to fluent readers: A five-year longitudinal study. *Dev Psychol* 1997;33:468–479.
15. Castles A, Coltheart M: Is there a causal link from phonological awareness to success in learning to read? *Cognition* 2004;91:77–111.
16. Wagner RK, Torgesen JK, Rashotte CA: The development of reading-related phonological processing abilities: New evidence of bi-directional causality from a latent variable longitudinal study. *Dev Psychol* 1994;30:73–87.
17. Vellutino F, Schatschneider C: Experimental and quasi-experimental design in literacy research, in Duke N, Mallette M (eds): *Literacy Research Methods.* New York, Guilford Press, 2004, 114-148.
18. Ehri L, Nunes S, Willows D, et al: Phonemic awareness instruction helps children learn to read: Evidence from the National Reading Panel's meta-analysis. *Read Res Q* 2001;36:250–287.
19. Ehri LC: Word reading by sight and by analogy in beginning readers, in Hulme C, Joshi M (eds): *Reading and Spelling: Development and Disorders.* Mahwah, NJ, Lawrence Erlbaum Associates, 1998, 87–112.
20. Torgesen JK: A model of memory from an information processing perspective: The special case of phonological memory, in Lyon GR (ed): *Attention, Memory, and Executive Function: Issues in Conceptualization and Measurement.* Baltimore, MD, Paul H. Brookes, 1996, 157–184.
21. Gathercole S, Willis C, Baddeley A, Emslie H: The Children's Test of Nonword Repetition: A test of phonological working memory. *Memory* 1994;2:103–127.
22. Baddeley AD: *Working Memory.* Oxford, UK, Clarendon Press, 1986.
23. Campbell R, Butterworth B: Phonological dyslexia and dysgraphia in a highly literate subject: A developmental case with associated deficits of phonemic processing and awareness. *Q J Exp Psychol* 1985;37: 435–475.
24. Snowling MJ, Hulme C: A longitudinal case study of developmental phonological dyslexia. *Cogn Neuropsychol* 1989;6:379–401.
25. Temple CM, Marshall JC: A case study of developmental phonological dyslexia. *Br J Psychol* 1983;74:517–533.
26. Hulme C: Short-term memory development and learning to read, in Gruneberg M, Morris P, Sykes R (eds): *Practical Aspects of Memory: Current Research and Issues, vol 2. Clinical and Educational Implications.* Chichester, UK, Wiley, 1998, 234–271.
27. Torgesen JK: Performance of reading disabled children on serial memory tasks: A review. *Read Res Q* 1978;19:57–87.
28. Torgesen JK, Houck G: Processing deficiencies in learning disabled children who perform poorly on the digit span task. *J Educ Psychol* 1980;72:141–160.
29. Torgesen JK, Rashotte CA, Greenstein J, et al: Academic difficulties of learning disabled children who perform poorly on memory span tasks, in Swanson HL (ed): *Memory and Learning Disabilities: Advances in Learning and Behavioral Disabilities.* Greenwich, CT, JAI Press, 1987, 217–232.
30. Bishop AG: Prediction of first-grade reading achievement: A comparison of fall and winter kindergarten screenings. *Learn Disabil Q* 2002;26:189–200.
31. Plaza M, Cohen H: The interaction between phonological processing, syntactic awareness, and naming speed in the reading and spelling performance of first-grade children. *Brain Cogn* 2003;53:287–292.
32. Wagner RK, Torgesen JK, Rashotte CA: The development of reading-related phonological processing abilities: New evidence of bi-directional causality from a latent variable longitudinal study. *Dev Psychol* 1994;30:73–87.
33. Wagner RK, Torgesen JK, Laughon P, et al: The development of young readers' phonological processing abilities. *J Educ Psychol* 1993;85:1–20.
34. Wolf M: *Dyslexia, Fluency, and the Brain.* Parkton, MD, York Press, 2001.
35. Wolf M, Bowers PG: The double deficit hypothesis for the developmental dyslexias. *J Educ Psychol* 1999;91:415–438.
36. Bowers PG, Golden J, Kennedy A, Young A: Limits upon orthographic knowledge due to processes indexed by naming speed, in Berninger VW (ed): *The Varieties of Orthographic Knowledge I: Theoretical and Developmental Issues.* Dordrecht, the Netherlands, Kluwer Academic Publishers, 1994, 173–218.
37. Bowers PG, Wolf M: Theoretical links between naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing: An Interdisciplinary Journal* 1993;5:69–85.
38. Wagner RK, Torgesen JK: The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychol Bull* 1987;101:192–212.
39. Torgesen JK, Wagner RK: Alternative diagnostic approaches for specific developmental reading disabilities. *Learn Disabil Res Pract* 1998;13:220–232.
40. Neuhaus GF, Swank PR: Understanding the relations between RAN letters subtest components and word reading in first grade students. *J Learn Disabil* 2002;35:1–12.
41. Denckla MB, Cutting LE: History and significance of rapid automatized naming. *Ann Dyslexia* 1999;49:29–42.
42. Catts HW, Gillispie M, Leonard LB, et al: The role of speed of processing, rapid naming, and phonological awareness in reading achievement. *J Learn Disabil* 2002;35:510–525.
43. Bowers PG: Exploration of the basis for rapid naming's relationship to reading, in Wolf M (ed): *Dyslexia, Fluency, and the Brain. Parkton,* MD, York Press, 2001, 41–63.
44. Compton DL: The influence of item composition on RAN letter performance in first grade children. *J Spec Educ* 2004;37:81–94.
45. Misra M, Katzir T, Wolf M, Poldrack RA: Neural systems for rapid automatized naming (RAN) in skilled readers: Unraveling the RAN-reading relationship. *Sci Stud Read* 2004;8:241-256.
46. Schatschneider C, Fletcher JM, Francis DJ, et al: Kindergarten prediction of reading skills: A longitudinal comparative analysis. *J Educ Psychol* 2004;96:265–282.
47. Meyer MS, Wood FB, Hart LA, Felton RH: Longitudinal course of rapid naming in disabled and nondisabled readers. *Ann Dyslexia* 1998;48:91–114.
48. Wolf M, Bally H, Morris R: Automaticity, retrieval processes, and reading: A longitudinal study in average and impaired readers. *Child Dev* 1986;57:988–1000.
49. Barker TA, Torgesen JK, Wagner RK: The role of orthographic processing skills on five different reading tasks. *Read Res Q* 1992; 27:334–345.

50. Cunningham AE, Stanovich KE: Tracking the unique effects of print exposure in children: Associations with vocabulary, general knowledge, and spelling. *J Educ Psychol* 1991;83:264–274.

51. Stanovich KE, West RF: Exposure to print and orthographic processing. *Read Res Q* 1989;24:402–433.

52. Torgesen JK: Recent discoveries from research on remedial interventions for children with dyslexia, in Snowling M, Hulme C (eds): *Advances from Research on Dyslexia*. Oxford, UK, Blackwell Publishers 2004, in press.

53. Scarborough HS: Early identification of children at risk for reading disabilities: Phonological awareness and some other promising predictors, in Shapiro BK, Capute AJ, Shapiro B (eds): *Specific Reading Disability: A View of the Spectrum*. Hillsdale, NJ, Lawrence Erlbaum Associates, 1998, 77–121.

54. Blachman B: Phonological awareness, in Kamil M, Mosenthal P, Pearson P, Barr R (eds): *Handbook of Reading Research*, vol 3. Mahwah, NJ, Lawrence Erlbaum Associates, 2002, 483–502.

55. Torgesen JK, Burgess SR: Consistency of reading-related phonological processes throughout early childhood: Evidence from longitudinal-correlational and instructional studies, in Metsala J, Ehri L (eds): *Word Recognition in Beginning Reading*. Hillsdale, NJ, Lawrence Erlbaum Associates, 1998, 161–188.

56. Good RH, Simmons DC, Kame'enui E: The importance and decision-making utility of a continuum of fluency-based indicators of foundational reading skills for third-grade high-stakes outcomes. *Sci Stud Read* 2001;5:257–288.

57. Good RH, Simmons D, Kame'enui E, et al: *Summary of Decision Rules for Intensive, Strategic, and Benchmark Instructional Recommendations in Kindergarten Through Third Grade. Technical Report No. 11*. Eugene, University of Oregon, 2002.

58. Torgesen JK, Al Otaiaba S, Grek M: Assessment and instruction for phonemic awareness and word reading skills, in Catts HW, Kamhi AG (eds): *Language Basis of Reading Disabilities*. 2nd ed. Needham Heights, MA, Allyn & Bacon, 2004, in press.

59. Shaywitz SE: *Overcoming Dyslexia*. New York, Alfred A. Knopf, 2003.

Special Article

Developmental Dyscalculia

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ABSTRACT

Developmental dyscalculia is a specific learning disability affecting the normal acquisition of arithmetic skills. Genetic, neurobiologic, and epidemiologic evidence indicates that dyscalculia, like other learning disabilities, is a brain-based disorder. However, poor teaching and environmental deprivation have also been implicated in its etiology. Because the neural network of both hemispheres comprises the substrate of normal arithmetic skills, dyscalculia can result from dysfunction of either hemisphere, although the left parietotemporal area is of particular significance. The prevalence of developmental dyscalculia is 5 to 6% in the school-aged population and is as common in girls as in boys. Dyscalculia can occur as a consequence of prematurity and low birthweight and is frequently encountered in a variety of neurologic disorders, such as attention-deficit hyperactivity disorder (ADHD), developmental language disorder, epilepsy, and fragile X syndrome. Developmental dyscalculia has proven to be a persisting learning disability, at least for the short term, in about half of affected preteen pupils. Educational interventions for dyscalculia range from rote learning of arithmetic facts to developing strategies for solving arithmetic exercises. The long-term prognosis of dyscalculia and the role of remediation in its outcome are yet to be determined. (*J Child Neurol* 2004;19:765–771).

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Arithmetic is of prime importance in everyday life, enabling us to comprehend number concepts and perform calculations. Budgeting our time and monetary resources, reading calendars, locating an address, and even following a recipe are examples of our dependence on elementary arithmetic skills. Yet the study of the various aspects of the normal and abnormal development of arithmetic has not received the same attention as have other learning disabilities.[1] In the case of dyslexia, its neurobiology has been convincingly demonstrated, and effective remedial options have been introduced and implemented.[2] But for dyscalculia, these issues have been relatively neglected, and only recently have they become the subject of scientific interest. In this review, I describe the clinical, biologic, and genetic aspects of dyscalculia and the role of the physician and educator in its diagnosis and management.