ANNUAL REVIEWS

1933

*Annual Review of Linguistics*

# Relations Between Reading and Speech Manifest Universal Phonological Principle

Donald Shankweiler[1,2] and Carol A. Fowler[1,2]

[1]Department of Psychological Sciences, University of Connecticut, Storrs, Connecticut 06269, USA; email: donald.shankweiler@uconn.edu, carol.fowler@uconn.edu

[2]Haskins Laboratories, New Haven, Connecticut 06511, USA



Annu. Rev. Linguist. 2019. 5:109–29

The *Annual Review of Linguistics* is online at linguist.annualreviews.org

https://doi.org/10.1146/annurev-linguistics-011718-012419



## Keywords

orthography, phonological awareness, phonology, reading, speech, writing system

## Abstract

All writing systems represent speech, providing a means for recording each word of a message. This is achieved by symbolizing the phonological forms of spoken words as well as information conveying grammar and meaning. Alphabetic systems represent the segmental phonology by providing symbols for individual consonants and vowels; some also convey morphological units. Other systems represent syllables (typically CVs) or morphosyllables. In all cases, learning to read requires a learner to discover the forms of language that writing encodes, drawing on metalinguistic abilities that are not needed for the acquisition of speech. Therefore, learning to read is harder and rarer than acquiring speech. Research reveals that skilled readers of every studied orthography access phonological language forms automatically and early in word reading. Although reading processes differ according to the cognitive demands of specific orthographic forms, the differences are subservient to the universal phonologic principle that all readers access phonological language forms.

# 1. INTRODUCTION

Reading is a language ability that we in literate societies tend to take for granted. Children in wealthier countries begin to acquire it soon after they acquire speech, but the process is far from automatic. Reading, unlike speech, requires a period of staged instruction with variable results. Fortunately, much has been learned about the science of reading in recent decades that is pertinent to teaching reading skills and investigating and addressing all-too-frequent reading difficulties.

The advances have largely come from research that crosses disciplinary boundaries. Adopting this perspective, we consider ways that the phonological aspect of language is fundamental to the nature of writing and reading, and we ask whether recovering phonology from print is essential to learners and skilled readers for reading. We pursue these matters first by stating some assumptions and raising some relevant issues and then by examining the pertinent evidence from research in linguistics, speech science, psychology, education, and cognitive neuroscience.



# 2. FUNDAMENTALS: THE ESSENTIAL ROLE OF PHONOLOGY IN THE MULTISTRUCTURED LANGUAGE SYSTEM

Natural languages universally relate sound and meaning via a system of interlocking parts: phonology, lexicon, syntax, semantics, and pragmatics. We focus on what we take to be the essentials of the phonological component of language. Descriptively, phonology refers to the distinctive patterning of sounds of a language and the gestures of tongue, lips, jaw, and larynx that produce them. In functional terms, phonology supplies the building blocks of word forms and the principles for binding them into syllables and larger metrical structures. Without identifying with any particular theory of phonology, we note that phonology is a systemization of that part of our language competence that reflects our ability both to produce and to perceive the spoken words of our language and to recognize utterances spoken and heard as equivalent (Fowler 2004). An essential role of phonology is to enable meanings to be conveyed by word forms composed of varied and repeated combinations of a small set of meaningless segments. Hence, phonology (together with syntax) enables linguistic utterances to be open ended, capable of generating an unlimited number of messages (Abler 1989, Hockett 1960, Studdert-Kennedy 2005).

## 2.1. What We Read

We agree with DeFrancis (1989) that phonology is the property of spoken language that made the development of fully expressive writing possible and that symbols for spoken language convey phonological forms in some way in all present-day writing. Certainly, if words were not composed of phonological segments, the existence of alphabetic writing would be paradoxical (Mattingly 1992). More importantly, it appears that all writing systems represent phonological units—whether they are alphabets or are based on larger segments (Perfetti et al. 2005).

## 2.2. The Historical and Ontogenetic Relation of Spoken and Written Languages

Speech evolved biologically in the species and is acquired first ontogenetically.[1] Writing and reading are products of cultural evolution that also modify the neurobiological substrate of spoken language (Castro-Caldas et al. 1998). At its origin, writing had limited purposes and limited powers.

[1]This is not to say that speech is an essential carrier of language. Languages can be signed (and written) as well as spoken. However, there is something special about speech that reflects its origin in human evolution: It is that speech is universal among (hearing) human communities. Signing may replace speech in communities predominantly of deaf people, or it may serve as a secondary carrier of language in hearing communities. Literacy, likewise, is far from universal.

The earliest visual signs were holistic, representing quantities, entities, or propositions rather than individual words or parts of words. Not originally a surrogate for speech, this proto-writing did not have the ability of speech to convey an unlimited variety of meanings. Gradually, by incorporating symbols for phonological structures or by cuing the pronunciations of words obliquely, writing gained in expressiveness (Klima 1972, Schmandt-Besserat 1997, Studdert-Kennedy 2000).

Writing, however pervasive in literate societies, is far from universal; most of the world's languages lack a written form (Anderson 2010), Furthermore, in language communities that have long possessed an orthography, reading, unlike speech, is not universally acquired, and when acquired, its use is often limited. Many people can read and write to a degree but are far less familiar and less skilled with the written language than they are with the more natural spoken form.

## 2.3. Writing Systems

Following other scholars (e.g., Braze & Gong 2017, Coulmas 1989), we use "writing system" to refer to a kind of mapping between written symbols and linguistic units; for example, alphabets map graphemic units (letters) to phonological segments, whereas syllabaries map graphemic units to syllables. The main kinds of writing systems include alphabets, syllabaries, and morphosyllabic systems. In contrast, "orthography" refers to a specific mapping in use by one or more language communities. Among alphabetic systems, there are, for example, the distinct orthographies for English, Hindi, Korean, and Serbian.

All writing systems and their associated orthographies represent the spoken language, and all provide some information about phonological language forms. However, across systems and orthographies, the phonological information provided differs in grain size (e.g., phonemes, syllables, morae, or morphemes) and in the completeness or consistency of the phonological information. Some writing systems incorporate into their segments semantic information as well as phonological information.[2]

As noted, alphabets map letters or functional spelling units (e.g., in English, <ch>; Venezky 1999) onto phonological segments. We refer to the latter segments as phonemes, following the usage in the psycholinguistics literature without implying any of the theoretical apparatus associated with linguistic theories of the phoneme. The segments to which letters of alphabets refer are phoneme-like in that they are abstractions over context-conditioned or free phonetic variation (for example, between aspirated and unaspirated realizations of voiceless stop consonants in English). Alphabetic systems vary in the consistency and completeness of mappings between letters and phonemes. The Serbian and Turkish systems are highly consistent, having nearly a one-to-one mapping. English is less consistent.[3] Unpointed Hebrew is consistent in its mappings from letters to consonants, but it omits vowels; accordingly, its mapping is incomplete. For historical reasons, systems with close to one-to-one mappings between graphemic and phonological word forms are called "shallow"; those with less consistent or less complete mappings are called "deep."[4]

[2]The following overview is necessarily brief and incomplete; for more information, see Coulmas (1989) and DeFrancis (1989).

[3]There are many true inconsistencies (e.g., *tough*, *through*, *though*). In addition, however, English sometimes preserves information about morphemes by spelling the same morpheme in the same way, even when it is pronounced differently (e.g., the suffix *-ed*, or words that share a stem morpheme, such as *heal* and *health*).

[4]These terms are somewhat accidental. Liberman et al. (1980a) noticed, following Chomsky & Halle (1968), that English spellings conform more closely to the (deep) lexical representations of words in Chomsky and Halle's generative phonological theory than to surface word pronunciations. For Liberman et al. (1980a), then, English spelling is deep, not in being inconsistent or incomplete but in mapping consistently to those deep lexical forms. Serbian spellings map consistently to more surface (shallow) forms. In the hands of psycholinguists who were unfamiliar with the deep/surface distinction in the generative phonological theory of the time, "deep" was used to mean "inconsistent" and "shallow" to mean "consistent," both with respect to phonemically specified word forms.

Syllabic systems, such as the kana systems of Japanese, represent syllables.[5] This is viable for a language such as Japanese that has a limited number of possible syllables, but not for languages such as English that have vastly more. The Chinese orthography is a morphosyllabic system in which characters represent both phonological and semantic information. Typical characters in Chinese writing have two parts that jointly represent a monosyllabic morpheme. One part indicates (more or less reliably) the syllable's pronunciation; the other indicates (more or less reliably) the morpheme's meaning.

Some orthographies are hybrids that use more than one writing system type. The Japanese orthography uses two syllabaries (hiragana, katakana) and a morphosyllabic system (kanji) borrowed from Chinese. In another example, the orthography used in Hindi is sometimes called an alphasyllabary (e.g., Bright 2000; compare with Rimzhim et al. 2014) because graphic representations of phonemes are combined into groups representing open syllables.

Different orthographies present readers with different kinds and qualities of information. Next, we focus on skilled readers and assess whether there are universal ways of reading and ways that are conditioned by the orthography.



## 3. SKILLED READING

We limit our review to word recognition. Of course, reading is not merely identification of printed words. Text consists of grammatically structured sentences organized into cohesive paragraphs, chapters, and so on. Readers have to process the text at these larger grains to comprehend what they read. However, to limit the scope of our contribution, we adopt the "Simple View of Reading" (e.g., Gough & Tunmer 1986, p. 7), which postulates that, beyond word identification, processes of language comprehension are shared substantially by reading and spoken language comprehension. [There are differences because, for example, spoken utterances include prosodic properties (e.g., intonation, stress) that serve as information for listeners but are absent or only coarsely provided in print; see Levasseur et al. 2008.]

### 3.1. Commonalities in Word Recognition Across Writing Systems and Orthographies

The vast majority of novice readers are competent users of the spoken language that their orthography transcribes, and thus they know many of the phonological word forms of their language and their associated meanings. They are expected to exploit systematic orthography–phonology mappings, because the mappings provide a gateway into the already well-learned spoken language knowledge system. Logically, however, skilled readers can have learned to map printed forms directly to word meanings, just as earlier they learned to map phonological word forms to meanings; that is, they might evade mapping from spelling to phonology. Even so, evidence from every orthography investigated overwhelmingly indicates that skilled readers rapidly and automatically access phonology from print.

In the late 1980s, the prevailing view of reading researchers, according to Perfetti & Bell (1991), was that skilled readers of English sometimes access phonological word information, but they tend to do so only if words are regular (so that spelling–sound rules yield the right pronunciations) and then only if the words are low in frequency (so that the direct mapping from orthography to meaning is slower than the spelling–phonology–meaning mapping). However, Perfetti and

[5] Strictly, Japanese kana represents morae—that is, V or CV syllables and postvocalic nasals.

colleagues (Perfetti & Bell 1991, Perfetti et al. 1988) as well as others (e.g., Van Orden 1987) began to obtain evidence challenging this commonsense view, instead showing that access to phonology by skilled English readers is fast, automatic, and nearly inevitable. Brysbaert (2001, p. 765) wrote: "It is becoming increasingly clear that phonology plays a substantial role in visual word recognition. Researchers no longer discuss whether phonology is involved or not" (see also Seidenberg 2011).

Perhaps the earliest convincing finding was Van Orden's (1987). His participant readers verified whether a target letter string (e.g., ROSE, ROWS, ROBS) named an instance of a particular semantic category (e.g., flowers). False alarms occurred significantly more often to homophones (ROWS) of category members than to spelling controls (ROBS). In this case, phonological access occurred despite fostering errors.

Other experimental paradigms provided additional evidence for automatic phonological access from print. For example, in research by Perfetti & Bell (1991), a briefly presented target word in lower case (e.g., *main*) was identified best if it was masked by a following pseudoword in uppercase print that was similar to the target word graphemically and phonologically (*MAYN*), next best if the mask was similar only graphemically (*MARN*), and least accurately if it was unrelated. Pseudowords were short in duration and were followed by a pattern mask (XXXXX) that generally made participants unaware of the pseudowords; this helped to ensure that their effects on processing of the targets were nonstrategic. A priming version of the task was used to chart the relative time courses of access to graphemic and phonological information. In this version, pseudoword primes were presented briefly (for durations between 25 and 65 ms) and followed immediately by the target, itself followed by a pattern mask. For 25-ms pseudoword durations, the different prime types did not differentially affect target identification. At 35-ms durations, target identification was better in the context of the two related pseudoword types compared with the unrelated primes. At 45-ms durations, performance was best in the context of phonologically related pseudowords. Thus, as should be the case, orthographic information is accessed earlier than phonological information, which nonetheless emerges very early in visual word processing.

The findings just summarized pertain to skilled readers of English. The orthography of English is special among alphabetic systems because its spelling–sound (and sound–spelling) mappings are frequently inconsistent. Given the findings on English, we might expect similar findings of automatic, fast access to phonology among readers of more consistent alphabetic systems, such as Serbian, or readers of other deep alphabetic systems, such as Hebrew. However, it is less evident that readers of nonalphabetic writing systems such as Chinese would show the same rapid, automatic access to phonology. Remarkably, however, findings suggest automatic access to phonology by skilled readers of all orthographies tested so far (Serbian, Lukatela & Turvey 1990; Hebrew, Gronau & Frost 1997; Chinese, Tan et al. 1995, 1996) and provide evidence that access to phonology by readers of Chinese, which provides less specific phonological information than the other orthographies, is slower than access by readers of alphabetic systems.

The array of findings showing early nonstrategic access to phonology from print across a variety of orthographies led Perfetti et al. (1992; see also Perfetti et al. 2013) to propose a universal phonological principle according to which skilled readers across all orthographies access phonological units of a grain size appropriate to the orthography (see Section 3.2.2) at the earliest time that the orthography allows after print presentation.

## 3.2. Orthography Can Affect Phonological Access

Although, as summarized above, skilled readers universally access phonological information when they read printed words, differences among orthographies modulate skilled reading in at least two ways. Below, we discuss effects on word reading of orthographic depth and of the grain size of orthographic units that maps most consistently to phonology.

**3.2.1. Orthographic depth.** Although access to phonology appears to be universal, the skilled reading of words represented in deeper and shallower orthographies differs in several ways. Frost et al. (1987) explored these differences among readers of Hebrew, English, and Serbian.

The investigators supposed that printed words could be named in either of two ways. Readers could map the orthographic forms of a word to their phonological counterparts and generate a naming response from that. Alternatively, they could map the orthographic form of a word directly to the word's entry in lexical memory to generate a naming response. The relative frequencies with which these routes might be taken should depend on the shallowness or depth of the orthography. In shallow Serbian, words can be named without first identifying them as members of the reader's mental lexicon. Nonwords must be named that way. For readers of English, however, some words (say, *choir*) cannot be named accurately by spelling–sound rules alone; determining the pronunciation requires lexical access. In unpointed Hebrew, lexical access is required for naming words to supply the missing vowels. For lexical decisions (whether a letter string is a word or a nonword), readers of all orthographies must access the lexicon to generate a response.

The investigators predicted that lexical decision times would be slower than naming times among readers of Serbian (because naming does not require lexical access). In contrast, they hypothesized that response times in the two tasks would be quite similar in Hebrew and in between in English. That is what they found. Furthermore, they also predicted and found differences between the writing systems in word-frequency effects, which should reflect lexical access. Word-frequency effects are evident when responses to high-frequency words are faster than to low-frequency words and slowest to nonwords. In naming, this pattern was weaker for Serbian readers than for readers of Hebrew and English. The relative effects of word frequency on lexical decision times in the three orthographies were similar.

**3.2.2. Grain size.** Differences across orthographies in spelling–phoneme consistency encourage readers to focus on smaller or larger orthographic and phonological grain sizes (e.g., Ziegler et al. 2001). In an orthography such as that of Serbian, there is no need to attend to grain sizes larger than letters and phonemes, because letter–phoneme mappings are wholly consistent. By contrast, it can be helpful for readers of English to focus on larger grain sizes as well as smaller ones. A letter such as *a* is associated with multiple pronunciations in English, but some of the ambiguity can be reduced by focusing, for example, on word bodies (the vowel and following consonants in a monosyllable) and (phonological) rimes. There is only one pronunciation of *a* in *-alk*, for example. Ziegler et al. (2001) compared word and nonword naming in English and German, two closely related languages with many cognate words (e.g., *sand*, *Sand*) but with letter–phoneme mappings that are more consistent in German than in English. They predicted that English readers would use larger grain size units than would German readers. Half of the nonwords and words in their sample, all English–German cognates, had word bodies with many exemplars in the language; half had word bodies with few exemplars. In addition, words and nonwords ranged from three to six letters in length. They hypothesized that word-body neighborhood size should matter more for English than for German readers and that German readers, predicted to focus more on letter–phoneme mappings than would English readers, should show a larger length effect than English readers. Their findings confirmed these hypotheses.

Overall, findings on skilled reading suggest that readers universally access phonological word forms automatically and rapidly. Differences across writing systems and orthographies in the consistency and completeness of the phonological information provided can affect such variables as the time required to access phonological word forms, the likelihood of lexical access in word naming, and the grain sizes of the orthographic and phonological word forms accessed by readers. Having briefly characterized skilled reading, we now address factors affecting how novice readers become skilled.

## 4. LEARNING TO READ

### 4.1. The Novice Reader: Cognitive Requirements for Learning to Read

This section concerns properties of writing that make reading learnable, though often with difficulty. As discussed above, word reading maps written to spoken forms, and language users' phonological competence provides the gateway through which novice readers, especially, can access their knowledge of spoken language (see Fowler 2011). However, the ability to use a language to communicate orally is not sufficient to enable a child to read or to write. A novice needs instruction from literate adults to forge links between writing and the speech the child already knows. The discussion that follows pertains to alphabetic writing; then we consider which parts may generalize to learners of other writing systems.

Alphabetic writing is a cipher on the phonemes of the language (Liberman 1970). It might therefore seem that reading in an alphabetic system is merely matching visual segments to phonemes, but that is an illusion (Liberman 1992). What makes reading hard, and what tools can reading instruction provide to smooth the learner's path? Space limitations allow us to consider only the early stages of reading acquisition.

### 4.2. Reading, the Alphabetic Principle, and Phoneme Awareness

Isabelle Liberman and her colleagues (Liberman 1973, Liberman et al. 1974) showed that prereaders are not generally aware that spoken words are composed of consonants and vowels. This observation was independently discovered by others (Bruce 1964, Calfee et al. 1972, Fox & Routh 1975, Rozin et al. 1971, Savin 1972) and widely confirmed (Adams 1990). To recognize that letters convey phonemes (i.e., the alphabetic principle), learners need to know explicitly that word forms are phoneme strings; in addition, they need to be able to identify phonemes in the words they know by ear.

Explicit segmentation of spoken words into their component phonemes is a meta-ability, usually called "phoneme awareness." The consonants and vowels that compose syllables are ordinarily not consciously identified in speech perception. The situation is similar in music: In recognizing or reproducing a melody, one need not explicitly identify the specific pitches or intervals, and surely most listeners do not do so.

Mattingly (1972, 1992) used the more inclusive term "linguistic awareness" to denote the abilities of language users to reflect on language, including its phonological aspects, which he maintained is critical for acquiring literacy but not used for ordinary speaking and listening. He called these "secondary . . .abilities" to distinguish them from the "primary linguistic activity" of speech communication (Mattingly 1972, p. 133).

Phoneme segmentation abilities have been tested in diverse ways—for example, by counting segments in syllables; by deleting a segment; by substituting one segment for another; or by moving and adding segments, as in Pig Latin manipulations. A related ability is to recognize recurrences of the same phoneme in different words; for example, *hat* and *pit* share final /t/ (Byrne & Fielding-Barnsley 1990). "Phoneme awareness" is an umbrella term that refers to one or more of these segmentation abilities (see Scarborough & Brady 2002). However, different tasks draw on different abilities that are achieved at different ages and experience levels, and discerning the role of phonological abilities in learning to read has engendered an immense amount of research (for reviews, see Byrne 1998, Natl. Read. Panel 2000, Rayner et al. 2001, Seidenberg 2017).

### 4.3. Reasons for Children's and Scientists' Difficulties with the Phoneme

Liberman et al. (1974) found that kindergarten children who had received little or no instruction in reading were much more successful in segmenting words by syllable than by phoneme. Why is phoneme segmentation obscure? To these authors, the most persuasive reason was that, in speaking and in the acoustic speech signal, consonants and vowels, unlike letters, temporally overlap. Due to this coarticulation, information for more than one phonetic segment is conveyed on the same stretch of sound. The word *bad* has three phonemes, but acoustic information for all three segments is conveyed throughout the syllable. This parallel transmission makes rapid transmission of speech possible (Liberman 1970, Liberman et al. 1967). Syllables, though their boundaries are often fuzzy, are nonetheless more individuated acoustically than phonetic segments, and arguably they are more salient perceptually, perhaps because most syllables are marked by an amplitude peak at the maximum opening associated with the vowel.

Liberman (1973) speculated about the difficulties that parallel transmission of speech might pose for learning to read and reading instruction. Many of the phonemes that letters represent (including those for most consonants) are not pronounceable in isolation. Consequently, to make a consonant pronounceable, teachers usually add a vowel. In sounding out the word *bad*, teachers may say "*b* says /bʌ/, *a* says /æ/, *d* says /dʌ/." However, because each of these component sounds is itself a syllable, it is impossible to fuse them into the single syllable /bæd/. Reading cannot be a matter of aggregating discrete letter sounds, so a teacher's injunction to "blend" can cause puzzlement.[6] Liberman and her associates proposed ways that teachers can get around the difficulty (partly by choosing examples, such as fricatives, that can be produced without a vowel) without pretending that blending of artificially separate letter sounds can be accomplished (Liberman et al. 1980b).

Prereading children may labor under a maturational handicap in their efforts to grasp the alphabetic principle: Fowler (1991) proposed that words may be stored in only partially differentiated form in prereaders' lexical memories. Particulate phonemic organization may require larger vocabularies than preschool children typically have (see also Metsala & Walley 1998). In particular, they may know few minimal pairs such as *bill* and *pill* that can only be distinguished lexically by complete phonological specification of the distinguishing consonants. From about age six, children's rapidly expanding vocabularies are densely filling in the gaps in phonetic space to include more and more of these minimal pairs. To accommodate vocabulary expansion without loss of discrimination, the representations of words in memory need to become more detailed. Prior to that, a child is poorly equipped to become aware of segments and lacks the basis for understanding how alphabetic writing works. (However, the evidence for this hypothesis is mixed; see Braze et al. 2011, Hindson et al. 2005.)

There are further reasons for the relative obscurity of phonemes in awareness. Byrne & Liberman (1999) maintained that children naturally seek units of meaning, not units of sound, on the basis of the way they learn the spoken language, and this can mislead them in their earliest attempts to cope with print. Individual phoneme segments are meaningless, a property that is essential to their function in speech and alphabetic writing (Studdert-Kennedy 1998).

[6] Bloomfield, who took a keen interest in the problems of learning to read, regarded this as a difficulty (e.g., Bloomfield & Barnhart 1961).

Byrne (1996) showed by an ingenious experiment that young children have a bias to impute meaning to novel bits of print. The experiment exploits the fact that some alphabetic systems incorporate meaning elements into the writing. In English, the comparative *-er* is a morpheme as well as a syllable. Having learned to distinguish *small* from *smaller*, and *green* from *greener*, prereading children more readily generalized to other word pairs (e.g., *fast* and *faster*) in which one member ended in the comparative *-er* than to word pairs (such as *corn* and *corner*) which would end or not in the letters *er* but in which *er* was not a morpheme. Byrne showed further that even adults with much reading experience are similarly biased to look for meaning. When asked to learn a new artificial system for writing, most participants did not spontaneously infer the alphabetic principle, although the system they were confronted with was an alphabet.

Like young children (and many laypeople), scientists who encounter the phoneme concept in their work often find it a stumbling block. Speech sciences have been caught in an awkward paradox: Phonemes both do and do not exist. They exist as mental units but not as units in the speech signal, where they have been considered (wrongly, in our view) to be obliterated by coarticulation (e.g., Liberman et al. 1967). However, the paradox may be more apparent than real. We (Fowler et al. 2016) assembled evidence for phonemes as real components of spoken words. In addition, we summarized research suggesting that, although the speech signal is not composed of temporally discrete segments, consonants and vowels are nonetheless distinctively signaled by separate, temporally overlapping acoustic patterns. Appropriate experimental methods reveal that listeners are sensitive to these distinct acoustic patterns for serially successive consonant and vowels. Hence, speech is alphabetic, too. If our conclusion is right, it removes the paradox and a chronic source of embarrassment to theories of both speech and reading. Alphabetic writing is not based on a fiction; phoneme-like units are real components of the language in both its private and public manifestations. Why, then, is explicit phoneme segmentation difficult for children and some others? There is probably no single reason. We have already identified some potential contributors to the difficulty. A further difficulty, discussed in Section 4.7, below, derives from differences in links from orthography to phonology.

## 4.4. Phonological Abilities and Reading Success

Is phoneme awareness a prerequisite for grasping the alphabetic principle, or do children gain meta-phonological skills as a consequence of their experience and instruction in reading? We do know that readers of Chinese not exposed to alphabetic pinyin perform more poorly than do readers with pinyin exposure on tests of phonemic awareness (Read et al. 1986). This result implies that phonemic awareness may not develop when it is not relevant to learning to read.

A related question is whether phonemic awareness can develop apart from alphabetic learning (see Brady & Shankweiler 1991, Mann 1991, Morais et al. 1979). This question has motivated experiments with oral language games designed to test (or promote) skill in segmentation. There are ways to call a child's attention to segments without using their corresponding written symbols, as Liberman et al. (1974) showed, thereby avoiding any confound between phonological abilities and orthographic knowledge.

Correlations between meta-phonological skills and success in reading do not prove that a causal relationship exists. Results of controlled experiments are usually required to support claims about causation (see Castles & Coltheart 2004, Hulme et al. 2005). However, real-world circumstances often pose obstacles to the design and implementation of valid educational experiments. Bradley & Bryant (1983) recognized that training studies with follow-up are among the few available ways to obtain evidence of causation, and they provided one of the earliest demonstrations of long-term gains in reading following instruction in phonological skills without the use of print. Lundberg et al. (1988), pursuing this question, asked prereading children to draw lines between pictured objects whose names had the same initial phoneme and to mark the number of phonemes in depicted words. The authors found that phonemic awareness can develop before reading ability and independently of instruction that relates segments to writing, and that the training improved reading achievement in later years (see also Elkonin 1973, Liberman et al. 1980b).

Phoneme awareness can be taught independently of print, but should it be routinely? Byrne & Fielding-Barnsley (1989) demonstrated that most preliterate children will not infer the alphabetic principle from experience with print alone, even experience that is contrived to facilitate the drawing of the inference. As we saw, however, there is substantial evidence that direct instruction in phoneme awareness is effective in promoting it (Bradley & Bryant 1983, Brady 2011, Byrne 1998, Lundberg et al. 1988, Shankweiler & Fowler 2004), and it is also effective for children who are environmentally or genetically at risk of developing reading difficulties (Blachman et al. 2013, Byrne et al. 2008, Foorman et al. 1998, Hindson et al. 2005). A series of studies by Byrne and colleagues (Byrne & Fielding-Barnsley 1995, Byrne et al. 2000), culminating in a six-year follow-up, showed that preschool children who were successfully taught to make phoneme identity judgments were modestly but measurably ahead of their peers when tested in reading six years later; however, some children became poor readers. Early segmentation training does not vaccinate children against reading failure.

The ability to segment words by syllables, onsets, and rimes frequently comes earlier in childhood than segmentation by phonemes, but only the latter ability is consistently related to measures of reading ability (Brady & Shankweiler 1991, Morais et al. 1979).[7] Moreover, the different ways of assessing phoneme segmentation are not equivalent in their relevance to reading skills. Most children probably do not achieve full phonemic segmentation abilities prior to instruction and experience with decoding and spelling written words. Bentin & Leshem (1993) compared children of the same age with different amounts of schooling and found that learning to read accounted for most of the great gains in phoneme segmentation during the first school year.

Knowing the letter names and sounds is also an important prereading ability. For one thing, it directs the learner's attention to the phonological aspect of writing and reading. Learning this ability in preschool correlates well with later reading (Hulme et al. 2012). However, knowing the letters alone will not bring about the ability to segment spoken words by their component phonemes. Ball & Blachman (1991) found that for first-grade learners without phoneme awareness, letter knowledge is not effective in promoting learning to recognize words. Drawing children's attention to the role of letters as the phonological building blocks of words is a further critical step (Foulin 2005). In best teaching practices, children are encouraged to notice segmentation through coordinated activities involving speech and writing (Brady 2011, Liberman et al. 1980b). Experience with reading and writing promotes phonological awareness and refines it such that there is reciprocal development of letter knowledge, printed word recognition, phoneme segmentation, and spelling (see Bus & van IJzendoorn 1999, Ehri 1992).

### 4.5. Building a Reading Vocabulary by Phonologic Decoding or Rote Learning?

Novice readers need to learn the alphabetic principle to make sense of how words are spelled, but exploiting the principle also requires rote learning, because the pairing of letters and sounds in an orthography is arbitrary. Other aspects of the reading process are also sometimes construed

[7]In keeping with that, adult illiterates have also proved unable to segment words by phoneme but able to segment them into syllables (Lukatela et al. 1995, Morais et al. 1979).

as best learned by rote. Before the conclusive findings summarized above (see Section 3), it was debated whether readers could bypass mapping letters to phonology. Would not educated guesses at words based on whole-word shape and context be the most efficient way to recognize printed words? If so, shouldn't teachers direct a novice learner's attention to visual word patterns from the very start? This is a contention of the so-called whole-word or whole-language method of teaching reading, which was the most favored approach in English-speaking regions for most of the last century (see Adams 1990, Goodman 1976, Smith 1973).

The whole-word approach to teaching reading falls short because it neglects the central fact that writing is based on phonology (see Liberman & Liberman 1990). Alphabetic writing was not designed to maximize visual discriminability of words. Indeed, many printed words in English look similar, but for readers, confusability is greater for words that sound similar than for those that are visually similar (Shankweiler & Liberman 1972). Practiced readers adjust quickly without adverse effects to unfamiliar variations in the visual presentation of words, such as writing that uses different fonts or alternates upper- and lowercase (Smith et al. 1969).

The whole-word approach to reading acquisition, by treating it as essentially a visual–spatial pattern recognition skill, puts the emphasis on rote learning and guessing. Instruction based on this view could well discourage children from grasping the alphabetic principle and encourage them to exercise their bias to look for meaning, thereby impeding their progress in developing autonomous word recognition skills. Instead of guessing on the basis of word shape and context, beginners are helped most by learning to use the alphabetic principle and discovering how it applies to word spellings (Adams 1990, Braze et al. 2011, Treiman 1993). We saw above (see Section 3) that skilled readers continue to make use of the alphabetic principle.

Bradley & Bryant (1980) proposed a third view of early-stage acquisition. For them, beginning reading is holistic and based on visual word shape, albeit only temporarily so. Spelling, in contrast, is inescapably phonologic because of the act of writing discrete letter segments. Consequently, reading and spelling are out of synchrony initially. However, Fletcher-Flinn et al. (2004) studied the coordination of reading and spelling abilities and found no evidence that novices were unable or unwilling to apply their phonological and alphabetic knowledge to reading, thereby challenging the contention that holistic word recognition is preferred at any stage of reading acquisition.



### 4.6. Developing Autonomous Reading Skills: Share's Self-Teaching Model

Teachers can teach only a small number of words in the classroom; however, skilled readers can read any word, whether previously encountered or not. Share (1995, p. 151) contends that current models of word recognition fail to address "the quintessential problem of reading acquisition—*independent* (i.e., unaided) generation of target pronunciations for novel orthographic strings" (emphasis in original). The self-teaching hypothesis is that phonological decoding functions as a self-teaching mechanism that enables learners to read new words independently and to acquire a print lexicon autonomously. Encounters with novel letter strings provide opportunities for a learner with a modicum of decoding skill to bootstrap word-specific print-to-language connections, leading to the progressive lexicalization of the reading skill (see also Tunmer & Chapman 2002). The value of phonological decoding as a stepping-stone to developing autonomous skills in reading is a further reason that the alphabetic principle is central in learning to read.

### 4.7. Learning in Different Orthographies

The hybrid science of reading has developed unevenly over the world in its roughly century-and-a-quarter existence. For most of that time, the greatest portion of the research has come from

English-speaking countries. Share (2008) contends that an overemphasis on English has warped the research agenda because English is an extreme example of an alphabetic system in which there is a variety of syllable types, and spelling departs greatly from one-to-one mapping of letters on phonemes.

Cross-language comparative findings on reading acquisition have multiplied in recent years. Space limitations allow us to mention only the major trends. The comparison of English with other, more consistent alphabetic systems has supported the suspicion that it takes children longer to acquire reliable word recognition skills in English. English-speaking children at age 8 lag two years behind German and Italian children in reading accuracy, reflecting the more regular grapheme–phoneme mappings in German and Italian spelling; they catch up in rate but not accuracy by age 12 (Cossu et al. 1988, Frith et al. 1998). Similar differences from English have been reported for Serbian (Ognjenovic et al. 1983), Hebrew (Share 2008), and other languages (Seymour et al. 2003).

Growing interest in the cognitive and linguistic bases of Chinese writing and related systems in Asia has resulted in a considerable body of research on learning to read in nonalphabetic orthographies, and especially in comparisons of Chinese and English. Research has evaluated the effects of the several differences between these orthographies as well as the important similarity that all writing systems represent phonology, but Chinese and English do so at different grains. Chinese engages phonology at the syllable level, not at the phoneme level. In view of this, one would expect that learning to read in Chinese would draw on phonologically based abilities, but perhaps to a lesser degree than in English, and that the phonological abilities engaged would be different in Chinese than in English. This has been confirmed. For example, phoneme awareness is less strongly related to success in reading Chinese than in reading alphabetic languages and more strongly related to rapidity of oral naming (Ho et al. 2004, McBride-Chang et al. 2003).

In Chinese, syllables are morphemes. McBride-Chang et al. (2003) confirmed the expectation that morphological abilities would be especially important in learning to read Chinese. They found that the ability to manipulate morphemes in the spoken language predicted learners' character reading after controlling for differences in phonological awareness and vocabulary.[8]

Given the sheer number of characters (at least 2,000 in common use) and the complexity of the graphological layout, developing Chinese reading skills should place a premium on visual memory. The orthographic skills that are important in reading Chinese are supported by practice in writing, and this is a major source of individual differences among learners (Chan et al. 2006, Perfetti et al. 2013). Here too, however, phonology proves to be a relevant factor: It is a near-universal practice in China to introduce reading by use of an alphabet, pinyin (Read et al. 1986).

This review of reading acquisition has been selective. It omits discussion of how phonological processes play out in later development of reading skills, in the management of memory, and in the coordination of linguistic and visual abilities. In Section 6 we note findings in genetics and brain imaging that shed further light on issues we have been discussing.

## 5. COMPUTATIONAL MODELS OF WORD AND NONWORD READING

Computational models provide a valuable tool for understanding word reading and the role of phonology in word reading. One value is that they require modelers to make the assumptions of their theoretical approach sufficiently explicit to allow them to simulate human reading behavioral and neural patterns. In turn, simulated patterns can be compared with human patterns to assess the viability of the theory.

[8]Morpheme awareness also plays a role in a learner's becoming a skilled reader of English (Carlisle 2010).

There are weaknesses associated with modeling as well. One is that lack of knowledge or even considerations of convenience can lead to model properties that are explicit but quite likely wrong. An example is the slot-based means of handling letter identification across serial positions of words in many models (e.g., Harm & Seidenberg 1999, 2004; McClelland & Rumelhart 1981). This slot-based system was never considered plausible, but lacking a more plausible approach, it permitted simulation of many benchmark behavioral findings. In another example, in the Dual Route Cascaded (DRC) model (e.g., Coltheart et al. 2001), mappings from print to word representations and from print to phonology are not learned; they are stipulated but may be inaccurate. Other models (e.g., the triangle model; Harm & Seidenberg 1999, 2004) do learn but may not use a realistic learning procedure (e.g., Coltheart et al. 2001), a view recently expressed about the commonly used backpropagation by one of its developers, Geoffrey Hinton (see LeVine 2017). A final weakness (Rueckl 2016) is that most models are products of reverse engineering—that is, they are specifically designed to simulate a benchmark set of findings, and their adequacy is assessed by their success in doing so. A better approach, were it feasible, would be for the model not only to explain behavioral patterns but also to be explained by a theory of the control parameters that should underlie its development (Rueckl 2016).

To illustrate computational modeling and its role in helping investigators understand the variable role of phonology in word reading across orthographies, we discuss the triangle model (e.g., Harm & Seidenberg 1999, 2004). This model is interesting because, as noted, it learns mappings between word representations (orthographic, phonological, semantic). Moreover, learning is of statistical relationships, a kind of learning that humans are very good at (e.g., Saffran 2003).[9]

The triangle model has three main types of units or nodes at the vertices: semantic (S), phonological (P), and orthographic (O). Orthographic units link directly to the other two unit types and also map to them via intermediate "hidden" units (hidden because they do not interface directly with the world outside the model). "Cleanup" units project to and from semantic units and to and from phonological units that help to clean up degraded patterns in each domain. (See Harm & Seidenberg 2004 for a full explanation of the architecture and processing in the model.)

The triangle model is a "parallel distributed processing" connectionist model (e.g., Rumelhart & McClelland 1986). It has neuron-like units or nodes that are linked by weighted excitatory and inhibitory connections. Before learning has occurred, the connection weights are set to random values. During learning of mappings for reading, words are presented to the orthographic nodes of the network. Activation spreads in both directions (to P and S nodes) for a period of time. Then the pattern of activation, say, on the phonological units is compared with a target (correct) pattern. Differences between the network's activation pattern and the target pattern are used to make small changes in weights on links that should, in subsequent cycles, reduce the errors. Therefore, over time the network learns to settle into the appropriate phonological activation pattern (and the appropriate semantic pattern) for printed words. Because the links from orthography to phonology are more systematic than those from orthography to semantics, achieving the target activation pattern on phonological nodes is generally faster than achieving the target semantic activation pattern. Nonetheless, for a particular task—for example, naming a printed word (or making a lexical decision)—the entire network contributes to the time the network needs to settle into a stable pattern of activation, affecting simulated response latencies and accuracies.

[9]There are other models that readers may wish to know about (see Norris 2013 for a review). Most notably, there is the DRC model of Coltheart and colleagues (e.g., Coltheart et al. 2001) and the Connectionist Dual Route family of models (CDP, Zorzi et al. 1998; CDP+, Perry et al. 2007; CDP++, Perry et al. 2010). For a discussion of deficiencies of triangle models relative to other dual route models, see Coltheart (2006, 2012); for a different point of view, see Seidenberg (2012).

Harm & Seidenberg (2004) first trained their network (using 6,103 monosyllabic words input according to their frequency of occurrence in the language) to map phonological input to the semantic features of words. This was meant to capture (roughly) the fact that before learning to read, children become proficient at understanding spoken words. After that training, the network was exposed to orthographic word inputs and learned to map those inputs both to their phonological forms and to their semantic features. Following training, Harm and Seidenberg showed in 18 simulations that the network could simulate benchmark findings in the literature—including, for example, the findings by Van Orden (1987)—as well as masked homophone priming similar to that of Perfetti and colleagues, described above. Because they were particularly interested in the division of labor among the parts of the network, Harm and Seidenberg also explored variables that should have an impact on that. One such finding that the model successfully simulated is the complex Strain effect (Strain et al. 1999), which postulates that there is an effect of the imageability (semantics) of words on naming latencies (and so an impact of the O–S–P route), but only if words are both low in frequency and irregular in their spelling–sound relations, two variables that would slow activation along the direct O–P route.

Another factor that should affect division of labor among the routes is the nature of the orthography, including orthographic depth, the grain size of orthographic and phonological units that map most consistently, and at least for Chinese, the fact that so much semantic information is provided orthographically. Although we found few extensions of the triangle model to other languages, there are indications (Yang et al. 2006, 2013) that a Chinese triangle model learns O–S mappings more rapidly than it learns O–P mappings, in contrast to English models, and that effects of the O–S–P mappings have a greater and more general impact on word reading in the Chinese model than in English models.

## 6. BRAIN SYSTEMS AND GENETIC INFLUENCES

Reading skills, like other cognitive abilities, are strongly influenced by genes, as shown by studies of twins comparing identical and fraternal twin pairs. Converging results show partly independent measures of genetic influence on oral language abilities, phonological awareness, and print decoding. These influences are not fixed but fluidly modulated by the environment, including nutritional, sociocultural, and educational factors (Olson et al. 2014).

Recent advances in investigating brain activity in reading have been made possible by tools that allow study of the uninjured brain in action: functional neuroimaging methods [e.g., functional magnetic resonance imaging (fMRI), positron emission tomography (PET)], computer averaging of electroencephalography (EEG) signals, and focal brain stimulation. The picture emerging from these ways of examining the working brain shows that the brain supports reading by appropriating much of the machinery that supports speech (Frost et al. 2009). Functional entities are neural circuits connecting adjacent and nonadjacent brain regions (Mesulam 1998). Progress has been made in identifying circuits created or co-opted by reading, in discovering spatial and temporal patterns of brain activity that vary with differences in task demands and with the effects of learning, and in exploring the modifications brought about by literacy on brain processes for speech (for reviews, see Dehaene 2009, Price 2012).

### 6.1. Neural Footprints of Phonology in Development of Word Reading Skill

Using fMRI to explore brain circuits, Pugh et al. (2001) identified three regions in the left hemisphere considered to be implicated in the phonological aspects of word reading: a temporoparietal (dorsal) area encompassing the angular gyrus, supramarginal gyrus (SMG), and Wernicke's area;

an occipitotemporal (ventral) region encompassing visual extrastriate areas, the inferior occipitotemporal/fusiform area, and middle and inferior temporal gyri; and an anterior region, the inferior frontal gyrus (IFG) that includes Broca's area. Pugh et al. (2010), among others, proposed that these regions can be functionally differentiated. Functions are inferred from studies in which participants' brains are imaged as they are presented with orthographic materials and are asked to perform tasks designed to isolate specific components of the reading process.

Pugh et al. (2010) hypothesized that the dorsal portion of the posterior left hemisphere is involved in mapping from orthography to word phonology and meaning; within the dorsal region, the SMG is more active for pseudowords than for real words, which may implicate it in learning new orthography-to-phonology mappings. The ventral region of the posterior left hemisphere becomes engaged later in the process of learning to read, and its development is related to reading skill development (Pugh et al. 2010, Shaywitz et al. 2004). In contrast to the SMG, the ventral region is active when mappings have become well learned and automatized. The IFG is engaged when materials are difficult to pronounce or to process otherwise.

### 6.2. Reading Co-Opts Brain Specializations for Speech

Corroboration that these regions are implicated in accessing phonology would be findings that brain activation during reading converges strongly with activation during listening to speech. That corroboration came from two investigations: one with adult readers at different skill levels (Shankweiler et al. 2008) and the other with developing readers (Preston et al. 2016). The former study reported robust cortical response in the left IFG that covaried with literacy level to a sentence comprehension task, suggesting that brain reorganization within this zone may continue after basic literacy is acquired. Similar results were obtained with the same participants when word and nonword reading and listening tasks replaced the comprehension task in the magnet (Shankweiler et al. 2008) and when the participants were children (Preston et al. 2016).

Castro-Caldas et al. (1998) obtained evidence that literacy modifies how the brain processes speech. They showed that acquiring basic literacy changes speech abilities and the cortical network for speech functions, finding differences between illiterate adults and barely literate adults in the accuracy of repeating lawful nonwords presented by ear and in the brain regions activated by the task. Both hemispheres are involved in reorganization, but the left remains the dominant hemisphere for written language as it is for speech (see also Dehaene et al. 2010).

### 6.3. Cross-Language, Cross-Orthography Comparisons Show Universal Patterning

Skilled adult readers of four highly contrasting languages—Spanish, Hebrew, English, and Chinese—performed a semantic categorization task to spoken and written words during fMRI recordings. The results, in keeping with the behavioral findings discussed above, demonstrated limited language-specific variation among proficient readers (for example, Chinese readers were more bilateral), with speech–print convergence emerging at common sites in both hemispheres whether the orthography was alphabetic or nonalphabetic (Rueckl et al. 2015).

## 7. CONCLUSION

A universal feature of writing is the wherewithal to convey the individual words of a message. Because word forms are intrinsically phonological, all writing systems represent phonology, but alphabetic and nonalphabetic systems do so at different grain sizes, with the consequence that the processes by which readers recognize words differ. Research from varied perspectives has revealed a different mix of skills for reading in different alphabetic orthographies and further differences between alphabetic and nonalphabetic systems. Nevertheless, evidence is converging that the similarities across systems outweigh the differences, reflecting a universal phonological principle and bringing a general theory of reading within reach.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

## ACKNOWLEDGMENTS

We are grateful to colleagues who helped: to Brian Byrne, who offered encouragement when it was needed, and to Susan Brady and the anonymous reviewer, whose astute comments on the manuscript led us to clarify several points.

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Annual Review of Linguistics

Volume 5, 2019

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**Errata**

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