Psychological Bulletin
2012, Vol. 138, No. 2, 322–352

0033-2909/12/$12.00 DOI: 10.1037/a0026744

Phonological Skills and Their Role in Learning to Read: A Meta-Analytic Review

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The authors report a systematic meta-analytic review of the relationships among 3 of the most widely studied measures of children's phonological skills (phonemic awareness, rime awareness, and verbal short-term memory) and children's word reading skills. The review included both extreme group studies and correlational studies with unselected samples (235 studies were included, and 995 effect sizes were calculated). Results from extreme group comparisons indicated that children with dyslexia show a large deficit on phonemic awareness in relation to typically developing children of the same age (pooled effect size estimate: −1.37) and children matched on reading level (pooled effect size estimate: −0.57). There were significantly smaller group deficits on both rime awareness and verbal short-term memory (pooled effect size estimates: rime skills in relation to age-matched controls, −0.93, and reading-level controls, −0.37; verbal short-term memory skills in relation to age-matched controls, −0.71, and reading-level controls, −0.09). Analyses of studies of unselected samples showed that phonemic awareness was the strongest correlate of individual differences in word reading ability and that this effect remained reliable after controlling for variations in both verbal short-term memory and rime awareness. These findings support the pivotal role of phonemic awareness as a predictor of individual differences in reading development. We discuss whether such a relationship is a causal one and the implications of research in this area for current approaches to the teaching of reading and interventions for children with reading difficulties.

Keywords: phonological awareness, reading, decoding, rime awareness, short-term memory

Supplemental materials: http://dx.doi.org/10.1037/a0026744.supp

Research on the foundations of learning to read has important theoretical and practical implications and has burgeoned in the last 20 years. This review focuses on the processes involved in the development of children's word reading: the ability to translate printed words into a speech code, as typically assessed by the accuracy and speed of reading aloud. Efficient word reading is, in turn, a necessary but not sufficient condition for the development of reading comprehension (Gough & Tunmer, 1986; Lervåg & Aukrust, 2010; Oakhill, Cain, & Bryant, 2003; Perfetti, Landi, & Oakhill, 2005). It is now well established that there is a close relationship between children's phonological (speech sound) skills and the development of word reading skills (National Institute for Literacy, 2008; Wagner & Torgesen, 1987). However, the details of this relationship remain controversial. One source of controversy is whether some phonological skills are more closely related to the development of word reading than others. This is a question about the structure of phonological skills and whether it is important to distinguish between different phonological abilities in relation to learning to read. A second source of controversy concerns issues of causality. Probably the dominant view among researchers in the field of reading development has been that variations in phonological skills are one cause of variations in how well children are able to learn to read (Anthony & Francis, 2005; Bradley & Bryant, 1978; Wagner & Torgesen, 1987). However, some have argued quite vehemently for the opposite causal hypothesis: that phonological skills are related to reading development but only because the process of learning to read changes children's phonological abilities (e.g., Castles & Coltheart, 2004). In this review we focus on two key theoretical issues: the nature of explicit phonological awareness and its possible role in the development of children's word reading skills, and the possible role of implicit phonological processing skills, particularly phonological memory skills, in the development of children's word reading.

In this article we concentrate on trying to systematize the large literature that has examined the degree of association between different measures of phonological awareness, phonological memory, and children's word reading skills. We believe that this correlational literature in turn has important implications for a variety of causal hypotheses about the role of phonological skills in learning to read. After presenting a systematic meta-analytic review of the evidence from correlational studies, we return to

This article was published Online First January 16, 2012.

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questions about the possible causal status of the effects demonstrated in the Discussion.

The Nature, Structure, and Development of Phonological Skills

An important distinction in relation to phonological skills and the development of word reading skills is that between implicit and explicit phonological processing. Implicit phonological processing tasks are those where phonological processing is automatically engaged, such as verbal short-term memory tasks or rapid automatized naming (RAN). These tasks require access to phonological codes without any explicit reflection on, or awareness of, the sound structure of spoken words. In contrast, explicit phonological tasks, which are usually referred to as phonological awareness or phonological sensitivity tasks, require the child to reflect upon and manipulate the speech sounds in words (Gombert, 1992). In the present review we use the term *phonological awareness* to refer to such tasks. In studies of reading development and reading disorders, measures of phonological awareness have been used more widely than measures of implicit phonological processing. We consider each in turn below.

According to current theories of developmental dyslexia (see Hulme & Snowling, 2009, for a review), the most widely accepted view is that the deficits in implicit and explicit phonological tasks shown by children with reading difficulties reflect a basic deficit in how the sound structures of words are represented in the brain (the phonological representations hypothesis). According to this hypothesis, children with dyslexia possess "coarsely coded, underspecified or noisy" (Szenkovits & Ramus, 2005, p. 254) phonological representations. In this view, difficulties on a wide array of phonological processing tasks and problems in learning to read words may all be products of a basic problem in representing phonological information (see Snowling & Hulme, 1994; Swan & Goswami, 1997). A critical question, in relation to the phonological representations hypothesis, is to specify what aspects of phonological representations are critical for successfully learning to read. This is a difficult question to answer, because such representations can never be directly observed. Rather, their properties have to be inferred from patterns of behavior on phonological tasks. A reasonable assumption, however, is that a person lacking phonemically structured phonological representations would find phoneme awareness tasks difficult or impossible to perform. Results from a large number of single studies indicate that performance on phoneme awareness tasks is particularly closely related to variations in the development of children's word reading skills (e.g., Bruno, et al., 2007; Compton, 2000; Georgiou, Parrila, & Papadopoulos, 2008; Lervåg, Bråten, & Hulme, 2009; Pennington, Cardoso-Martins, Green, & Lefly, 2001; Wagner, Torgesen, & Rashotte, 1994), and deficits on such tasks are one of the core symptoms seen in dyslexic children (e.g., Barbosa, Miranda, Santos, & Bueno, 2009; Boada & Pennington, 2006; Fletcher et al., 1994; Frederickson & Frith, 1998). We argue that two reasonable inferences from these findings are that (a) possessing phonemically structured phonological representations is particularly critical for learning to read effectively and (b) dyslexic children have particular difficulties in establishing this level of phonological representation.

Phonological Awareness

Phonological awareness refers to an individual's ability to reflect upon and manipulate the sound structure of spoken words. Many have argued that the development of phonological awareness in children follows a hierarchical pattern, progressing from the ability to isolate large sound units (words or syllables) to intermediate units (onsets vs. rimes) to small units (phonemes; Stanovich, 1992; Treiman & Zukowski, 1991). The onset–rime division corresponds to the division of a spoken syllable into the consonant or consonant string preceding the vowel (the onset) and the vowel and succeeding consonants (the rime). So, for example, the monosyllabic word *TRIP* can be divided into an onset /TR/ and a rime unit /IP/. Syllables in English do not necessarily have an onset (e.g., *AT* or *IT*), but all syllables must have a rime. Onsets and rimes are in some cases composed of smaller units; for example, the onset of *TRIP*, /TR/, consists of two phonemes, as does the rime unit /IP/. In some cases, however, the onset and the rime unit of a syllable consist of just a single phoneme (as in the word *BE*). The term *rime* refers to the phonological unit of a syllable that follows the onset. In studies of phonological awareness in children, monosyllabic words are invariably used, and we use the term *rime awareness* throughout this article to refer to tasks involving judgments about the similarity between spoken words that share rime units. (We note that rhyming relationships between words with more than one syllable may involve overlap in larger segments of the word than a single rime unit [e.g., *fever*, *believer*], but such cases do not concern us in the present article.)

A wide variety of tasks have been used to assess phonological awareness. These tasks differ in terms of the size of the phonological units manipulated (most commonly syllables, rime units, or phonemes) and the type of judgment that has to be made (from forced-choice judgments, such as "Do these two words start with the same sound?" to more explicit tasks, such as "What word do we make if we take the /b/ sound off of the word *bright*?"). McBride-Chang (2004) argued that tasks assessing small phonological units (phonemes) are harder than tasks assessing larger phonological units (rime units or syllables) and that tasks requiring explicit manipulation of speech sounds are harder than those relying simply on forced-choice judgments.

Undoubtedly, the most widely used tests of phonological awareness have been rime awareness and phonemic awareness tasks. Unfortunately, in many empirical studies (Eisenmajer, Ross, & Pratt, 2005; Gathercole, Alloway, Willis, & Adams, 2006; Petrill, Deater-Deckard, Thompson, DeThorne, & Schatschneider, 2006; Stuart & Coltheart, 1988) and reviews (e.g., Bus & van IJzendoorn, 1999; Ehri et al., 2001; Swanson, Trainin, Necoechea, & Hammill, 2003) these two measures have been conflated and referred to simply as measures of "phonological awareness." In fact, however, there has been considerable controversy about the extent to which rime awareness and phonemic awareness are differentially related to the development of word-level reading skills. A major aim of the current review is to clarify the extent to which these measures differ in terms of their predictive relationships with word reading skill.

One of the clearest and most influential statements of the importance of rime awareness for the development of children's word reading skills was provided by Goswami and Bryant (1990). They argued that children initially learn to read words by paying attention to the letters that correspond to the onset and the rime units of spoken words; and those children who are good at manipulating these units have an advantage over those who are less good (Bradley & Bryant, 1983). They also argued that the ability to attend to phonemes develops later, possibly as a consequence of onsets tending to correspond to phonemes (e.g., /d/ in *dock*) and possibly as a consequence of a reciprocal relationship between reading and phonological awareness (Perfetti, Beck, Bell, & Hughes, 1987). This, then, is a developmental theory that sees children progressing from initially being capable of dealing with relatively large phonological units (syllables, and then shortly afterward onset–rime divisions of the syllable) to later being able to deal with small (phoneme) units. A critical claim of the theory, however, is that children's progress in acquiring early reading skills depends upon onset–rime-level skills and that phonemic skills become important only later in development, possibly as a consequence of learning to read an alphabetic script (see also Ziegler & Goswami, 2005).

In contrast to theories that see rime awareness as a critical foundation for children's word reading skills, several studies suggest that when direct comparisons are made between the two, phonemic awareness is a more powerful predictor of children's word reading skills than rime awareness. For example, data from a number of concurrent correlational studies (Bowey, Cain, & Ryan, 1992; Hatcher & Hulme, 1999; Høien, Lundberg, Stanovich, & Bjaalid, 1995; Mann & Foy, 2003; Nation & Hulme, 1997) show that phonemic awareness is a stronger predictor of reading and spelling development than rime awareness, at least from the age of 6–7 years. Similarly, data from three longitudinal studies (Hulme et al., 2002; Muter, Hulme, Snowling, & Stevenson, 2004; Muter, Hulme, Snowling, & Taylor, 1998) have supported the conclusion that when phonemic awareness and rime awareness are measured prior to, or in the early stages of, learning to read, measures of phonemic awareness are more powerful concurrent and longitudinal predictors of children's word reading skills than are measures of rime awareness.

Although some may feel there is a growing consensus that phonemic awareness tasks are particularly strong correlates of individual differences in children's word reading skills (e.g., National Institute for Literacy, 2008), controversy in this area continues. It is possible to discern at least three influential positions with regard to the relationships between phonemic awareness, rime awareness, and children's word reading that are proposed by different researchers in the field. According to the first, rime awareness is a critical foundation for learning to read words, and phonemic awareness is essentially a by-product of having learned to read (e.g., Goswami & Bryant, 1990; Ziegler & Goswami, 2005). So, for example, Ziegler and Goswami (2005) claimed that "access to phonemes only develops once children are taught to read and write, irrespective of the age at which reading and writing is taught" (p. 6).

A second, opposing view is that phonemic awareness is a critical skill for learning to read. For example, Hulme, Caravolas, Málkova, and Brigstocke (2005) stated:

> We conclude that the present data are consistent with the theory that variations in children's nascent phonemic manipulation skills, when they start to learn to read, are one important cause of variations in the ability to learn to read in alphabetic languages. (pp. B8–B9)

It should be noted that this view typically accepts that there is a reciprocal relationship between phonemic awareness and learning to read, so that the development of word reading skills leads to further refinements in phonemic awareness (Bentin & Leshem, 1993; Burgess & Lonigan, 1998; Perfetti et al., 1987).

A third view, adopted by some other researchers (Anthony & Lonigan, 2004; Anthony et al., 2002; Papadopoulos, Spanoudis, & Kendeou, 2009), is that phonological awareness is best regarded as a unitary skill, in the sense that it is not useful or important to distinguish between different sizes of phonological unit when predicting individual differences in word reading skill. For example, Anthony and Francis (2005) stated, "Methodologically sound studies using large samples, multiple measures, and advanced statistics support a unified phonological awareness construct—that is, phonological awareness as a single cognitive ability that manifests behaviorally in a variety of skills" (p. 256).

The issue of the relative importance of phonemic versus rime awareness as correlates of word reading ability speaks to whether phonological skills can be regarded as unitary or whether different sized phonological units play differential roles in learning to read words. There are now many different studies, over different developmental periods and in different languages, that have assessed the role of phonemic awareness and rime awareness as predictors of variations in children's word reading skills. Similarly, there are many studies that have compared phonemic awareness and rime awareness tasks in dyslexic and typically developing readers. In the present review, we directly compare the relative strength of association between measures of phonemic awareness and rime awareness and children's word reading ability. If phonemic awareness shows a particularly close relationship to the development of children's word reading skills, this has important implications for the theoretical positions just described and for practical concerns about how best to teach reading skills and to treat children's reading difficulties.

Implicit Phonological Tasks

Implicit phonological processing tasks require access to phonological codes without any explicit reflection on, or awareness of, the sound structure of spoken words. Two widely used measures of phonological processing are RAN and verbal short-term memory tasks such as digit span. Verbal short-term memory tasks, such as digit and word span, are probably the most widely used measures of implicit phonological processing.

As in the case of studies of the relationship between reading development and phonological awareness, there are a number of different theoretical positions regarding the best explanation for the association between reading development and verbal short-term memory processes. One view is that there is a causal connection between variations in verbal short-term memory and learning to read words that is separable from other aspects of phonological processing and language ability (Gathercole & Baddeley, 1993; Wagner & Torgesen, 1987). Some have argued that the efficient operation of phonological codes in memory is necessary for various phonological processes, such as segmenting and blending sounds in spoken words, which are involved in learning to read words (Baddeley, 1986; Beneventi, Tønnessen, Ersland, & Hugdahl, 2010; Gathercole & Baddeley, 1993; Wagner &

Torgesen, 1987). For example, Gathercole and Baddeley (1993) stated:

> Both these suggestions—that phonological memory contributes to the learning of letter–sound correspondences, and that it may store sound segments generated during phonological recoding—provide the possible basis for the causal link between phonological memory and later reading and spelling. (p. 172)

In contrast, others have argued that verbal short-term memory tasks are not directly related to variations in children's word reading skills, once other underlying phonological skills that contribute to short-term memory performance and learning to read are controlled. In this view, verbal short-term memory measures are only correlated with reading ability because both rely on access to phonological information and "short-term memory capacity in itself may not have much effect on the process of learning to read" (McDougall, Hulme, Ellis, & Monk, 1994, p. 128). According to this view, verbal short-term memory tasks involve access to the same phonological representations that underlie phonological awareness tasks (Melby-Lervåg & Hulme, 2010), and correlations between verbal short-term memory abilities and word reading are actually reducible to a more fundamental relationship between the quality of underlying phonological representations and learning to read (Hulme & Roodenrys, 1995; Wagner, Torgesen, Laughon, Simmons, & Rashotte, 1993).

In this review, we assess the strength of association between measures of verbal short-term memory and the development of children's word reading skills. A critical issue, as in the case of phonological awareness, is the extent to which different correlated skills can be separated. Specifically, we assess the extent to which verbal short-term memory is a correlate of variations in children's word reading skills after accounting for effects that may be attributable to other measures of phonological skills, particularly measures of phonemic awareness.

Differences Among Languages in How Phonological Skills Relate to Learning to Read

Studies of the role of phonological skills in learning to read have, until recently, been largely restricted to children learning to read in alphabetic orthographies, and these studies have predominantly involved children learning to read in English. There is now a growing recognition that phonological skills may also be intimately involved in learning to read in nonalphabetic orthographies such as Chinese as well as alphabetic languages (Hanley, 2005; McBride-Chang et al., 2005). This review, however, is restricted to considering the role of phonological skills in learning to read in alphabetic scripts.

Within alphabetic scripts it has sometimes been argued that English, the most studied script, is an "outlier" in terms of the consistency with which letters in printed words map onto the phonemes in spoken words (Share, 2008). Indeed, many other orthographies, such as Italian, German, and Spanish, show considerably greater degrees of spelling-to-sound consistency. However, others have argued that phonological awareness plays a universal role in predicting variations in word reading skill across more and less consistent alphabetic orthographies (e.g., Caravolas, Volín, & Hulme, 2005; Ziegler et al., 2010). In the current review, we assess the extent to which patterns of prediction from phonological skills to word reading may differ between English and other, more consistent orthographies. For the studies comparing children with dyslexia and control children, there were 91 English studies and 36 studies from 10 other, more consistent orthographies. For the correlational studies, there were 125 English studies and 30 studies spanning 14 other, more consistent orthographies.

Letter Knowledge

Letter knowledge is a strong predictor of individual differences in early word reading skills. For example Bond and Dyjkstra (1967) reported correlations varying between .5 and .6 for letter knowledge assessed at the beginning of first grade and word identification skills measured at the end of the school year; Muter et al. (2004) reported a correlation of .35 between letter knowledge assessed at the beginning of Year 1 and reading skills assessed 1 year later. High correlations between letter knowledge and later decoding skills are also reported in other longitudinal studies (Badian, 1998; Roth, Speece, & Cooper 2002; Stephenson, Parrila, Georgiou, & Kirby, 2008). Studies differ in whether they assess letter–name or letter–sound knowledge. In the United States, typically children are taught letter names first (Treiman, Pennington, Shriberg, & Boada, 2008), and U.S. studies typically report relationships between letter–name knowledge and reading ability (e.g., Bond & Dyjkstra, 1967). Conversely, in the United Kingdom and many other European countries, letter sounds are usually taught before letter names, and accordingly studies in these countries often report measures of letter–sound knowledge. Many studies do not distinguish between letter–name and letter–sound knowledge and report a composite measure of both skills (Lervåg et al., 2009; Muter et al., 2004).

A small number of studies (e.g., Caravolas, Hulme, & Snowling, 2001; McBride-Chang, 1999) have reported separate measures of letter–name and letter–sound knowledge from the same children, and in those studies both measures (name and sound knowledge) are typically correlates of reading ability. Concurrent measures of letter–name and letter–sound knowledge typically correlate moderately with each other (.43–.80 at different time points in McBride-Chang, 1999, and Caravolas et al., 2001), and both measures typically correlate with reading ability, with letter–sound knowledge tending to show the stronger relationship (Caravolas et al., 2001; McBride-Chang, 1999).

The explanation for the role of letter knowledge as a predictor of learning to read may be multifaceted. Perhaps most obviously, knowledge of letter–sounds is fundamental to the child's understanding of the alphabetic principle: the way in which individual speech sounds in spoken words are represented by letters in printed words (Byrne & Fielding-Barnsley, 1989). In this view, a good knowledge of letter–sound correspondences is a fundamental foundation for learning to read, because it provides the child with a self-teaching strategy whereby unknown words can be "sounded out" on a letter-by-letter basis and so decoded (Jorm & Share, 1983; Share, 1995, 1999). By successfully decoding unfamiliar words, a child may add such words to the set of words that he or she can recognize directly "by sight." There is also the possibility that learning letter names and sounds provides a measure of the sort of visual–phonological learning that is fundamental to learning to read. For example, Hulme, Goetz, Gooch, Adams, and Snowling (2007) showed that a measure of paired-associate learning (associating abstract shapes with a nonsense word) was a concurrent predictor of individual differences in reading skill among children. Such visual–verbal paired-associate learning is directly analogous to the process of learning to associate letters with their sounds or names.

Whatever the mechanisms that explain the association between letter knowledge and reading development, there is no doubt that it is an important predictor and one that is partly independent of the effects of phonological awareness and phonological processing (Lervåg et al., 2009; Muter et al., 2004). We return to the role of letter knowledge in learning to read in the Discussion.

Relationship of This Review to Previous Reviews

Research on the role of phonological skills and learning to read is a mature field, and there have been a number of previous narrative reviews in this area (e.g., Brady, 1986; Castles & Coltheart, 2004; Cooney & Swanson, 1987; Jorm, 1983; MacMillan, 2002; Mody, 2003; Torgesen, 1978–1979; Wagner, 1986; Wagner & Torgesen, 1987). There have also been a number of meta-analytic reviews dealing with the role of phonological skills and learning to read (Hammill & McNutt, 1981; National Institute for Literacy, 2008; Scarborough, 1998; Swanson et al., 2003; Wagner, 1988), as well as meta-analyses of the nonword reading deficit seen in children with dyslexia (Herrman, Matyas, & Pratt, 2006; Metsala, Stanovich, & Brown, 1998) and of the effects of phonological awareness training on reading skills (Bus & van IJzendoorn, 1999; Ehri et al., 2001; National Institute for Literacy, 2008).

We contend that a further meta-analysis is needed of the large literature dealing with phonological skills and learning to read. Our aim in conducting such a meta-analysis is to clarify the relative importance of different measures of phonological ability as predictors of word reading ability. This question is of theoretical and practical importance. Theoretically, there has been much debate about the possible role of phonemic awareness, rime awareness, and verbal short-term memory as possible influences on children's word reading skills. The present review clarifies the strength of association between these different abilities and children's word reading skills, with important implications for theories of reading development. On a practical level, such knowledge is also relevant to debates about how best to teach reading and methods for treating reading disorders.

The Current Review

Our meta-analysis examines studies using three designs. First, we present a series of meta-analyses comparing children with dyslexia to age-matched and reading-level-matched control children on measures of phonemic awareness, rime awareness, and verbal short-term memory. We then present a further series of meta-analyses examining the strength of correlation in unselected groups of children between word reading skills and measures of phonemic awareness, rime awareness, and verbal short-term memory.

Meta-Analytic Methods

In the current meta-analyses, we use random-effects models, which assume that there is systematic variation between studies in the effect sizes that they obtain (Borenstein, Hedges, Higgins, & Rothstein, 2009). Using random-effects models leads naturally to the consideration of factors (moderators) that differ between studies that may account for the variations in effect sizes obtained. In the current article, we consider a wide range of potential moderators of the effect sizes obtained in different studies, including age, reading level, IQ, oral language ability, orthography (i.e., language of instruction), and the type of test used to assess key constructs. We also consider a number of measures of methodological quality of the studies as potential moderators. We describe in detail the moderators used in the Method section; here we briefly outline the rationale for some possibly critical moderators that we use: age of children in a study, reading level, IQ, oral language skills, reading test type, and orthography (language of instruction).

Studies comparing children with dyslexia to typically developing readers vary in the severity of the reading problem used for the diagnosis of dyslexia (reading level), as well as the oral language skills and nonverbal IQ levels of the children selected. The studies also differ as to whether they use a nonword or a word reading test (or a composite of the two) to diagnose dyslexia. We therefore examined these factors as possible moderators of the effect sizes obtained. It might be expected that studies selecting children with more severe reading problems and with greater discrepancies between their reading level and oral language and IQ levels, might show larger effect sizes.

Age is another potentially important influence on the effect size obtained in a study, because it has sometimes been argued that rime skills are critical for the early stages of learning to read, whereas phonemic skills come in to play only when children are older, possibly partly as a consequence of learning to read (e.g., Ziegler & Goswami, 2005). Using age as a moderator in our analyses allows us to address this issue.

The language of instruction is another potentially important influence on the effect size obtained in a study, because it has sometimes been argued that phonemic awareness is critical for learning to read only in irregular orthographies (of which English is the most extreme and most studied example), whereas in regular orthographies such as German phonemic awareness is not an important limiting factor for children learning to read (Aro & Wimmer, 2003; Seymour, Aro, & Erskine, 2003; Wimmer, 1993). In the meta-analyses presented, we consider language of instruction (orthography) as a moderator of differences in effect size across studies.

Summary of the Aims of This Review

This article presents a systematic meta-analytic review of the relationships between children's word reading skills and the three most commonly assessed measures of phonological ability: phonemic awareness, rime awareness, and verbal short-term memory. We seek to establish the strength of the relationship between each of these measures and children's word reading skills. As we have documented, each of these skills has been claimed by some authors to be a potential causal influence on the development of children's word reading skills. A basic prerequisite of such causal theories is to demonstrate robust correlations between these putative causes and variations in reading skill. A further issue, if reliable correlations are found between each of these correlated skills and reading, is to establish whether the effects are reducible to a unitary construct (a general phonological ability construct) or whether, in contrast, it is necessary to conclude that certain specific phonological skills play a particularly critical role in the development of children's word reading skills. We emphasize, however, that identifying highly specific correlations between key phonological skills and individual differences in children's word reading skills cannot establish any causal connections between these variables. We return to a consideration of the issue of the possible causal status of effects in the Discussion.

On the basis of the studies described above, we have the following hypotheses we wish to test in our meta-analyses:

Hypothesis 1: Phonemic awareness, rime awareness, and verbal short-term memory will all be significant correlates of individual differences in children's word reading skills, whether assessed in extreme group comparison studies or in correlational studies with unselected samples of children.

Hypothesis 2: Of these three predictors, phonemic awareness will be most closely associated with individual differences in children's word reading skills.

Hypothesis 3: Correlational studies allow us to examine the extent to which each of these three predictors (phonemic awareness, rime awareness, and verbal short-term memory) is independently associated with individual differences in children's word reading after controlling for the effects of the other two. Our hypothesis is that only phonemic awareness will be an independent predictor of individual differences in children's word reading skills.

Method

To ensure methodological rigor, our study was designed and reported in line with the consensus statement for meta-analyses of observational studies by Stroup et al. (2000).

Data Collection, Inclusion Criteria, and Coder Reliability

The data collection, coding, and inclusion process is summarized in Figure 1. Notably, only studies published in English were included in the meta-analysis. When locating studies, we used combinations of keywords related to reading (*reading*, *reading level*, *word recognition*, *decoding*) crossed with terms related to memory (*short-term memory*, *working memory*, *verbal memory*, and *memory span*) and phonological awareness (*phon** *awareness*, *phon** *sensitivity*, *metalinguistic awareness*, *rime awareness*). Citations from 1975 to October, 21, 2011, for peer-reviewed journals, book chapters, reports, non-peer-reviewed journals, dissertations, and conference proceedings were collected. The following journals were also hand searched: *Annals of Dyslexia*, *Dyslexia*, *Journal of Research in Reading*, *Scientific Studies in Reading*, *Reading and Writing*, and *Reading Research Quarterly*.

Preestablished criteria were used to specify acceptable measures that were to represent reading, phonemic awareness, rime awareness, and verbal short-term memory. We focused on studies that assessed the accuracy or fluency of word recognition in reading and included measures of accuracy or fluency of word or nonword reading. Studies with a composite reading measure based on both accuracy and comprehension were also included, but studies that assessed only reading comprehension were excluded.

Measures of phonemic awareness had to involve the manipulation, generation, or detection of phonemes in spoken words or nonwords. Some common tests consist of a combination of phoneme and syllable items. Such measures were coded as measures of phonemic awareness if the majority of the items involved phoneme manipulation. Rime awareness measures had to involve the manipulation, generation, or detection of rimes in spoken words or nonwords. Studies reporting data based on composite scores from rime- and phoneme-based measures were not included.

Measures of verbal short-term memory involved tasks where the child was instructed to repeat a spoken list of words in the same order as presented immediately after presentation. Working memory measures where the child has to respond to a distracter task before or during recall were not included. In addition, backward span tasks, such as backward digit span, where the list presented has to be recalled in reverse order, were excluded as well, because such measures are typically regarded as tapping working memory processes (studies using composite scores of forward and backward digit span were not included either). Measures of working memory were excluded because theoretical accounts linking decoding to memory have mainly focused on verbal short-term memory rather than working memory tasks that require both processing and recall (see Gathercole & Baddeley, 1993; Wagner & Torgesen, 1987). In addition, several studies using confirmatory factor analysis have demonstrated that working memory and verbal short-term memory measures tap different, although related, abilities and correlate differently with higher level skills (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Gathercole, Pickering, Ambridge, & Wearing, 2004).

Several precautions were taken to avoid including data from the same sample more than once. In cases where studies reported more than one measure of phonemic awareness, phoneme deletion was used, as many studies have established that this is a measure with high reliability (e.g., Lervåg et al., 2009). Also, since many studies used this measure, selecting phoneme deletion serves to make the studies of phonemic awareness that are analyzed less diverse. If a study used more than one rime awareness measure, measures of rime generation rather than rime detection (such as the rime oddity task) were included, because (a) rime oddity tasks can be solved also at a phoneme level (MacMillan, 2002) and (b) rime oddity tasks may be of low reliability (Hulme et al., 2002). If a study reported data from more than one reading test, tests based on word reading were preferred to composite measures of both word and nonword reading, and pure nonword reading tests were coded only if data neither for word reading nor composite tests were reported. When assessing studies from the same author, the studies were examined carefully in order to judge whether they were based on independent samples. In longitudinal studies, data were coded from the first time point after formal reading instruction had started. For intervention studies only pretest data were coded.

All studies were coded twice, and coder reliability was estimated for a random sample of 25% of the studies coded by a doctoral student trained in meta-analysis. The intercoder correlation (Pearson's) for the main constructs (i.e., phoneme awareness, rime awareness, verbal short-term memory, and their correlation with reading) was .99 (95% CI [.98, 1.00], $p < .001$, agreement

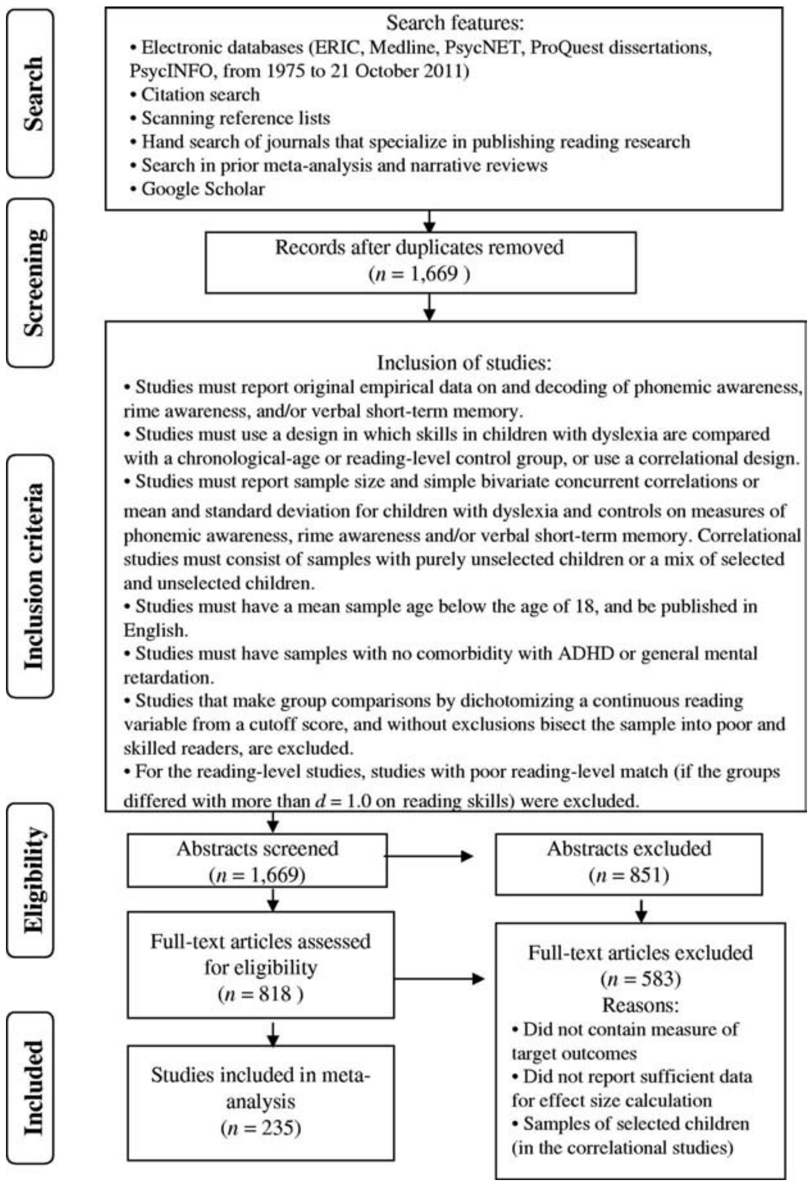

Figure 1. Flow diagram for the search and inclusion of studies. ADHD = attention-deficit/hyperactivity disorder.

rate = 90%). The intercoder correlation for continuous moderator variables was .99 (95% CI [.99, 1.00], $p < .001$, agreement rate = 94%). Cohen's kappa for categorical moderator variables was .99 (95% CI [.99, 1.00], $p < .001$, agreement rate = 99%). Any disagreements were solved by consulting the original article or by discussion.

Coding Protocol and Moderator Variables

For studies reporting group comparisons between children with dyslexia and typically developing control children, means and standard deviations for each group were coded for measures of phonemic awareness, rime awareness, and verbal short-term memory. Variations in effect sizes between the studies were examined and related to key moderator variables. In the original studies, data for all moderator variables except age were based on tests using different scales. To compare data from test-based moderator variables between the studies, we calculated an effect size (d) from the mean and standard deviation for both groups. This effect size was used as a predictor in the metaregression to see whether group differences in the moderator variable predicted variations in group differences on phonemic awareness, rime awareness, and verbal short-term memory between studies. This procedure makes it possible to analyze how differences between studies in their operational definitions of dyslexia (i.e., cutoff levels for IQ, oral language, and reading) affect group differences in phonemic awareness, rime awareness, and verbal short-term memory. For the correlational studies, all combinations of correlations between decoding, phonemic awareness, rime awareness, and verbal short-term memory were coded.

Moderator variables were selected on the basis of prior studies and theory (as outlined in the introduction). In addition, we coded moderators that could be used as indicators for methodological quality. The following moderator variables were coded from the studies involving group comparisons.

Age. Mean age of the samples in months was coded. Notably, the age range for the studies was 5 years 4 months to 16 years 10 months, and none of the samples had children that reached the upper age limit for inclusion (18 years).

Reading. Means and standard deviations for the reading test that determined the classification of participants were coded.

IQ. The means and standard deviations in IQ reported for each group in the original article were coded. For studies that separately report results from verbal and nonverbal IQ, we coded verbal IQ as an oral language measure and nonverbal IQ as IQ. However, a large number of studies reported only a composite of verbal and nonverbal IQ, which we coded as IQ.

Oral language. Means and standard deviations for each group on tests based on receptive vocabulary tests (e.g., British Picture Vocabulary Scale), verbal IQ measures (i.e., verbal composite scores or subtests from the Wechsler Intelligence Scale for Children or verbal scales from other intelligence tests), expressive vocabulary tests (word definition tests or picture naming tests), or listening comprehension tests (e.g., oral cloze) were coded as measures of oral language. The reason for combining these somewhat disparate measures (receptive vocabulary, verbal IQ, expressive vocabulary, and listening comprehension) into a single construct was to get sufficient power in the moderator analysis. Separating the oral language tests into two or more constructs would lead to reduced power in the overall analysis, and in some instances there would not be enough studies to perform a moderator analysis. However, we included oral language test type as a moderator to examine whether this affected study result. In cases with more than one indicator, picture vocabulary tests such as the British Picture Vocabulary Scale were coded, because these measures are widely used and have good internal reliability (e.g., Lervåg & Aukrust, 2010).

Orthography. Orthography was coded as a moderator variable and separated in two categories: consistent and inconsistent (English).

Test type. The type of test used for the main constructs was coded as a moderator. For phonemic awareness, the tests were separated into four categories: composite measures of phoneme and syllable tasks, phoneme deletion (e.g., "What is *bright* if you remove the *b*?"), spoonerism tasks (i.e., requiring the exchange of phonemes between two words, e.g., *cat flap–fat clap*), and other tasks (e.g., phoneme segmentation, phoneme blending, or phoneme detection). Rime awareness was separated into three categories: rime detection tasks (e.g., "Does *hat* rime with *pet*?"), rime generation ("How many words can you say that rhyme with *cat*?"), and rime oddity tasks ("Which word is the odd one out: *cat*, *dog*, *hat*?"). Tests of verbal short-term memory were separated into three categories: word span, digit span, or a composite of the two. Decoding was separated into measures of word reading, nonword reading, or a composite of the two.

Methodological quality. Publication status, peer review status, sampling method, year of publication, test standardization, alpha reliability, and the ratio between the standard deviation and the mean for each of the main constructs measured (i.e., phonemic awareness, rime awareness, and verbal short-term memory) were coded as possible indicators of methodological quality. The ratio between the standard deviation and the mean (coefficient of variability) was calculated by dividing the standard deviation by the mean in each study and multiplying by 100. This statistic expresses the standard deviation as a percentage of the mean. This moderator was used, as there were indications of floor effects (i.e., skewed distributions because of the difficulty level of some measures) for the dyslexic groups in some of the studies.

Meta-Analytic Procedures

The majority of analyses were conducted with the Comprehensive Meta-Analysis program (Borenstein, Hedges, Higgins, & Rothstein, 2005). Effect sizes for studies involving group comparisons were computed with Cohen's *d*, with corrections for small sample sizes (Hedges, 1981). When Cohen's *d* is negative, the control children have the highest group mean. For the correlational studies, we used Pearson's *r*.

Overall effect sizes were estimated by calculating a weighted average of individual effect sizes. A 95% confidence interval (CI) was calculated for each effect size, to examine whether the effect size was significantly larger than 0. CIs were based on a random-effects model, which assumes that variation between studies can be systematic and not simply due to random error. For studies involving group comparisons, a separate effect size was calculated for each of the main constructs (i.e., phonemic awareness, rime awareness, and verbal short-term memory), and for the correlational studies all combinations of pairwise correlations between phonemic awareness, rime awareness, verbal short-term memory, and decoding were coded. We tested the statistical significance of any difference in mean effect sizes between the main constructs.

Forest plots were used to examine the distributions of effect sizes and to detect outliers, and we performed sensitivity analyses to determine the impact of outliers. Sensitivity analyses allow for an adjusted overall effect size to be estimated after removing studies one by one when extreme effect sizes are detected. This procedure makes it possible to report the range of the overall effect size (i.e., highest and lowest effect size) when outliers at each end of the distribution have been taken into account.

To examine the variation in effect sizes between studies, we used the *Q* test of homogeneity (Hedges & Olkin, 1985). We also used I^2 to determine the degree of heterogeneity. I^2 assesses the percentage of between-study variance that is attributable to true heterogeneity rather than random error (Borenstein et al., 2009).

For the continuous moderator variables, we used metaregression based on the method of moments for random-effects models to predict variations in effect size across studies from the moderator variables. We report the percentage of between-study variance explained (R^2) as measure of the effect size of the moderator. We conducted the metaregression using macros developed for SPSS (Lipsey & Wilson, 2001; Wilson, 2006). Such analyses were not conducted when there were fewer than six studies. For categorical moderator variables, we separated studies into subsets based on the categories in the categorical moderator variable, using a *Q* test to examine whether the effect sizes differed between subsets. When there were fewer than three studies in a category, this analysis was not conducted.

For the correlational studies, a correlation matrix was estimated by using a random-effects model to calculate a weighted mean for all combinations of correlations between measures of reading, phonemic awareness, rime awareness, and verbal short-term memory. To compare the relative contribution from each of the predictors of reading, we analyzed the correlation matrix with Cholesky factoring (de Jong, 1999). Cholesky factoring is analogous to hierarchical regression and estimates the independent variance accounted for by a variable after the shared variance with other variables has been partitioned out. The results from the Cholesky factoring are reported in terms of percentage variance explained (R^2) along with a significance test of the unique contribution made by each variable. Because the studies analyzed vary in the number of correlations reported, the sample size also varies for each path in the Cholesky regression model. In all analyses, the sample size used is that corresponding to the path in the Cholesky model representing the variable that is entered last. This therefore gives the independent R^2 value, CI, and significance level for the variable entered last, after the other predictor variables have been controlled.

We examined funnel plots for random-effects models to determine the presence of retrieval bias. In a funnel plot, sample size (or a sample-size-dependent statistic such as standard error) is plotted on the *y*-axis and effect size on the *x*-axis. In the absence of retrieval bias, this plot should form an inverted symmetrical funnel, based on the logic that small studies will typically show more variability in effect sizes than larger studies. Because there are typically fewer larger studies than smaller studies, if there is no publication bias, the scatterplot will be symmetric (Cooper, Hedges, & Valentine, 2009). In the presence of bias, the funnel will be asymmetric. To detect retrieval bias, we examined funnel plots for all analyses presented. Finally, the "trim and fill" (Duval & Tweedie, 2000) method for random-effects models was used to examine the possible influence of studies that may have been missing due to publication bias. The trim and fill method imputes values in the funnel plot to make it symmetrical and calculate an adjusted overall effect size on this basis.

As we coded articles, it became clear that there were numerous instances of missing data. In some cases, if data were critical to calculate an effect size, articles with missing data were excluded (see inclusion criteria in Figure 1). In cases where an effect size could be computed but data were missing on moderator variables, the study was not included in the moderator analysis for which data were missing, but was included in all the analyses for which sufficient data were provided.

Results

For studies involving group comparisons, we present the characteristics of each study in Table 1 of the online supplementary material. For correlational studies, we present parallel characteristics in Table 2 of the online supplementary material. Table 3 of the online supplementary material shows mean bivariate correlations (weighted by random-effects models) between phonemic awareness, rime awareness, and verbal short-term memory effect sizes and moderator variables (chronological age studies below the diagonal, reading-level studies above the diagonal). The number of studies contributing data to each pairwise correlation is also shown.

Comparisons of Children With Dyslexia and Age-Matched Controls

Phonemic awareness. Eighty-eight independent comparisons were made of phonemic awareness in children with dyslexia and age-matched control children. The studies included 2,652 children with dyslexia (mean sample size = 30.13, *SD* = 20.79; range: 9–93) and 3,163 control children (mean sample size = 35.94, *SD* = 43.28; range: 8–333). Effect sizes with CIs for the different studies are shown in Figure 2. The overall mean effect size was large and significant ($d = -1.37$, 95% CI [−1.50, −1.23]), confirming that children with dyslexia perform poorly on phonemic awareness compared with age-matched children without reading difficulties. The variation in effect sizes between studies was large and significant, $Q(87) = 395.35$, $p < .01$, $I^2 = 77.99\%$, $k = 88$. A sensitivity analysis showed that after removing outliers, the overall effect size was in the range of −1.34 (95% CI [−1.46, −1.22]) to −1.38 (95% CI [−1.51, −1.25]). The funnel plot indicated that studies were missing on the left side of the mean (i.e., studies with larger effect sizes than the overall mean effect size). In a trim and fill analysis, 12 studies were imputed, and the adjusted overall mean was −1.53 (95% CI [−1.67, −1.38]).

Results from the moderator analyses for phonemic awareness are shown in Table 1. In the studies examining phonemic awareness, the children with dyslexia had a reading level that, on average, was 2.70 standard deviation units poorer than that of the controls. Differences between studies in the severity of the reading deficit in samples with dyslexia reliably explained variation between studies in the size of the phonemic awareness deficit. Table 1 also shows that the children with dyslexia on average scored significantly worse than control children on measures of IQ and oral language, but only oral language reliably explained between-study variations in the size of the phonemic awareness deficit. For oral language, we note that there were no statistically significant differences in the magnitude of group differences between children with dyslexia and chronological age controls yielded by the different tests of oral language, $Q(3) = 4.93$, $p = .17$ (expressive vocabulary, $d = -0.93$, 95% CI [−1.68, −0.18], $k = 6$; listening comprehension, $d = -1.00$, 95% CI [−2.31, −0.29], $k = 2$; receptive vocabulary, $d = -0.44$, 95% CI [−0.70, −0.17], $k = 26$; and verbal IQ, $d = -0.82$, 95% CI [−1.07, −0.57], $k = 26$). Also for IQ, it is notable that there was no significant difference between studies reporting composite IQ and the studies reporting nonverbal IQ, $Q(1) = 2.59$, $p = .11$ (mean difference between children with dyslexia and control children on the composite IQ was $d = -0.53$, 95% CI [−0.74, −0.33], $k = 63$, but for pure nonverbal IQ, $d = -0.34$, 95% CI [−0.46, −0.22], $k = 53$).

Age had no significant impact on effect size ($\beta = -.03$, $p = .72$, $k = 79$, $R^2 = .00$), suggesting that the phonemic awareness deficit in children with dyslexia is stable across the age range studied (5 years 4 months–16 years 10 months). There was no statistically significant effect of orthography on the size of the phonemic awareness deficit, $Q(1) = 0.13$, $p = .72$. Studies based on 26 samples from transparent orthographies demonstrated an

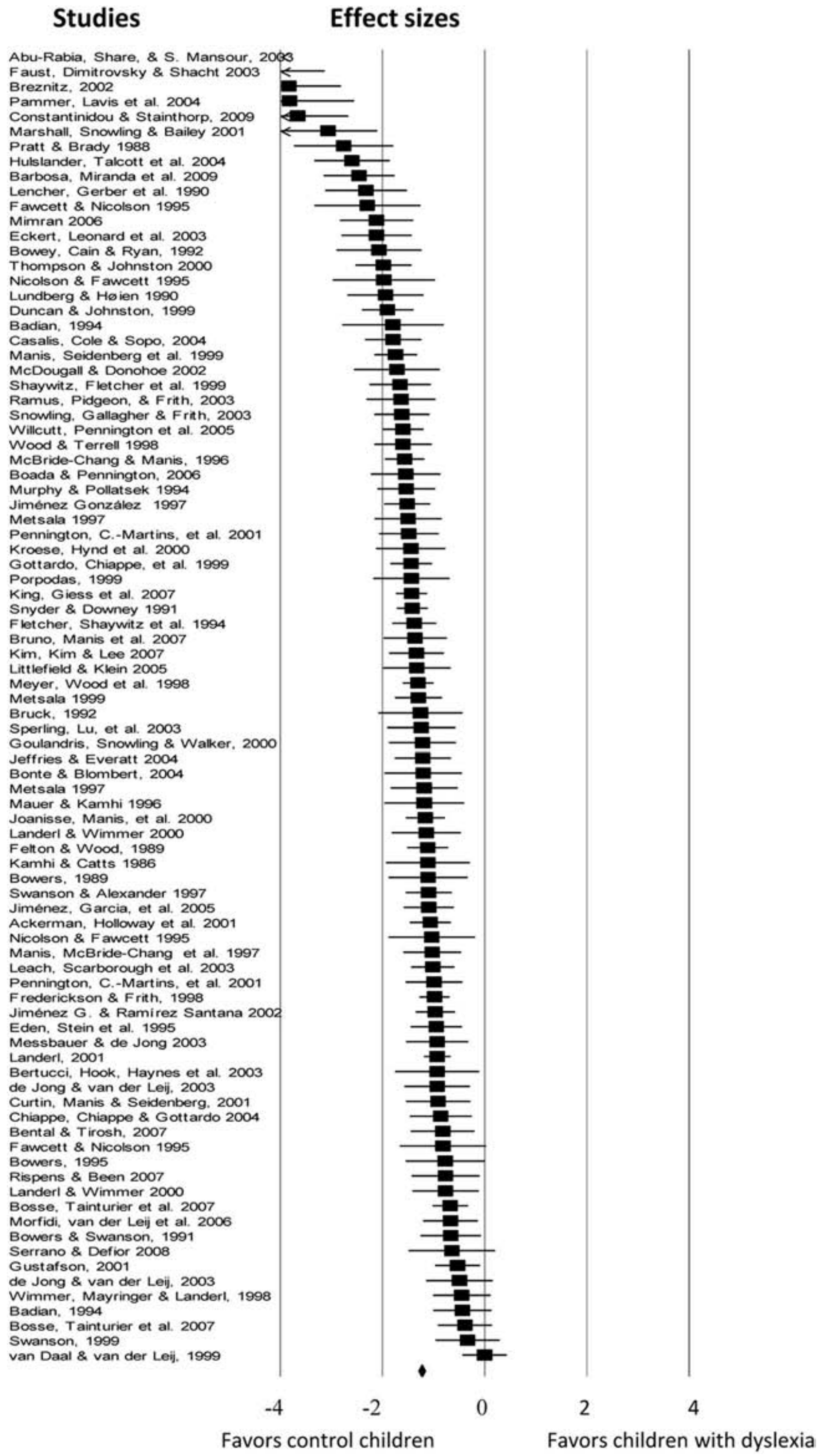

Figure 2. Overall average effect size for phonemic awareness (displayed by the black diamond) and effect size with confidence interval for each study comparing children with dyslexia and chronological age controls.

effect size of −1.43 (95% CI [−1.79, −1.08]), whereas the 61 English samples showed −1.37 (95% CI [−1.48, −1.25]). There was also no statistically significant effect of the type phonemic awareness test used on the size of the phonemic awareness deficit, $Q(3) = 2.28$, $p = .52$. For the 22 studies that used tests that, in addition to phoneme tasks, also contained syllable deletion, $d = -1.52$ (95% CI [−1.80, −1.24]); for 41 studies that used phoneme deletion, $d = -1.37$ (95% CI [−1.50, −0.92]); for seven studies

Table 1
Number of Effect Sizes, Effect Size With 95% Confidence Interval, Heterogeneity Statistics, and Regression Analysis for Moderators of Phonemic Awareness, Rime Awareness, and Verbal Short-Term Memory in Studies Comparing Children With Dyslexia With Chronological Age Controls

		Effect size			Metaregression	
Moderator variable	*k*	*d*	95% CI	I^2 (%)	β	R^2
Phonemic awareness						
Decoding	78	−2.70	[−2.93, −2.47]	88.07**	.29	.08**
IQ	50	−0.45	[−0.58, −0.32]	67.22**	.06	.00
Oral language	51	−0.77	[−0.97, −0.56]	85.49**	.28	.08**
Rime awareness						
Decoding	24	−2.86	[−3.22, −2.55]	78.18**	.12	.01
IQ	18	−0.38	[−0.52, −0.24]	19.64	.10	.01
Oral language	11	−0.55	[−1.02, −0.07]	87.34**	.59	.35*
Verbal short-term memory						
Decoding	46	−2.95	[−3.27, −2.64]	84.80**	.12	.01
IQ	29	−0.39	[−0.55, −0.23]	55.19	.06	.00
Oral language	26	−0.60	[−0.89, −0.31]	84.22**	.52	.27**

Note. *k* = number of effect sizes; *d* = the effect size of group differences between children with dyslexia and control children on each moderator variable; CI = confidence interval; I^2 = the proportion of total variation between the effect sizes that are caused by real heterogeneity rather than chance; R^2 = explanatory value of the moderator for differences between studies.
* $p < .05$. ** $p < .01$.

that used spoonerism tasks (i.e., requiring the exchange of phonemes between two words, e.g., *cat flap–fat clap*), $d = -1.34$ (95% CI [−1.86, −0.82]); and for 18 studies using other tasks (e.g., phoneme segmentation, phoneme blending, or phoneme detection), $d = -1.21$ (95% CI [−1.50, −0.92]). There was no significant difference between studies using a word reading test, a nonword reading test, or a composite of both to select their samples with dyslexia, $Q(2) = 1.38$, $p = .50$. For the 65 studies that used a word reading test, $d = -1.36$ (95% CI [−1.50, −1.21]); for 18 studies that used a composite test of word and nonword reading, $d = -1.50$ (95% CI [−1.86, −1.15]); and for five studies that used a nonword reading test, $d = -1.12$ (95% CI [−1.66, −0.59]).

Concerning moderator analyses of variables related to methodological quality, in spite of special efforts to include unpublished studies in our meta-analysis, we retrieved only three studies that could be classified as unpublished, precluding its inclusion as a moderator variable. The same was the case for peer review status, sampling method, and alpha reliability. As for characteristics related to the distribution of the data, the difference between studies where the standard deviation in the dyslexic group was small compared with the mean (standard deviation less than 20% of the mean) and other studies was not significant, $Q(1) = 2.50$, $p = .11$ (for studies with standard deviation less than 20% of the mean, $d = -1.07$, 95% CI [−1.47, −0.68], $k = 11$; other studies, $d = -1.41$, 95% CI [−1.55, −1.27], $k = 77$). There was no significant difference between studies using a standardized norm-referenced test and studies using other tests, $Q(1) = 0.11$, $p = .74$ (for standardized norm-referenced tests, $d = -1.33$, 95% CI [−1.54, −1.13], $k = 19$; for other tests, $d = -1.38$, 95% CI [−1.54, −1.22], $k = 69$). Publication year was not a significant predictor of effect size ($\beta = -.03$, $p = .72$, $k = 88$, $R^2 = .00$).

Rime awareness. Twenty-eight independent studies compared rime awareness in children with dyslexia and age-matched controls. The studies included 746 children with dyslexia (mean sample size = 26.64, *SD* = 15.31; range: 11–89) and 802 control children (mean sample size = 28.64, *SD* = 14.37; range: 15–89). Effect sizes with CIs for the different studies are shown in Figure 3. The overall mean effect size was large and significant ($d = -0.93$, 95% CI [−1.07, −0.79]), confirming that children with dyslexia perform much more poorly on rime awareness than age-matched children without reading difficulties. However, the effect size for rime awareness was reliably smaller than that for phonemic awareness, $Q(1) = 19.79$, $p < .001$. The variation in effect sizes between studies was significant, $Q(27) = 44.78$, $p = .02$, $I^2 = 379.7\%$, $k = 28$. A sensitivity analysis showed that after removing outliers, the overall effect size was in the range of −0.95 (95% CI [−1.09, −0.82]) to −0.90 (95% CI [−1.03, −0.77]). The funnel plot indicated that studies were missing on the right side of the mean (i.e., studies with smaller effect sizes than the overall mean effect size). In a trim and fill analysis, seven studies were imputed, and the adjusted overall mean was −0.77 (95% CI [−0.93, −0.61]).

Results from the moderator analyses for rime awareness are shown in Table 1. In studies reporting group differences in rime awareness, the reading level in children with dyslexia was on average 2.86 standard deviation units poorer than that of the controls. Variation between studies in the severity of the reading deficit in samples with dyslexia was not significantly related to the severity of the rime awareness deficit. The samples with dyslexia also scored significantly lower, on average, on measures of IQ and oral language, and oral language skills were significantly related to variations in rime awareness between studies.

Age had no significant impact on effect size ($\beta = -.16$, $p = .41$, $k = 26$, $R^2 = .02$; age range: 5 years 4 months–15 years 11 months). Orthographic transparency had no significant effect on the effect size obtained, $Q(1) = 1.38$, $p = .24$. Studies based on 11 samples from transparent orthographies demonstrated an effect size of −0.82 (95% CI [−1.06, −0.58]), whereas the 17 English samples showed −0.99 (95% CI [−1.16, −0.83]). Similarly, the

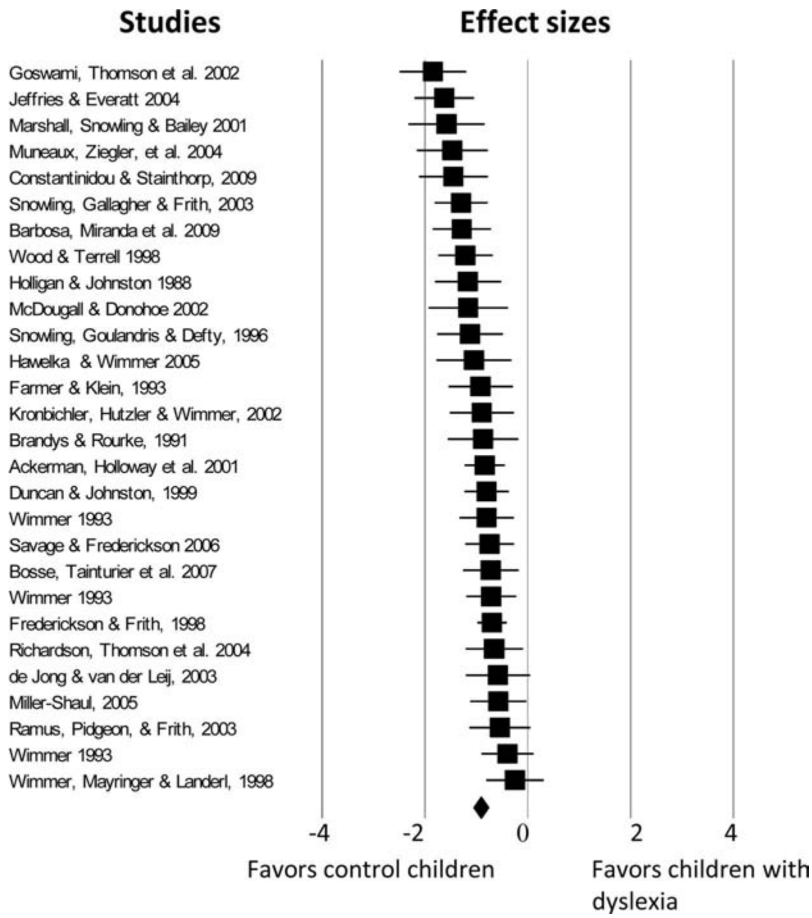

Figure 3. Overall average effect size for rime awareness (displayed by the black diamond) and effect size with confidence interval for each study comparing children with dyslexia and chronological age controls.

type of rime awareness test used had no significant effect on the effect size obtained, $Q(2) = 3.39$, $p = .18$. For the 11 studies that used a rime detection task, $d = -0.86$ (95% CI [-1.05, -0.66]); six studies that used rime generation, $d = -0.78$ (95% CI [-1.01, -0.56]); and 10 studies that used rime oddity tasks, $d = -1.13$ (95% CI [-1.44, -0.83]). The difference between studies using a word reading test and studies using a composite of word and nonword reading to select their samples with dyslexia was not significant, $Q(1) = 1.43$, $p = .23$ (for studies that used a word reading test, $d = -0.93$, 95% CI [-1.08, -0.78], $k = 23$; for studies that used a composite test of word and nonword reading, $d = -0.70$, 95% CI [-1.05, -0.34], $k = 3$). As for characteristics related to the distribution of the data, the difference between studies where the standard deviation in the dyslexia group was small compared with the mean (standard deviation less than 20% of the mean) and other studies was not significant, $Q(1) = 0.57$, $p = .45$ (for studies with standard deviation less than 20% of the mean, $d = -0.85$, 95% CI [-1.07, -0.63], $k = 6$; other studies, $d = -0.96$, 95% CI [-1.13, -0.79], $k = 22$). Publication year was not a significant predictor of effect size ($\beta = -.24$, $p = .20$, $k = 28$, $R^2 = .06$).

Verbal short-term memory. Fifty-three independent studies compared verbal short-term memory in children with dyslexia and age-matched controls. The studies included 1,220 children with dyslexia (mean sample size = 23.01, $SD = 11.08$; range: 7–51) and 1,733 control children (mean sample size = 32.70, $SD = 44.80$; range: 10–333). Effect sizes with CIs for the different studies are shown in Figure 4. The overall mean effect size was medium to large and significant ($d = -0.71$, 95% CI [-0.83, -0.60]), indicating that children with dyslexia perform poorly on verbal short-term memory tasks compared with age-matched children without reading difficulties. However, the effect size for verbal short-term memory was reliably smaller than for phonemic awareness, $Q(1) = 51.65$, $p < .001$, and rime awareness, $Q(1) = 5.4$, $p = .02$. The variation in effect sizes between studies was significant, $Q(52) = 110.21$, $p < .001$, $I^2 = 52.82\%$, $k = 53$. A sensitivity analysis showed that after removing outliers, the overall effect size was in the range of -0.73 (95% CI [-0.85, -0.61]) to -0.69 (95% CI [-0.81, -0.60]). The funnel plot indicated that studies were missing on the right side of the mean (i.e., studies with smaller effect sizes than the overall mean effect size). In a trim and fill analysis, 16 studies were imputed, and the adjusted overall mean effect size was -0.50 (95% CI [-0.63, -0.36]).

Results from the moderator analyses for verbal short-term memory are presented in Table 1. In studies reporting group differences in verbal short-term memory, the reading level in children with

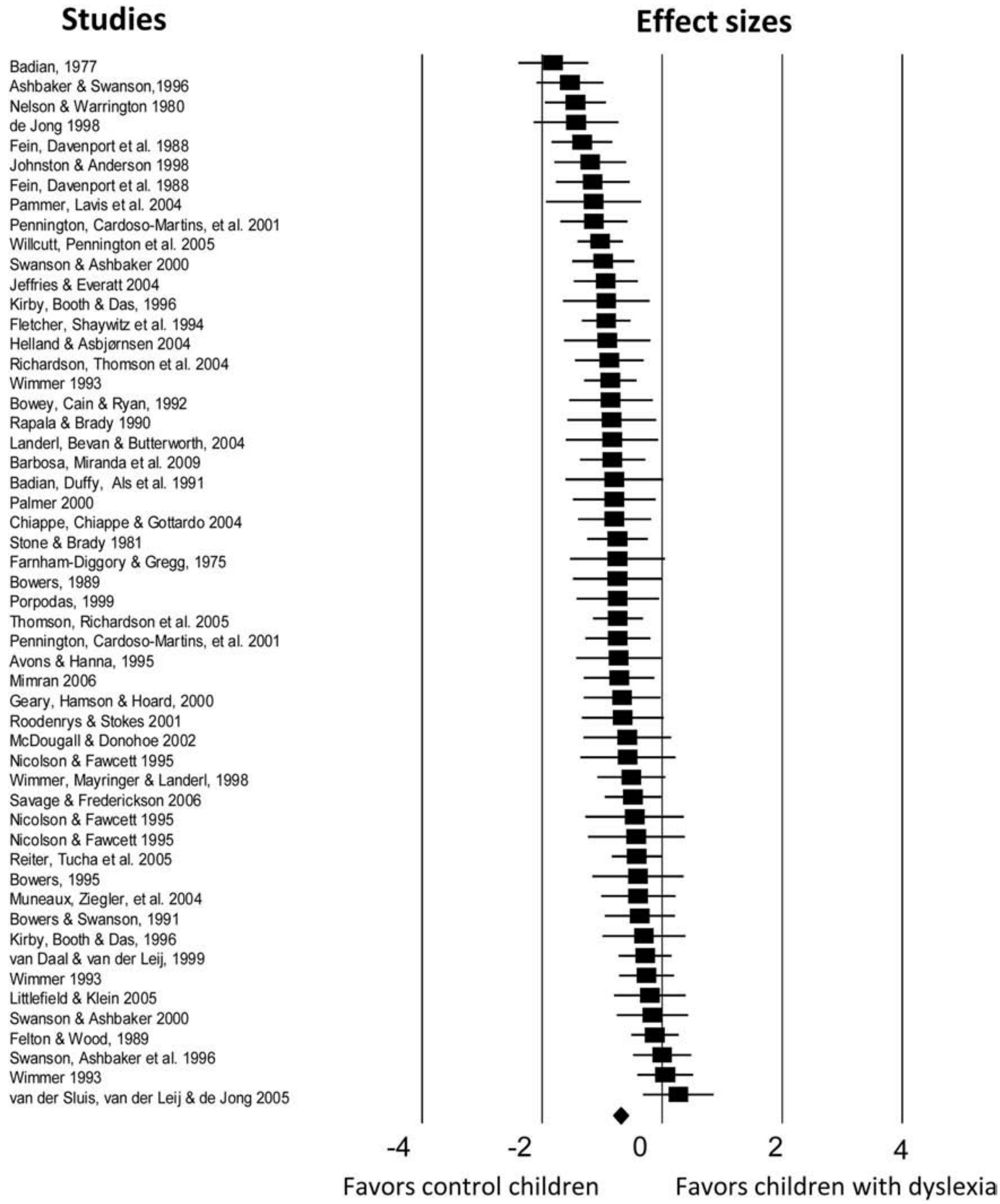

Figure 4. Overall average effect size for verbal short-term memory (displayed by the black diamond) and effect size with confidence interval for each study comparing children with dyslexia and chronological age controls.

dyslexia was close to 3 standard deviation units poorer than that of the controls. Variation between the studies in the severity of the dyslexic reading deficit was not significantly related to the severity of verbal short-term memory group differences. Further, the samples of children with dyslexia have, on average, poorer scores on measures of IQ and oral language, and oral language reliably predicts variation in verbal short-term memory. When entered together, oral language and phonemic awareness accounted for 48% of the between-study variation in verbal short-term memory group differences ($\beta = .49$, $p = .053$, $k = 13$).

Age had no significant impact on effect size ($\beta = -.09$, $p = .52$, $k = 47$, $R^2 = .01$; age range: 6 years 8 months–16 years 4 months), nor was there any difference in effect size between regular and irregular orthographies, $Q(1) = 2.41$, $p = .12$. Studies based on 12 samples from transparent orthographies demonstrated an effect size of -0.56 (95% CI [-0.77, -0.35]), whereas the 41

English samples showed −0.76 (95% CI [−0.89, −0.62]). Similarly, there were no reliable differences between the different types of short-term memory test used, $Q(1) = 0.05$, $p = .82$ (for the 25 studies that used digit span, $d = -0.69$, 95% CI [−0.87, −0.55]; for the 35 studies that used word span, $d = -0.71$, 95% CI [−0.87, −0.55]). The difference between studies using a word reading test and a composite of word and nonword reading to select their samples with dyslexia was not significant, $Q(1) = 0.003$, $p = .95$ (for studies that studies used a word decoding test, $d = -0.71$, 95% CI [−0.84, −0.58], $k = 45$; for studies that used a composite test of word and nonword reading, $d = -0.69$, 95% CI [−1.25, −0.13], $k = 5$). As for characteristics related to the distribution of the data, the difference between studies where the standard deviation in the dyslexia group was small compared with the mean (standard deviation less than 20% of the mean) and other studies was not significant, $Q(1) = 0.07$, $p = .80$ (for studies with standard deviation less than 20% of the mean, $d = -0.69$, 95% CI [−0.83, −0.56], $k = 21$; for other studies, $d = -0.72$, 95% CI [−0.90, −0.55], $k = 32$). There was no significant difference between studies using a standardized norm-referenced test and studies using other tests, $Q(1) = 0.06$, $p = .81$ (for standardized norm-referenced tests, $d = -0.73$, 95% CI [−0.93, −0.53], $k = 24$; for other tests, $d = -0.70$, 95% CI [−0.83, −0.59], $k = 29$). Publication year was not a significant predictor of effect size ($\beta = .24$, $p = .08$, $k = 53$, $R^2 = .06$).

Comparisons of Children With Dyslexia and Reading-Level Controls

Phonemic awareness. Thirty-seven independent studies compared phonemic awareness in children with dyslexia and reading-level controls. The studies included 1,188 children with dyslexia (mean sample size = 32.11, $SD = 20.31$; range: 10–89) and 953 control children (mean sample size = 25.76, $SD = 12.42$; range: 10–65). Effect sizes with CIs for the different studies are shown in Figure 5. The overall mean effect size was medium ($d = -0.57$, 95% CI [−0.73, −0.41]), confirming that children with dyslexia perform less well on phonemic awareness than younger control children without reading difficulties with the same level of reading skill. The variation in effect sizes between studies was large and significant, $Q(36) = 115.78$, $p < .01$, $I^2 = 68.91\%$, $k = 37$. A sensitivity analysis showed that after removing outliers, the

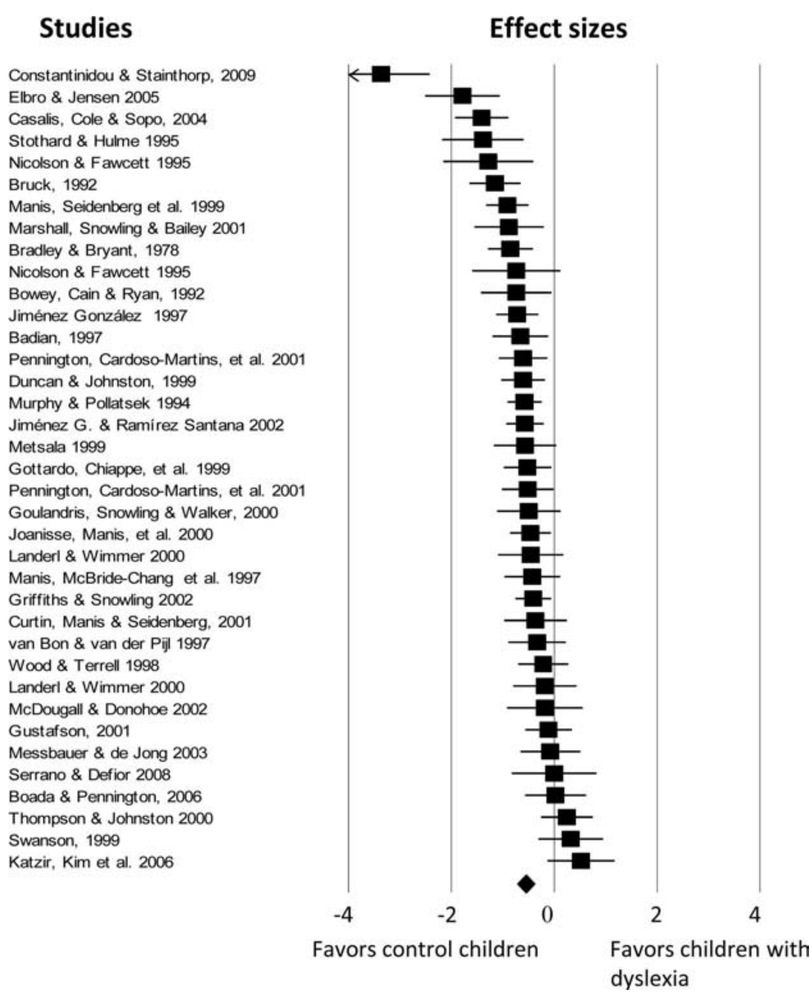

Figure 5. Overall average effect size for phonemic awareness (displayed by the black diamond) and effect size with confidence interval for each study comparing children with dyslexia and reading-level controls.

overall effect size was in the range of −0.60 (95% CI [−0.75, −0.44]) to −0.52 (95% CI [−0.66, −0.38]). The funnel plot indicated that studies were missing on the left side of the mean (i.e., studies with larger effect sizes than the overall mean effect size). In a trim and fill analysis, seven studies were imputed, and the adjusted overall mean was −0.73 (95% CI [−0.90, −0.55]).

Results from the moderator analyses for phonemic awareness are shown in Table 2. The children with dyslexia were well matched with the reading-level controls, as the effect size for decoding differences between the groups was −0.07, and there were no significant variation between the studies in reading-level differences. The children with dyslexia also scored significantly worse than control children on IQ and oral language, but variations in IQ or oral language did not explain variation between the studies in the size of the phonemic awareness deficit. For oral language, there were no reliable differences, as a function of the different tests of oral language used, in the magnitude of group differences between children with dyslexia and chronological age controls, $Q(2) = 1.68$, $p = .43$ (for expressive vocabulary, $d = -0.55$, 95% CI [−1.14, 0.26], $k = 2$; listening comprehension, $d = 0.18$, 95% CI [−0.43, 0.81] [note that only one study reported results from listening comprehension, and this study was therefore not included in the significance test]; receptive vocabulary, $d = -0.01$, 95% CI [−0.66, 0.64], $k = 10$; and verbal IQ, $d = -0.47$, 95% CI [−0.85, −0.10], $k = 8$). For IQ, there was no significant difference between the studies reporting composite IQ and the studies reporting nonverbal IQ, $Q(1) = 0.03$, $p = .85$ (mean difference between children with dyslexia and control children on the composite IQ was $d = -0.19$, 95% CI [−0.37, −0.01], $k = 13$, whereas for pure nonverbal IQ, $d = -0.16$, 95% CI [−0.42, 0.09], $k = 13$).

The impact of the age of children with dyslexia was not significant ($\beta = -.08$, $p = .60$, $k = 36$, $R^2 = .00$; age range: 6 years 4 months–16 years 4 months). There was no statistically significant effect of orthography on the size of the phonemic awareness deficit, $Q(1) = 1.77$, $p = .18$. The 27 English studies demonstrated an effect size of −0.49 (95% CI [−0.64, −0.35]), whereas the 10 studies based on consistent orthographies showed −0.83 (95% CI [−1.29, −0.36]). There was no statistically significant effect of phonemic awareness test type, $Q(3) = 3.00$, $p = .39$. For the four studies that used tasks that also contained syllable deletion, $d = -0.69$ (95% CI [−0.99, −0.37]); for 15 studies that used phoneme deletion, $d = -0.43$ (95% CI [−0.74, −0.35]); for five studies that used phoneme spoonerism tasks, $d = -1.13$ (95% CI [−2.08, −0.18]); and for 13 studies that used other tasks (e.g., phoneme segmentation, phoneme blending, or phoneme detection), $d = -0.54$ (95% CI [−0.74, −0.35]). The difference between studies using a word reading test and a composite of word and nonword reading to select their samples with dyslexia was not significant, $Q(1) = 0.16$, $p = .70$ (for studies that used word reading tests, $d = -0.58$, 95% CI [−0.77, −0.39], $k = 31$; for studies that used a composite test of word and nonword reading, $d = -0.64$, 95% CI [−0.89, −0.40], $k = 5$). As for characteristics related to the distribution of the data, the difference between studies where the standard deviation in the dyslexia group was small compared with the mean (standard deviation less than 20% of the mean) and other studies was not significant, $Q(1) = 0.75$, $p = .39$ (for studies with standard deviation less than 20% of the mean, $d = -0.37$, 95% CI [−0.84, 0.11], $k = 4$; for other studies, $d = -0.59$, 95% CI [−0.77, −0.42], $k = 33$). There was no significant difference between studies using a standardized norm-referenced test and studies using other tests, $Q(1) = 0.08$, $p = .77$ (for standardized norm-referenced tests, $d = -0.50$, 95% CI [−1.02, 0.03], $k = 5$; for other tests, $d = -0.58$, 95% CI [−0.75, −0.41], $k = 32$). Publication year was not a significant predictor of effect size ($\beta = .08$, $p = .58$, $k = 37$, $R^2 = .00$).

Rime awareness. Thirteen independent studies compared rime awareness in children with dyslexia and reading-level controls. The studies included 344 children with dyslexia (mean sample size = 26.46, $SD = 12.28$; range: 12–59) and 377 control children (mean sample size = 29.00, $SD = 16.81$; range: 14–67).

Table 2
Number of Effect Sizes, Effect Size With 95% Confidence Interval, Heterogeneity Statistics, and Regression Analysis for Moderators of Phonemic Awareness, Rime Awareness, and Verbal Short-Term Memory in Studies Comparing Children With Dyslexia With Reading-Level Controls

Moderator variable	k	Effect size: d	Effect size: 95% CI	I^2 (%)	Metaregression: β	Metaregression: R^2
Phonemic awareness						
Decoding	26	−0.07	[−0.17, 0.02]	0.00	.22	.05
IQ	16	−0.27	[−0.52, −0.02]	61.67**	−.07	.00
Oral language	18	−0.45	[−0.81, −0.09]	85.53**	−.21	.04
Rime awareness[a]						
Decoding	12	−0.21	[−0.37, −0.05]	0.00	.20	.04
IQ	7	−0.09	[−0.32, 0.13]	0.00	−.26	.07
Verbal short-term memory						
Decoding	21	0.06	[−0.08, 0.19]	6.92	−.13	.02
IQ	14	−0.35	[−0.59, −0.11]	53.55**	.03	.01
Oral language	8	−0.23	[−0.76, 0.30]	85.25**	.07	.00

Note. k = number of effect sizes; d = the effect size of group differences between children with dyslexia and control children on each moderator variable; CI = confidence interval; I^2 = the proportion of total variation between the effect sizes that are caused by real heterogeneity rather than chance; R^2 = explanatory value of the moderator for differences between studies.
[a] For rime awareness there were too few studies that included measures of oral language to conduct a moderator analysis.
* $p < .05$. ** $p < .01$.

Effect sizes with CIs for the different studies are shown in Figure 6. The overall mean effect size was small ($d = -0.37$, 95% CI [-0.61, -0.12]), and significantly smaller than for phonemic awareness, $Q(1) = 9.12$, $p = .003$. The variation in effect sizes between studies was large and significant, $Q(12) = 30.62$, $p < .01$, $I^2 = 60.80\%$, $k = 13$. A sensitivity analysis showed that after removing outliers, the overall effect size was in the range of -0.41 (95% CI [-0.65, -0.17]) to -0.29 (95% CI [-0.50, -0.08]). The funnel plot indicated that studies were missing on the left side of the mean (i.e., studies with larger effect sizes than the overall mean effect size). In a trim and fill analysis, two studies were imputed, and the adjusted overall mean was -0.46 (95% CI [-0.70, -0.21]).

Results from the moderator analyses for rime awareness are shown in Table 2. For the reading-level studies of rime awareness, children with dyslexia had significantly poorer decoding skills than the controls, whereas the IQ levels between the groups were not reliably different. Oral language could not be analyzed, since only five studies reported this together with rime awareness. Neither reading-level differences nor IQ-level differences varied significantly between studies, and this leaves little variation between studies left to be explained by these variables.

The impact of the age of children with dyslexia was significant ($\beta = .61$, $p = .01$, $k = 12$, $R^2 = .38$; age range: 6 years 4 months–14 years 1 month). Orthography had no significant impact on effect size, $Q(1) = 0.16$, $p = .68$. The 10 English studies demonstrated an effect size of -0.34 (95% CI [-0.58, -0.09]), whereas for the three studies based on consistent orthographies, the effect size was -0.51 (95% CI [-1.33, 0.30]). Similarly, the type of rime awareness test used had no significant impact on effect size, $Q(2) = 0.05$, $p = .83$. For the six studies that used the rime oddity task, $d = -0.34$ (95% CI [-0.72, 0.05]); for the seven studies that used other tests, $d = -0.39$ (95% CI [-0.63, -0.05]). The difference between types of reading test was not analyzed because only one study used a nonword reading test and no studies used composite tests. As for characteristics related to the distribution of the data, the difference between studies where the standard deviation in the dyslexia group was small compared with the mean (standard deviation less than 20% of the mean) and other studies was not significant, $Q(1) = 1.22$, $p = .27$ (for studies with standard deviation less than 20% of the mean, $d = -0.20$, 95% CI [-0.42, 0.02], $k = 4$; for other studies, $d = -0.45$, 95% CI [-0.82, -0.08], $k = 9$). Publication year was not a significant predictor of effect size ($p = .69$, $k = 13$, $R^2 = .01$).

Verbal short-term memory. Twenty-four independent studies compared verbal short-term memory in children with dyslexia and reading-level controls. The studies included 518 children with dyslexia (mean sample size = 21.58, $SD = 9.17$; range: 10–47) and 518 control children (mean sample size = 21.58, $SD = 11.77$; range: 10–67). Effect sizes with CIs for the different studies are shown in Figure 7. The overall mean effect size was small and nonsignificant ($d = -0.09$, 95% CI [-0.28, 0.10]). Compared with the effect size for phonemic awareness, the effect size for verbal short-term memory was reliably smaller, $Q(1) = 13.80$, $p < .001$. The effect size for verbal short-term memory was also smaller than the effect size for rime awareness, but this difference did not quite attain significance, $Q(1) = 2.98$, $p = .08$. The variation in effect sizes between studies was significant, $Q(23) = 54.38$, $p < .01$, $I^2 = 57.70\%$, $k = 24$. A sensitivity analysis showed that after removing outliers, the overall effect size was in the range of -0.14 (95% CI [-0.32, 0.03]) to -0.06 (95% CI [-0.26, 0.12]). There were no indications of publication bias in the funnel plot or trim and fill analysis.

Results from the moderator analyses are presented in Table 2, showing that the reading level in children with dyslexia was well matched with that of the controls, but there were significant differences between the groups on IQ. Neither reading level, IQ, nor oral language reliably predicted variations between studies in verbal short-term memory group differences.

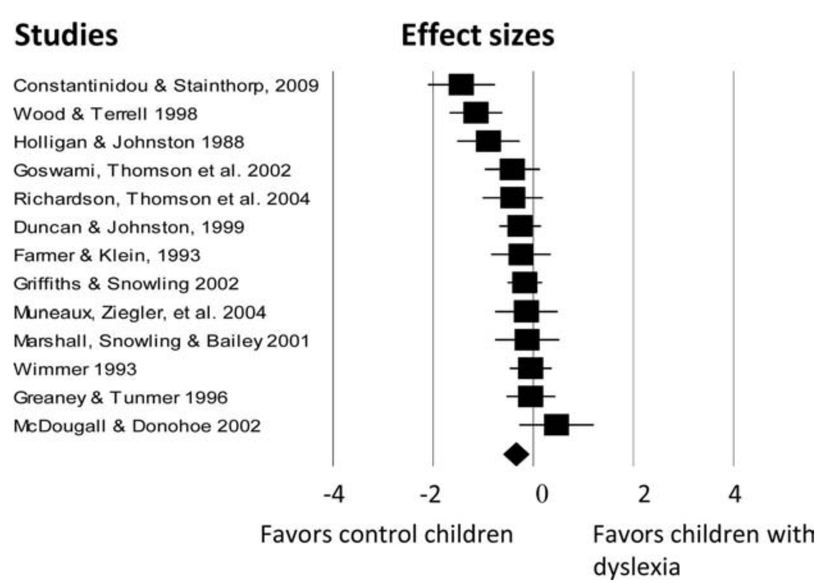

Figure 6. Overall average effect size for rime awareness (displayed by the black diamond) and effect size with confidence interval for each study comparing children with dyslexia and reading-level controls.

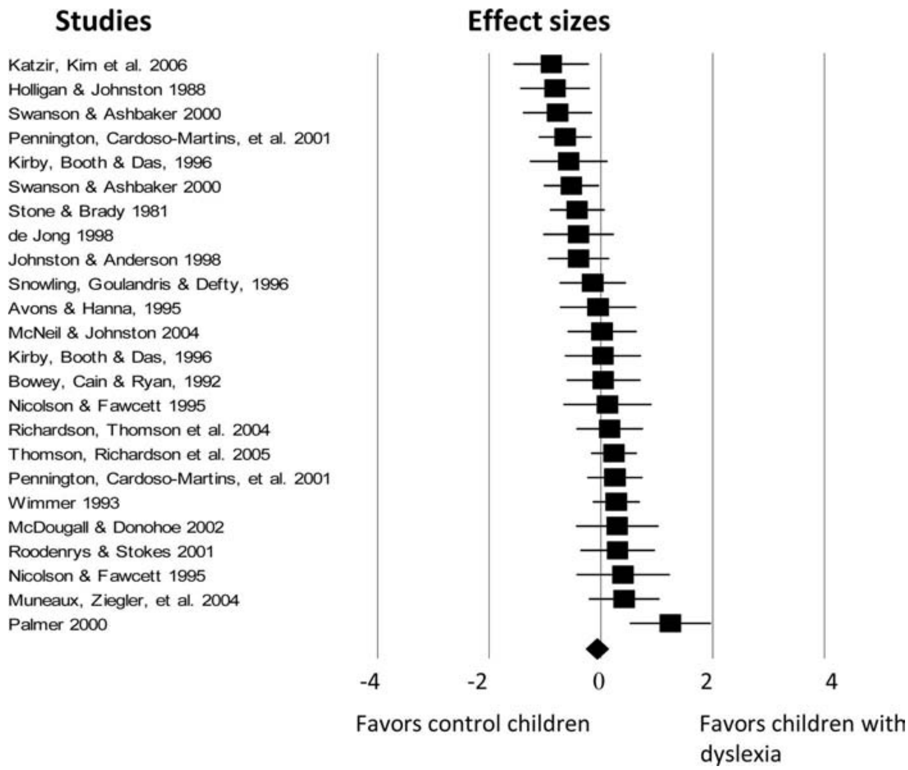

Figure 7. Overall average effect size for verbal short-term memory (displayed by the black diamond) and effect size with confidence interval for each study comparing children with dyslexia and reading-level controls.

The impact of the age of children with dyslexia was significant ($\beta = -.04$, $p = .01$, $k = 24$, $R^2 = .10$; age range: 8 years 6 months–16 years 4 months). Orthographic transparency had no significant effect on the effect size obtained, $Q(1) = 0.95$, $p = .33$. The 21 English studies demonstrated an effect size of -0.12 (95% CI [-0.33, -0.09]), whereas for the three studies based on consistent orthographies, the effect size was -0.12 (95% CI [-0.33, 0.57]). Verbal short-term memory test type did not have significant impact on the effect size obtained, $Q(1) = 0.45$, $p = .50$. For the five studies that used digit span, $d = 0.10$ (95% CI [-0.49, 0.69]); for the 18 studies that used word span, $d = -0.11$ (95% CI [-0.30, 0.08]). The difference between types of reading test was not analyzed because only one study used a nonword reading test and two studies used composite tests of word and nonword reading. As for characteristics related to the distribution of the data, the difference between studies where the standard deviation in the dyslexia group was small compared with the mean (standard deviation less than 20% of the mean) and other studies was not significant, $Q(1) = 0.01$, $p = .91$ (for studies with standard deviation less than 20% of the mean, $d = -0.08$, 95% CI [-0.39, 0.24], $k = 13$; for other studies, $d = -0.10$, 95% CI [-0.32, 0.13], $k = 11$). There were no significant difference between studies using a standardized norm-referenced test and studies using other tests, $Q(1) = 0.04$, $p = .84$ (for standardized norm-referenced tests, $d = -0.14$, 95% CI [-0.28, 0.11], $k = 4$; for other tests, $d = -0.20$, 95% CI [-0.30, 0.13], $k = 20$). Publication year was not a significant predictor of effect size ($\beta = .20$, $p = .33$, $k = 24$, $R^2 = .04$).

Correlational Studies of Phonemic Awareness, Rime Awareness, Verbal Short-Term Memory, and Reading

One hundred and thirty-five studies with 155 independent samples were included in this meta-analysis. Table 3 shows the mean correlations (with 95% CIs), heterogeneity, trim and fill, and sensitivity analyses for all combinations of correlations between decoding, phonemic awareness, rime awareness, and verbal short-term memory. Table 3 also shows the mean correlations when corrected for reliability (Cronbach's alpha). Mean alpha reliability for phonemic awareness was .86 (reported in 13 studies); for decoding, .95 (10 studies); for rime awareness, .87 (five studies); and for verbal short-term memory, .77 (six studies). On the basis of this information, both variables in all the pairwise correlations were corrected with formulas provided by Hunter and Schmidt (1990).

The mean correlation between phonemic awareness and decoding was high ($r = .57$, $N = 14{,}853$, mean sample size $= 106.09$, $SD = 110.77$; range: 17–884). For the magnitude of the correlation between phonemic awareness and reading, the difference between studies that used a word reading test, a composite of word and nonword reading, or a nonword reading test was not significant, $Q(2) = 0.39$, $p = .82$ (for studies that used a word reading test, $r = .56$, 95% CI [.53, .59], $k = 119$; for studies that used a nonword reading test, $r = .60$ 95% CI [.48, .70], $k = 5$; and for studies that used a composite test of word and nonword reading, $r = .57$, 95% CI [.48, .65], $k = 16$). The difference between studies that reported alpha reliability and studies not reporting this was not

Table 3
Number of Effect Sizes, Effect Size With 95% Confidence Interval, and Heterogeneity Statistics for Studies Correlating Decoding, Phonemic Awareness, Rime Awareness, and Verbal Short-Term Memory

Correlation	k	r	95% CI	Corrected correlation[a]	I^2 (%)	Adjusted effect estimate after trim and fill	Sensitivity analysis
Phonemic awareness–decoding	140	.57	[.54, .59]**	.63	83.63**	.58, .63	.56, .57
Rime awareness–decoding	31	.43	[.35, .50]**	.47	79.19**	.35, .50	.42, .44
Verbal short-term memory–decoding	57	.34	[.30, .37]**	.40	65.20**	.32, .40	.33, .34
Verbal short-term memory–phonemic awareness	41	.34	[.31, .37]**	.42	39.43*	.31, .38	.34, .36
Verbal short-term memory–rime awareness	7	.37	[.27, .44]**	.43	40.65	.27, .45	.32, .39
Phonemic awareness–rime awareness	20	.49	[.40, .57]**	.55	79.21**	.40, .64	.47, .51

Note. k = number of effect sizes; CI = confidence interval; I^2 = the proportion of total variation between the effect sizes that are caused by real heterogeneity rather than chance.
[a] Corrected for reliability.
* $p < .05$. ** $p < .01$.

significant, $Q(1) = 0.68$, $p = .40$ (for studies reporting reliability, $r = .60$, 95% CI [.51, .68], $k = 13$; for studies not reporting reliability, $r = .56$, 95% CI [.53, .59], $k = 127$). Publication year was not a significant predictor of effect size ($\beta = -.03$, $p = .73$, $k = 140$, $R^2 = .00$).

The mean correlation between rime awareness and reading was medium ($r = .43$, $N = 2{,}390$, mean sample size = 77.10, SD = 45.49; range: 29–244). The correlation between phonemic awareness and reading was significantly larger than that between rime awareness and reading, $Q(1) = 12.15$, $p < .001$. The impact from reading test type on the magnitude of the correlation between rime awareness and reading could not be examined because only two studies used a composite test and no studies used nonword reading tests. The difference between studies reporting and not reporting alpha reliability was not significant, $Q(1) = 0.60$, $p = .44$ (for studies reporting reliability, $r = .37$, 95% CI [.21, .52], $k = 6$; for studies not reporting reliability, $r = .44$, 95% CI [.35, .53], $k = 25$). Publication year was not a significant predictor of effect size ($\beta = .14$, $p = .45$, $k = 31$, $R^2 = .02$).

The mean correlation between verbal short-term memory and reading was also medium in size ($r = .34$, $N = 7{,}410$, mean sample size = 130.0, $SD = 141.85$; range: 17–884). The correlation between phonemic awareness and reading was also significantly larger than the correlation between verbal short-term memory and reading, $Q(1) = 89.23$, $p < .001$. The difference in the size of correlations between rime awareness and reading and verbal short-term memory and reading was also significant, $Q(1) = 4.39$, $p = .04$, in favor of rime awareness. For the magnitude of the correlation between verbal short-term memory and reading, the difference between studies that used a word reading test and studies that used a composite of word and nonword reading was not significant, $Q(1) = 0.10$, $p = .75$ (for studies that used a word reading test, $r = .33$, 95% CI [.29, .37], $k = 48$; for studies that used a nonword reading test, $r = .41$, 95% CI [.26, .54] [not included in the significance test because only two studies reported this]; for studies that used a composite test of word and nonword reading, $r = .36$, 95% CI [.20, .49], $k = 7$). The difference between studies reporting and not reporting alpha reliability was not significant, $Q(1) = 0.02$, $p = .88$ (for studies reporting reliability, $r = .33$, 95% CI [.22, .43], $k = 9$; for studies not reporting reliability, $r = .34$, 95% CI [.30, .38], $k = 48$). Publication year was not a significant predictor of effect size ($\beta = .03$, $p = .85$, $k = 57$, $R^2 = .00$).

The correlations in Table 3 (weighted by a random-effects model) were entered as a matrix in Mplus (Muthén & Muthén, 2006) in order to perform Cholesky factoring, which allows estimation of the amount of independent variance in reading ability accounted for by each of the predictors. These analyses showed that phonemic awareness, rime awareness, and verbal short-term memory together explained 37% of the variance in reading skills. When the effects of both verbal short-term memory and rime awareness were partialed, phonemic awareness explained 14.4% additional variance ($z = 5.38$, $p < .001$). When both phonemic awareness and verbal short-term memory were partialed, rime awareness explained a nonsignificant 1.7% additional variance in reading skills ($z = 0.96$, $p = .34$). When rime awareness and phonemic awareness were partialed, verbal short-term memory explained a nonsignificant 1.3% additional variance ($z = 1.09$, $p = .27$).

Such Cholesky factoring analyses were repeated on the correlations corrected for reliability in accordance with computational formulas given by Hunter and Schmidt (1990). These analyses showed that phonemic awareness, rime awareness, and verbal short-term memory together explained 43.2% of the variance in reading skills. When the effects of both verbal short-term memory and rime awareness were partialed, phonemic awareness explained 16.1% additional variance ($z = 5.93$, $p < .001$). When both phonemic awareness and verbal short-term memory were partialed, rime awareness explained a nonsignificant 1.2% additional variance in reading skills ($z = 0.83$, $p = .41$). When rime awareness and phonemic awareness were partialed, verbal short-term memory explained a nonsignificant 1.3% additional variance ($z = 1.14$, $p = .26$).

These analyses clearly show that phonemic awareness is the only independent predictor of reading ability among these analyses and that rime awareness and verbal short-term memory account for variance in reading that is shared with phonemic awareness.

Discussion

Patterns of Association Between Phonological Skills and Learning to Read

We began with three hypotheses about the association between phonological skills and the development of word reading skills in children. We hypothesized the following:

1. Phonemic awareness, rime awareness, and verbal short-term memory would all be reliable correlates of individual differences in children's word reading skills.

2. Of these three correlates, phonemic awareness would show the strongest correlation with individual differences in children's word reading skills.

3. After controlling for the effects of other predictors (rime awareness and verbal short-term memory), only phonemic awareness would be a unique predictor of individual differences in children's word reading skills.

The results from our meta-analyses provide clear support for all three hypotheses. In extreme group studies comparing children with specific reading difficulties (dyslexia) and typically developing control children of the same reading level, there is a substantial dyslexic group deficit ($d = -0.57$). By comparison, the corresponding group deficits for rime awareness ($d = -0.37$) and verbal short-term memory ($d = -0.09$) are both significantly smaller. The same pattern—of a stronger association between children's word reading skills and phonemic awareness than with either rime awareness or verbal short-term memory—emerges from our analysis of correlational studies with unselected samples of children. Furthermore, the relation between phonemic awareness and children's word reading skills was not accounted for by shared variance between measures of phonemic awareness and measures of either rime awareness or verbal short-term memory. In other words, there is a specific and substantial association between concurrent measures of phonemic awareness and children's word reading skills. In contrast, rime awareness and verbal short-term memory are significantly weaker correlates of children's word reading skills, and these associations are explicable by the correlation of these measures with phonemic skills. These results lead to the conclusion that, contrary to some earlier arguments (Anthony & Francis, 2005; Anthony et al., 2002; Papadopoulos, Spanoudis, & Kendeou, 2009), phonological skills are not unitary and that different measures of phonological ability tap meaningfully different constructs.

For studies comparing children with dyslexia to control children of the same age, the size of the dyslexic deficit on measures of phonemic awareness, rime awareness, and verbal short-term memory did not differ reliably as a function of age, severity of the reading problem, or IQ. However, perhaps not surprisingly, the size of the dyslexic deficit on measures of phonemic awareness, rime awareness, and verbal short-term memory was more severe in children with poorer oral language skills. Notably, measures of methodological rigor were not significantly related to variation in the effect size between studies.

A subsidiary issue is the possible role of language of instruction (differences between orthographies in their transparency or orthographic depth) as a moderator of the effects of phonological skills on learning to read. In line with a number of recent studies (Caravolas et al., 2005; Vaessen et al., 2010; Ziegler et al., 2010), we found that the predictive relationships between phonological skills and children's word reading skills do not show any substantial differences between English and other, more consistent alphabetic orthographies.

Phonological Skills and Learning to Read: Issues of Causality

Perhaps the most critical issue that arises from this meta-analytic review is whether the strong and selective relationship documented between phonemic awareness and children's word reading skills is a causal one. Our meta-analyses all come from nonexperimental studies that cannot directly establish causal effects. In the last 20–30 years, there has been a rapid growth in the sophistication of methods for making causal inferences from nonexperimental data (see, e.g., Foster, 2010; Greenland & Brumback, 2002; Pearl, 2000, in press; Shipley, 2000). It is beyond the scope of the present article to discuss these methods, which essentially deal with how, given certain assumptions, patterns of association between variables in nonexperimental designs may be given plausible causal interpretations. To date, these methods have had little impact on studies of reading development.

Regarding models of causal inference, concurrent correlational studies (in which we include extreme group designs that assess differences between children with dyslexia and typically developing controls) provide the weakest evidence for a causal interpretation of the link between phonemic skills and variations in reading skills. In short, concurrent correlations of this form give essentially no evidence for the direction of any causal linkage, even if other explanations for the association (confounding variables) can be convincingly ruled out.

In the comparison of extreme groups, we have placed particular emphasis on effect sizes based on reading-level-matched designs (i.e., comparisons between children with dyslexia and younger, typically developing controls who have the same absolute level of reading skill). It is clear that children with dyslexia have substantially poorer phonemic awareness than reading-level controls. The usual logic of the reading-level design is that any differences found cannot be a consequence of differences in reading skills and are therefore more likely to represent causal effects (Backman, Mamen, & Ferguson 1984; Goswami & Bryant, 1989). Again, however, such a pattern at best provides extremely weak evidence for a causal interpretation of the association between phonemic skills and children's word reading ability, as it is difficult or impossible to rule out the effects of possible confounding variables.

A second line of evidence comes from longitudinal studies, which arguably provide somewhat stronger evidence for claims about causal relationships. If one event (or condition) precedes another, the first event might be a causal influence on the later event, but the later event clearly cannot have been an influence on the earlier one. This is sometimes referred to as "the logic of causal order" (Davis, 1985). For example, if a person falls off his or her bike on the way to a tennis match, the cycling accident might be a cause of the person's losing the tennis match; but losing the tennis match cannot possibly have influenced the earlier cycling accident (Foster, 2010). If phonemic awareness, measured before children have any appreciable reading skills, is a reliable longitudinal predictor of the growth of reading skills, this pattern is at least consistent with a possible causal influence of phonemic awareness on later reading skills. There are now a number of studies showing robust longitudinal correlations between phonemic awareness in prereaders (or children with very limited reading skills) and the rate of growth in reading in the first few years of reading instruction (Lervåg et al., 2009; Muter et al., 2004; Roth et al., 2002; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004). In the studies analyzed herein with a longitudinal design, the mean correlation between phonemic awareness measured in preschool–kindergarten and later decoding skills was .43, whereas the corresponding correlation for rime awareness was .28. These figures are similar to those reported in the meta-analysis of longitudinal studies by the National Institute for Literacy (2008), where phonemic awareness measured in preschool–kindergarten had a mean correlation with later decoding skills of .42, whereas the corresponding correlation for rime awareness was .29. Serious problems remain, however, in giving a causal interpretation to such patterns of longitudinal association. It is always difficult to eliminate other factors (confounders) that may be the true underlying cause of the association between early phonemic skills and later reading skills; both might arise as a result of differences in other skills that have not been measured. Measuring a wide range of possible confounders may help to strengthen causal inferences, but in practice it is impossible to be sure that all such confounders have been identified and adequately measured.

Traditionally, theories of causation have argued that the strongest evidence for the operation of causal influences (causal risk factors) comes from experimental studies that manipulate a variable by randomly assigning participants to receive or not receive a specified treatment (e.g., Little & Rubin, 2000; Rothman & Greenland, 1998). Random assignment frees a study from concerns that the effects are attributable to preexisting differences between treated and untreated groups. According to Fisher (1966), one of the first to pursue this logic, "randomisation relieves the experimenter from the anxiety of considering and estimating the magnitude of the innumerable causes by which his data may be disturbed" (p. 49). Most critical, therefore, would be evidence from training studies that support a causal role of phonemic awareness in the development of children's word reading skills.

The results of the present meta-analyses, which have dealt purely with correlational evidence, can usefully be related to several studies that have shown that training phonemic awareness in children is effective (particularly when coupled with appropriate phonically based reading instruction) in helping to improve word reading skills (Bentin & Leshem, 1993; Hatcher, Hulme, & Snowling, 2004; Lundberg, Frost, & Petersen, 1988; National Institute for Literacy, 2008; National Institute of Child Health and Human Development, 2000; Troia, 1999). A meta-analysis by the National Institute for Literacy (2008) reported an effect size of 0.67 (based on seven studies) for training phonemic awareness on word reading.

In short, the present meta-analyses have clarified the strength and specificity of the association between phonemic skills and the development of word reading skills in children. We would argue that the pattern from the present meta-analyses can be combined with evidence from longitudinal and training studies to provide converging evidence that phonemic awareness is likely to be one causal influence on the development of word reading skills in children. The findings that early phonemic skills, measured at or just before the time at which reading instruction begins, are moderate to strong predictors of later word reading abilities, coupled with experimental evidence from training studies, provide converging evidence.

We emphasize, however, that concluding that early phonemic skills may be one causal influence on the development of children's word reading skills does not in any way conflict with the idea that there may be reciprocal relationships between word reading skills and phonemic awareness. That is, once reading starts to be established, experience with printed words may help to facilitate the further development of phonemic skills (e.g., Bentin, Hammer, & Cahan, 1991; Castles & Coltheart, 2004; Hulme, Snowling, Caravolas, & Carroll, 2005; Perfetti et al., 1987).

Theoretical Implications

Our conclusion that phonemic skills are one plausible causal influence on the development of children's word reading skills has important implications for theories of reading development. One key issue is whether it is phonemic awareness per se that is a critical determinant of early reading skills, or whether phonemic awareness is simply a proxy for the nature and organization of a child's phonological representations that underlie the development of reading. According to the phonological representations hypothesis (Snowling & Hulme, 1994; Swan & Goswami, 1997), the successful development of word reading skills depends upon the child's possessing phonemically structured phonological representations; phonemic awareness tasks may simply be one way of tapping the integrity and quality of such representations. We argue that the present meta-analyses are consistent with the claim that the development of phonemically structured phonological representations is one critical foundation for learning to read successfully in an alphabetic script (Metsala & Walley, 1998) and that a failure to develop such phonemically structured phonological representations is a principal cause of the difficulties in learning to read experienced by children with dyslexia (Hulme & Snowling, 2009; Szenkovits & Ramus, 2005).

Evidence from a recent study (Melby-Lervåg & Hulme, 2010) showed that training children to manipulate phonemes in unfamiliar words improved phonemic manipulation and serial recall of those words. Conversely, training on rime tasks with the same words for the same amount of time improved rime skills but had no significant effect on serial recall or the ability to manipulate phonemes in those words. These findings suggest that establishing phonemically structured phonological representations of words in lexical memory is critical for the recall of words in immediate memory tasks. We therefore speculate that the same representations underlie phonemic awareness tasks and classic verbal short-term memory tasks (memory span tasks). Given evidence, briefly summarized earlier, that training phonemic awareness facilitates the development of children's word reading, it is possible that the same phonemically structured phonological representations of words in lexical memory are critical determinants of phonemic awareness, immediate memory performance, and learning to read.

The idea that access to a phonemically structured representation of speech is one critical determinant of the ability to learn to read is compatible with a number of different theoretical perspectives on reading development. In alphabetic writing systems, letters are used to represent phonemes, and it has been argued that children need to master the alphabetic principle in order to learn to read efficiently (Byrne & Fielding-Barnsley, 1989). Mastering the alphabetic principle involves children's understanding the mappings between letters in printed words and the phonemes in spoken words; in order to achieve such understanding, they will need to possess phonemically structured representations of speech as well as letter–sound knowledge. As the studies reviewed in the introduction documented, letter knowledge appears to be another strong correlate of children's ability to develop word reading skills.

Several models of reading development embody these ideas in slightly different forms. According to the lexical quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002), words vary in the quality with which different aspects of their form (phonology, morphosyntax, orthography) and meaning (semantics) are represented in memory. A word with good lexical quality has all aspects of linguistic knowledge about the word represented in a precise and flexible way. On the basis of this view, it is natural to expect that children will learn to read words with well-specified phonological representations more quickly than words with poorly specified representations. Similarly, in the connectionist "triangle model" of reading aloud, one pathway in the model involves learning mappings between the orthographic input units used to code written words and the phonological output units that code the words' pronunciations (e.g., Harm & Seidenberg, 1999, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996). Harm and Seidenberg (1999) modified earlier versions of this model by pretraining the phonological output units in the model prior to the model being trained to read. This phonological pretraining given to this model effectively meant that it could be said to have phonemically structured phonological representations before it was trained to read. Harm and Seidenberg showed that such pretraining facilitated learning and generalization in comparison to a model that lacked such phonological knowledge (see also Hulme, Quinlan, Bolt, & Snowling, 1995). This model therefore aligns well with the conclusions of our meta-analyses that phonemic skills are one critical determinant of success in learning to read.

Educational Implications

Our findings are relevant to practical issues relating to the teaching of reading and to methods of remedial teaching for children with reading difficulties. Accepting that phonemic skills are one causal influence on the development of reading skills leads directly to recommendations that these skills should be directly taught to children in the early stages of learning to read. This idea is already embodied in current educational recommendations in both the United States (National Institute of Child Health and Human Development, 2000) and the United Kingdom (Rose, 2006). In line with this, evidence from a recent intervention study with children identified as having weak oral language skills at school entry showed that an intervention involving daily phonemic awareness and letter–sound training was effective in boosting early reading and spelling skills (Bowyer-Crane et al., 2008). These results, coupled with the results from the present meta-analyses, suggest that training letter–sound knowledge and early phonemic skills may be particularly valuable foundations for the teaching of early reading skills. It is also the case that training phonemic manipulation skills and training letter–sound knowledge may very naturally be done together in the early reading curriculum in schools.

Our meta-analyses clearly show that children with dyslexia show a large deficit on phonemic awareness tasks, suggesting that such children will require direct instruction to target this area of difficulty in order to help them to learn to read. There is now evidence from several randomized trials showing that training in phonemic awareness in the context of high-quality phonically based reading instruction is effective in helping to ameliorate children's word-level reading difficulties (Bowyer-Crane et al., 2008; Hatcher, Hulme, & Ellis, 1994; Hatcher et al., 2006; National Institute for Literacy, 2008; Torgesen et al., 2001, 1999).

Conclusions

There is now a large, complex, and sometimes seemingly contradictory literature on the associations between different phonological skills and learning to read. This meta-analytic review substantially clarifies the patterns in this literature. It appears that phonemic skills measured in children at the earliest stages of learning to read are closely related to the early growth in children's word reading skills. We have argued that converging evidence from longitudinal and training studies suggests that this relationship may be a causal one, such that adequate phonemic skills may be one prerequisite for learning to read effectively. These effects seem to be essentially universal across the different alphabetic languages that have been studied. In contrast, the two other skills considered here (rime awareness and verbal short-term memory) are less closely correlated with individual differences in learning to read, and their relationships with reading seem to be explicable in terms of shared variance with phonemic skills.

These findings have important applied implications in that they strengthen the view that the early teaching of reading, as well as the remedial teaching given to children with dyslexia, should include direct teaching of phonemic skills (in addition to training letter–sound knowledge). On a theoretical note, the studies reviewed here need to be fully incorporated into formal models of reading development. More specifically, the clear implication of our findings is that any adequate model of reading development needs to acknowledge the central role played by phonemic representations in learning to read.

Regarding future research, we believe the evidence from existing cross-sectional studies is so clear that future studies should be confined to longitudinal and training studies. There is no doubt that phonemic skills can be trained, but future studies should concentrate on how such training can be most effectively delivered and what other skills need to be in place for such phonemic training to be maximally effective in facilitating reading development. Letter–sound knowledge is one other critical skill that is clearly closely related to phonemic awareness and to learning to read. Future training studies that assess the effects of training either phonemic awareness, letter–sound knowledge, or both on the development of reading skills would be valuable. Such studies will also be important in helping to clarify the likely reciprocal relationships between phonemic skills and letter–sound knowledge and their separable and joint effects on the development of early reading skills.

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Received December 20, 2010
Revision received October 30, 2011
Accepted November 3, 2011 ■