Visual Word Recognition

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Models and methods, orthography, and phonology

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An early and integral role in identifying words

Laura K. Halderman, Jane Ashby, and Charles A. Perfetti

Huey (1908), in his classic volume on the science and teaching of reading, reported clear evidence that the sounds of spoken language are part of reading: '...Of nearly thirty adults who were thus tested, the large majority found inner speech in some form to be a part of their ordinary reading. Purely visual reading was not established by any of the readers, ...' (p. 119).

It took a while for later views on reading to come around to this conclusion. After a period in which the role of phonology was seen as, at most, a secondary and optional part of reading, Huey's conclusion now holds a privileged place in explanations of reading. In this chapter, we explain how the research has come to force a very strong conclusion: that the 'sounds' of words, both their phonemes and their larger, prosodic constituents (stress, syllabic structures), are an integral (and early) part of word identification. Phonology doesn't merely affect word identification, it fundamentally constrains and shapes it.

Of course, Huey was not talking about phonology in this specific sense, but rather the form of inner speech, a trailing echo of the print, formed into prosodic contours – the voice in the head. A contribution of modern research has been to decompose the phonology of reading into two related but different components. Huey's inner speech is one. Word identification is another. Baddeley and Lewis (1981) showed that these two components could be partially independent. In particular, it could be false that phonology produced word identification and true that there is a tendency for readers to have the trailing echo. This distinction corresponds approximately to the question of whether phonology is 'pre-lexical' or 'post-lexical', although it is not identical to it. It is the word identification question that is at issue in this chapter. Does phonology constrain the identification of words, or is it a product of identification? Is its role fundamental (shaping identification) or incidental (providing an output that can optionally fill the role identified by Huey)?

In what follows, we review research on these questions that affirms one part of what Frost (1998) termed the 'strong phonological hypothesis' – that phonology is an automatic part of word identification. However, we consider evidence that causes some reconsideration of what this hypothesis claimed about pre-lexical phonology – that it is 'minimal' in its content and that the full phonological form is retrieved from the lexicon rather than activated by pre-lexical processes. Certainly, the final phonological form has to be affected by the lexical entry including its morphosyntax; otherwise, whether RECORD receives first or second syllable stress remains undetermined. However, we review evidence indicating that a broad range of phonological content is activated very early during word identification. Our review suggests a stronger role for phonology than the role proposed by the 'strong phonological hypothesis': a role that is early and integral to word identification.

We begin by evaluating phonological processing in different writing systems, because the question of a general role for phonology cannot be exclusively based upon alphabetic writing systems. We then discuss behavioral and neurophysiological evidence from reading research in alphabetic systems on the time course of phonological representation in skilled reading. Finally we review evidence about the content of these phonological representations.

Phonology's universal role

For alphabetic writing, reading procedures can operate on letters or graphemes by activating their corresponding phonemes. English, however, is an alphabetic system with a complex and inconsistent mapping to phonology. Other alphabetic orthographies, e.g., Finnish, Welsh, and Serbo-Croatian, are built on a more consistent mapping of graphemes to phonemes. The variability in the mapping of graphemes to phonemes in alphabetic writing has led to hypotheses about corresponding variations in word reading (e.g., Share, 2008). The orthographic depth hypothesis (Katz & Frost, 1992) aimed to explain how variation in the way different writing systems encode speech (i.e., more or less transparently) can affect word reading processes, especially the relative dependence of word reading on sublexical phonological procedures compared with lexical procedures. Beyond alphabetic writing, the universal phonological principle (Perfetti, Zhang, & Berent, 1992) claimed that reading engages phonology at the earliest moment and smallest unit allowed by the writing system. More recently, Ziegler and Goswami (2005) hypothesized that readers process phonology according to the grain size of the orthography, with readers of German utilizing one grain size and readers of English using multiple grain sizes. Each of these related ideas – orthographic depth, universal phonology, and grain size – has been the object of experimental research. The generalization seems to be that although the orthographic structure of a writing system affects the phonological information that readers process, all alphabetic writing – from inconsistent English and French to highly consistent Finnish and Welsh – is read using phonological processes to identify words. Even in Hebrew, an alphabetic orthography that does not visually represent most vowels, both phonological and orthographic effects are found with as little as 14 ms of target word exposure (Frost & Yogev, 2001).

The point of high contrast with alphabetic writing is the morpho-syllabic (or logographic) systems represented by Chinese and the Japanese Kanji. If word reading occurs without phonology, Chinese is where one should find it. A review of the first burst of research (1990s) on the role of phonology in reading Chinese concluded that phonology provided an early source of constraint in reading Chinese characters, just as it does in reading words in alphabetic writing (Tan & Perfetti, 1998). This conclusion was based on many of the behavioral and eye-tracking paradigms that were used in alphabetic studies reviewed in the next section. These include brief exposure combined with masking (Tan, Hoosain, & Siok, 1996), primed perceptual identification experiments (Perfetti & Zhang, 1991), semantic decision experiments (Perfetti & Zhang, 1995; Xu, Pollatsek, & Potter, 1999), eye-tracking studies of parafoveal viewing (Liu, Inhoff, Ye, & Wu, 2002; Pollatesek, Tan, & Rayner, 2000; Tsai, Lee, Tzeng, Hung, & Yen, 2004), and ERP studies (Liu, Perfetti, & Hart, 2003), all of which have provided evidence for phonological processing in Chinese. Important too for the conclusion that phonology is general is the result that phonology is seen in the identification of high- as well as low-frequency Chinese words (Zhang, Perfetti, & Yang, 1999).

Along with the evidence for universal phonology came hypotheses about differences in its implementation across writing systems. Two key differences in Chinese are the dependence of phonology on whole-character orthography in general (although radical effects can be found for less frequent characters) and the unit of phonology activated (syllabic rather than phonemic). The onset of phonology in character reading is synchronized to character identification in a specific sense: phonological (syllable level) information is activated at the moment that the character's orthographic representation of the character is sufficient to distinguish it from perceptually similar (and partially activated) characters (Perfetti & Tan, 1998). This contrasts with the simultaneous rise of phonemic activation with letters prior to lexical access in alphabetic writing. Still, similarities in the process of phonological activation across the two writing systems can be captured by statistical learning models (Yang, McCandliss, Shu, & Zevin, 2009) as well as by the lexical constituency model (Perfetti & Tan, 1998; Perfetti, Liu, & Tan, 2005). The latter model proposes the idea of constituency: that words have graphic, phonological, and morphological constituents that constitute the word identity. All constituents become available when a graphic input initiates the identification process, although the detailed timing or connection strengths of the constituents vary with circumstances within a language (e.g., frequency, consistency) and across writing systems (phonemes, syllables).

We turn now to evidence from alphabetic reading, where there is sufficient research to show a detailed, yet complex picture of phonology's early role in word recognition.

Phonology's early role in alphabetic reading

Behavioral evidence

Behavioral evidence supports early phonological processing that arises immediately from visual contact with a letter string in skilled alphabetic reading. This early phonology may be approximately automatic as well, even if strategic influences can sometimes alter its expression in specific tasks. When phonology interferes with performance on a task (e.g., semantic categorization with homophonic foils), this is evidence that phonology is at least difficult to suppress (Van Orden, Johnston, & Hale, 1988).

Tasks' demands are critical to consider in reviews of phonological effects. For example, naming and lexical decisions, the bread-and-butter tasks of word recognition research, differ in whether they require phonology to perform the task. Naming does, lexical decision does not. Accordingly, one might take lexical decision to be the more appropriate task to reveal early phonology, as it avoids the articulatory processes that mandate phonological processing. Indeed, lexical decision studies have found longer reaction times for homophones, suggesting that phonology is accessed and a conflict arises when one phonological form activates more than one orthographic form (MADE, MAID) in the lexicon (Pexman, Lupker, & Jared, 2001). However, because lexical decisions involve *discriminating* between letter strings that are words and letter strings that are not, they are susceptible to strategies that control decision-making processes. These strategies can vary with the properties of the real words and the foils used in the experiments.

Other non-articulatory tasks also provide evidence for phonological processing in word identification. In semantic categorization tasks, subjects are more likely to accept pseudohomophones (e.g., ROZE) and homophones (e.g., ROWS) as members of the category FLOWER because these have the same phonological form as a correct category member (ROSE) (Van Orden et al., 1988; Jared & Seidenberg, 1991). Here, phonology is generated and leads to poorer performance in a task that on the surface, doesn't require the activation of phonology. This effect, however, is limited to low-frequency items sharing phonology with low-frequency exemplars.

Although naming tasks, because they require phonology, cannot provide completely persuasive evidence for the phonological processes that occur in silent reading, tasks such as mediated priming present interesting findings. Mediated priming experiments exploit the phonological relationships between words that are not presented in the experiment. The mediation effect requires activation of the mediating prime's pronunciation even though the word itself has not been presented. For example, the presentation of the prime SOFA delays the naming of TOUCH even though the two words are unrelated. This is because SOFA activates the semantically-related word COUCH, whose pronunciation is inconsistent with that of TOUCH, thus slowing the pronunciation of TOUCH (Farrar, Van Orden, & Hamouz, 2001). By contrast, when the mediator prime (COUCH) and the target (e.g., POUCH) share the same phonology for the orthographic body, then the prime facilitates identification.

Despite compelling evidence in several non-naming tasks, one does find inconsistent effects of phonology. Some studies find evidence for phonology's role in recognizing high-frequency words whereas other studies report phonological effects restricted to low-frequency words. Some studies suggest that access to meaning is mediated by phonology, whereas other studies do not. Such loose ends, along with differences among tasks, help sustain the debate about the role of phonology.

Phonological effects can depend on the degree of strategic processing encouraged by a task. For example, many of the tasks involve priming, with manipulations of the prime's orthography and phonology. A pseudohomophone (TODE) or homophone (TOWED) prime can facilitate the positive lexical decision to a word (TOAD) compared with an orthographic control prime (TODS, TOLD) (Drieghe & Brysbaert, 2002). But these priming effects turn out to be dependent on prime durations. Drieghe and Brysbaert (2002) report pseudohomophone priming effects at both short and long prime durations, but homophone priming at short prime durations only. This suggests that a short time-window is needed to observe automatic phonological processing. Drieghe and Brysbaert concluded phonology is activated automatically, however, strategic processes (e.g., spelling verification) can influence or minimize phonology's role in lexical decision.

To generalize this observation, the more room for strategic processing, the less likely it is that phonological effects will appear. Indeed, Berent and Perfetti (1995) concluded that methods that allow unlimited exposure to a target word encourage strategic processing and produce inconsistent phonological effects. In contrast, methods that limit exposure and/or interrupt processing tend to tap early (perhaps automatic) processes that are less subject to strategic control. Although all standard behavioral tasks are subject to strategies, studies that limit exposure may give a clearer picture on the earliness of phonology. Accordingly, we take a closer look at such studies.

Studies of brief exposure with masking

Restricting the availability of visual information available through a brief exposure can reveal early phonological processes. When information is presented so quickly that participants are not aware of it, strategic processing is suppressed and more automatic effects appear in word recognition. There are a number of variations on this basic idea that use perceptual identification (i.e., what word did you see?), lexical decisions, and even naming combined with a masking procedure that limits exposure. An important paper by Rastle and Brysbaert (2006) reviewed and critiqued these paradigms in a meta-analysis of previous research. In addition, they provided new data as well as computer simulations that modeled reading data to help clarify what has been learned about masked phonological priming to date. We illustrate here, two of the paradigms studied, perceptual identification with backward masking and lexical decisions with masked priming.

Backward masking limits the duration of the target word by immediately masking it with a letter string whose relation to the target varies in terms of orthographic and phonological similarity (see Figure 10.1 for an example). The logic is that the mask interrupts target processing and reduces the probability of word identification. Unidentified words nonetheless have their component letters and (by hypothesis) phonemes activated. If the nonword mask can reinstate these orthographic and phonological units of the word, it reduces the deleterious effects of the mask, resulting in higher identification accuracy than with masks with no shared letters or phonemes. In the case of phonology, if readers do activate the

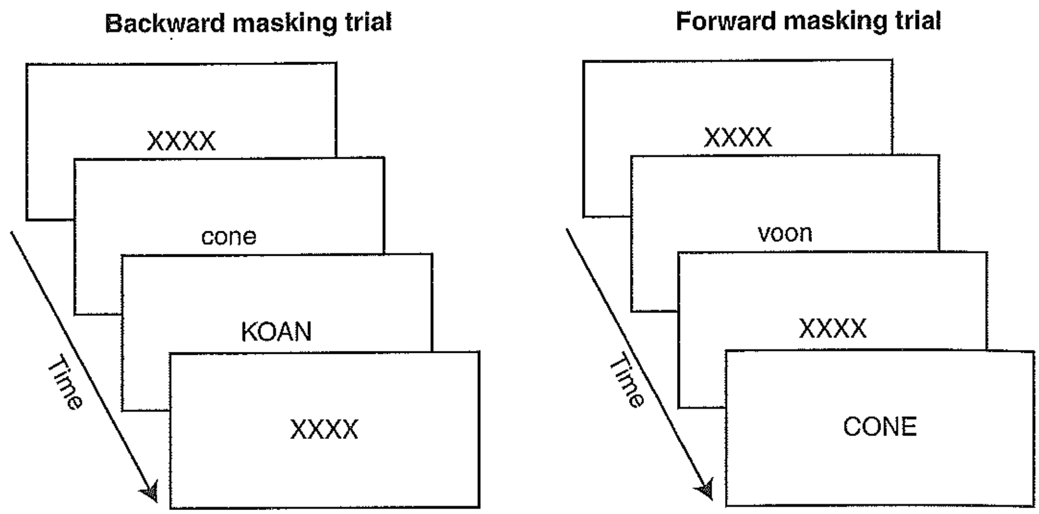

Figure 10.1 The left side shows an example of a backward masking trial using a phonologically similar nonword mask. A trial begins with a forward pattern mask (e.g., XXXX) that is followed by the target (e.g., crew). A nonword mask immediately follows the target and can be related to the target phonologically (e.g., KROO), orthographically (e.g., CRAE), both (e.g., CRUE) or unrelated baseline condition (e.g., GILF). A trial ends with another pattern mask. The right shows an example of a masked priming trial using an orthographic control nonword mask. In both cases, the targets and nonword masks or primes are presented very briefly (i.e., 14–66 ms each).

phonology of words within the brief target presentation before complete identification occurs, then phonological similarity between the target and nonword will benefit recognition. Some backward masking experiments have used controls to minimize the impact of guessing such as including trials with no target words (Perfetti, Bell, & Delaney, 1988). The results from backward masking experiments generally show the predicted pattern – more accurate target identification following phonologically similar nonword masks compared to orthographically similar masks when the target words were presented for 35–55 ms (Perfetti & Bell, 1991; Perfetti et al., 1988; Tan & Perfetti, 1999; Verstaen, Humphreys, Olson, & d'Ydewalle, 1995; Xu & Perfetti, 1999). With shorter target durations, phonological and orthographic effects tend to be equivalent.

These studies were taken as support for the hypothesis that phonology is activated early and automatically during word identification. However, the backward masking method has been subject to the criticism that, despite controls for guessing, the identification procedure allows guessing to play a role (e.g., Rastle & Brysbaert, 2006). Related controversies arose around strategic effects controlled by stimulus conditions such as a low proportion of related trials or using homophones as targets (Brysbaert & Praet, 1992; Verstaen et al., 1995; Xu & Perfetti, 1999). Our conclusion is that the studies using this paradigm produced evidence for phonological facilitation effects in identification that go beyond strategic effects. This conclusion also applies to related paradigms using masked presentation, including priming studies.

In masked-priming studies, nonword primes are presented briefly (<50 ms) before a target word. The participant identifies the word or makes a lexical decision depending on the experiment. The prime improves performance when it is similar to the target orthographically and/or phonologically. For example, Ferrand and Grainger (1994) found both orthographic and phonological priming effects in lexical decision, with phonological priming requiring slightly longer exposures to produce effects (25 ms or more). Perfetti and Bell (1991) reported similar results with perceptual identification instead of lexical decisions. This lag between orthography and phonology is not usually found in backward masking. Phonological effects are delayed relative to the orthographic effects in forward masking because the first stimulus is a nonword, and it may take more time to compute the phonology of an unknown string. In backward masking, the initial stimulus is a word, whose phonology may become more quickly stabilized from top-down lexical influences.

These backward masking and masked priming studies represent two of the four methods from published results that were the object of a meta-analysis by Rastle and Brysbaert (2006). (See Table 10.1 for the phonological effect sizes that they report.) They concluded that each paradigm produced reliable but small effects of phonology on word recognition, whether measured by backward–masking perceptual identification, masked-priming lexical decision, or masked-priming with naming.

However, Rastle and Brysbaert (2006) were critical of the procedures and controls typically used in these experiments, and raised the question of whether there really was evidence for phonological effects. Specifically focusing on lexical decisions with masked priming, they carried out two new experiments that controlled for the problems they identified. Rastle and Brysbaert found clear evidence for phonological priming effects on lexical decisions. Similar to the meta-analysis data, words (GROW) preceded by phonologically similar primes (GROE) were recognized 13 ms faster on average than words in the orthographic control condition (GROY). Phonological facilitation was also found in their second experiment, even though using phonology here would have made the task

Table 10.1 Average phonological facilitation beyond orthographic facilitation and average effect sizes reported in Rastle and Brysbaert's (2006) meta-analysis

Methodology	*Phonological facilitation*	*Effect size(r)*
Forward masked perceptual identification	9.11%**	0.240
Backward masked perceptual identification	3.89%**	0.193
Forward masked naming	10 ms**	0.312
Forward masked lexical decision	10 ms*	0.204

$*p < 0.05$, $**p < 0.01$

more difficult. Therefore, the behavioral evidence supports claims of early phonological processing that begins immediately with the viewing of a word. Whereas strategic effects may play a role in the inconsistent findings of phonology in word identification, the evidence in favor of early, automatic phonological effects stands up to careful scrutiny.

In the next section, we present evidence from eye movement experiments. As eye movements are measured online during silent reading, rather than being a post-reading measure such as lexical decision time, they are considered to be relatively free from strategic effects.

Evidence from eye movements

Eye movements provide a fairly direct window on word recognition processes that affect fixation duration and fixation location. We say 'direct' because measurements are taken during silent reading without any additional task demands that could encourage strategic processes. Because when and where the eyes move during reading is driven mainly by automatic word recognition processes; fixation times are a sensitive measure of word processing variables (Rayner, 1998; Rayner, Pollatsek, Ashby, & Clifton, 2012).

Eye movements have a high spatial (within half a letter) and temporal (1000 samples per second) resolution that allows experimenters to unobtrusively manipulate what text readers see and when they see it by changing the display during reading (Rayner, 1975). Two types of display changes are relevant to understanding phonological processing in word identification – the fast-priming paradigm and the parafoveal preview paradigm. These paradigms enable researchers to manipulate variables during the initial moments of word recognition.

Fast-priming experiments provide information about word recognition once a word is fixated. In this procedure, a consonant string is displayed in the location of a target word that is embedded in a sentence (Sereno & Rayner, 1992). When the eyes saccade across an invisible boundary to the left of the target, a display change presents a prime for the first 20–45 ms of the fixation at the target location. The prime is then masked by the target word that appears during fixation. Rayner et al. (1995) presented skilled readers with sentences such as *The bird prefers beech trees for nesting*, with BEECH being the target word. At the 36-ms prime duration, targets preceded by homophone primes (BEACH) were read faster (i.e. produced shorter fixation times) than targets preceded by visually similar primes (BENCH), indicating that 36-ms primes can engage phonological processes during silent reading.

Lee, Rayner, & Pollatsek, (1999) used fast-priming to examine the relative time course to uptake orthographic, phonological, and semantic information in word recognition. Phonological primes in the 29–35 ms range facilitated word recognition, whereas semantic priming appeared at the 32-ms duration only. Thus, the Lee et al. data indicate that the foveal uptake of phonological information happens at least as quickly as the uptake of semantic information, contrary to the wide-spread perception that phonological processing is slow (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). This conclusion is consistent with the results of isolated word paradigms that compare the timing of semantic and phonological effects (e.g., Tan & Perfetti, 1999).

Whereas most content words are identified foveally during a fixation, readers also begin extracting information parafoveally before actually fixating the word (Dodge, 1907). Readers typically recognize words 40–50 ms faster with parafoveal preview than when preview is denied (Rayner, 2009; Rayner, Liversedge, & White, 2006). The parafoveal preview paradigm manipulates the relation of parafoveal information to the upcoming word. If readers process the information parafoveally, then congruent previews will facilitate recognition once the word is fixated. Thus, parafoveal preview studies measure effects of the initial information that skilled readers process during word recognition and provide singular insights into early lexical access processes.

The paradigm works as follows: A fixation cross on the far left side of the screen dissolves into a sentence display that initially includes the preview string (see sentence 1). Readers begin reading the sentence, with asterisks indicating hypothetical fixation points. They process the preview (either BALL or BAIL) parafoveally when they fixate the word just left of the target region (WON'T). During the saccade into the target region, the eyes cross an invisible boundary that triggers the display change (see sentence 2). The target word (BAWL) displays before the eyes begin the fixation, making the change very difficult to detect and the text appears completely normal in most cases.

1. *   *   *   *
   He claims he won't | ball/bail if his team loses.

2.   * ⟶
   He claims he won't | bawl if his team loses.

Pollatsek, Lesch, Morris, & Rayner (1992) conducted the initial parafoveal preview study of phonological processing using such materials. Shorter first-fixation durations in the homophone preview condition (BALL) as compared to the orthographic control condition (BAIL) indicated that readers use phonological information parafoveally to facilitate word recognition. The data provide evidence for phonological priming that converges with that found in masked priming paradigms reviewed in the previous section (e.g., Rastle & Brysbaert, 2006). Parafoveal phonological effects have been found in several other languages as well, including Chinese and French (Miellet & Sparrow, 2004; Pollatsek et al., 2000). The preview studies make several contributions to the question of phonology in word reading. First, because readers have no way of knowing which word is the 'target', the findings suggest that skilled readers routinely assemble phonological information during word identification in the course of silent reading. Second, these studies discovered that skilled readers engage phonological processes automatically in the initial parafoveal phase of word recognition, even before a word is consciously perceived.

Thus, eye movement evidence extends the findings of many isolated word experiments to word recognition in context by indicating that skilled readers routinely activate phonological information during silent reading. The fact that the critical word (on which measurement is taken) is not visibly marked as different compared to the rest of the sentence means that the reader uses standard reading processes rather than some special strategic process. Another sense of 'routine' is that phonological processes apply not only to a subset of unfamiliar words, but to words in general. Experiments using several paradigms have demonstrated phonological effects for low, moderate, and high frequency words (Ashby, 2006; Ashby, Treiman, Kessler, & Rayner, 2006; Miellet & Sparrow, 2004; McCutchen & Perfetti, 1982; Newman, Jared, & Haigh (in press); Perfetti et al., 1992; Rayner, Sereno, Lesch, & Pollatsek, 1995). Such general effects are expected given the automaticity of parafoveal processing, which gains phonological information about a word before its frequency is determined.

The eye movement data also suggest that parafoveal phonological processing may contribute to the rate of skilled reading (Ashby et al., 2006; Ashby & Rayner, 2004; Fitzsimmons & Drieghe, 2011; Pollatsek et al., 1992). This leads to the interesting conclusion that automatic phonological processing may be a principal contributor to reading fluency, contrary to the assumption that speed depends on by-passing phonology. This would be consistent with observations of individual differences in reading skill. For example, preliminary research indicates that skilled readers benefit from parafoveal phonological information, but less skilled readers do not (Chase, Rayner, & Well, 2005). Also, remediated dyslexic readers who develop normal accuracy often remain slow readers, and slow reading is characteristic of dyslexia in any writing system (Rawson, 1995; Shaywitz & Shaywitz, 2008). The connection between phonology and fluency also helps to explain why phonological processing persists across reading development. Early readers intentionally employ phonological coding to accurately read words they haven't seen before, and skilled readers activate phonology parafoveally to speed word recognition.

The eye movement research leaves some unanswered questions about the time course of phonological processing. Subtracting the lag time needed to execute a saccade from the mean fixation duration, Rayner et al. (1995) estimated that phonological information is processed within the first 200–250 ms of reading a word in the fast-priming paradigm. However, it is difficult to narrow down that time window with eye movement measures because brief prime durations do not necessarily indicate when phonological processes operate. Prime duration simply indicates how long phonological information must be presented for uptake into the cognitive system in order for congruency effects to manifest at some future point in time (Rayner, Liversedge, White, & Vergilino-Perez, 2003). Nor can parafoveal preview experiments indicate the time course of phonological processing. Although the previewed information gets into the cognitive system sometime before a word is fixated, we cannot determine when readers compute phonological congruency. We turn now to event-related potentials (ERP) and magnetoencephalography (MEG) studies that can illuminate the time course of phonological processes.

Neurophysiological evidence from ERP and MEG studies

ERP studies

Event-related potentials contribute unique information about on-line reading processes as they unfold over time, capturing changes in brain electrical potentials recorded at the scalp during reading. Because ERPs measure the electrical potentials from brain activity, rather than the hand or eye movements that result from the sum of such activity, they are a sensitive indicator of the cognitive processes engaged during word recognition. Several ERP studies have found lexical and semantic effects in the first 200 ms of word recognition (e.g., Pulvermüller, Lutzenberger, & Birmbaumer, 1995; Sereno, Rayner, & Postner, 1998). In contrast, the majority of ERP experiments have not registered phonological effects until later in word recognition, or between 260–450 ms following word onset (Kutas & Van Petten, 1990; Kramer & Donchin, 1987; Rugg, 1984; Rugg & Barrett, 1987). These relatively late phonological effects provide evidence for post-lexical phonological processing during explicit tasks, such as deciding whether two words rhyme or have the same meaning. However, neurophysiological evidence of phonological processing prior to 200 ms is now beginning to accumulate.

Several studies have demonstrated early phonological effects in word recognition using the masked priming paradigm we discussed above. Using a four-field paradigm that displayed a mask between the prime and target, Grainger, Kiyonaga, and Holcomb (2006) were the first to combine masked priming and ERPs to examine the time course of orthographic and phonological code activation in word recognition. When words such as BRAIN were preceded by pseudohomophone primes (BRANE), Grainger et al. found the magnitude of the N250 to be reduced, compared with an orthographic control condition (BRAIN followed by BRANT). This phonological N250 effect leaves open the question about the timing of phonological processing relative to semantic processing, as the effect occurred later than the lexical-semantic effects observed within 100–200 ms of word onset (Pulvermüller, 2001).

Ashby and colleagues conducted two ERP masked-priming studies in order to investigate the nature of phonological priming and its time course in word recognition. Because visual information can affect early ERPs, both studies used a visually matched design in which the prime and target letter overlap were identical in the phonological and control conditions so that phonological congruency depended strictly on the pairing of prime and target. To minimize task effects, participants read words silently and made semantic categorization judgments about filler items during the EEG recording. The first study examined the time course of sub-phonemic feature processing. Ashby, Sanders, and Kingston (2009) measured the ERPs elicited by words (e.g., FAT and FAD) that were preceded by nonword primes that were congruent (fak-FAT) or incongruent (faz-FAT) in terms of a sub-phonemic feature (voicing) of the final consonant. In this example, the prime-target pair fak-FAT is congruent, because both final consonants are unvoiced, whereas faz-FAT is incongruent because faz has voiced final consonant and FAT does not. In faz-FAD, however, both have a voiced final consonant so this pair is congruent. In both experiments, phonological congruency effects appeared around 80 ms, reducing the magnitude of the first peak in the waveform (N1) elicited by the target. In a second study, Ashby (2010) examined the time course of phonological processing at the syllable level. This study measured the ERPs elicited by words with either two or three phonemes in the initial syllable (e.g., PONY [po] and PONDER [pon]). These target words were preceded by partial word primes that were congruent or incongruent with the initial syllable of the target (PO## or PON# before PONY and PO#### or PON### before PONDER). In both experiments, a syllable congruency effect appeared: targets in the congruent conditions elicited a reduced N1 compared to targets in the incongruent conditions, with the effect appearing as early as 100 ms after target onset.

Taken together, the phonological congruency effects reported in Ashby (2010) and Ashby et al. (2009) indicate that skilled readers process both suprasegmental and sub-phonemic information quite quickly. The replicated effects in each study appeared on or before the N1, coincident with the timing of the semantic effects reviewed in Pulvermüller (2001). The observed effect of two very different types of phonological congruency on the magnitude of the N1 demonstrates the wide range of phonological information that is activated within 100 ms of seeing a word.

Magnetoencephalography studies

MEG studies, which measure the magnetic fields generated when large numbers of neurons fire, provide both spatial and temporal data about brain activity patterns. Accordingly, MEG studies of word reading can track the time course of phonology in relation to the brain's reading network. Of particular interest for the interplay of orthography and phonology are a posterior circuit that includes the infero-temporal (IT) area that responds to visually presented words and word-like stimuli (often referred to as the Visual Word Form Area) and an anterior circuit that includes the inferior-frontal gyrus (IFG), which is involved in linguistic processing. Studies using time frequency analysis show very early involvement of the left IFG (Broca's area) in word reading (Cornelissen, Kringelbach, Ellis, Whitney, Holliday, & Hansen, 2009; Pammer et al., 2004; Wheat, Cornelissen, Frost, & Hansen, 2010). For example, Pammer et al. (2004) manipulated lexical status by using words and anagrams (e.g., HOUSE/HOSUE). Pammer et al. found that the anterior (IFG) and posterior (IT) circuits became active in tandem for words but not for anagrams. The IT area also responded to anagrams, but in a somewhat later time window.

Finding concurrent activity in the IT and IFG areas contrasts with the intuition that words are initially processed primarily orthographically, and that phonological processes enter later. Were that the case, activation should appear earlier in IT than in IFG (Simos, Breier, Fletcher, Foorman, Mouzaki, & Papanicolaou, 2001). Pammer's measurement of concurrent activity in the IT and the IFG areas during word recognition was replicated when readers processed word-like letter strings, as opposed to consonant-only strings and faces (Cornelissen et al., 2009). They found visual areas active at 110 ms followed by concurrent activity in the IFG at 125 ms and IT at 145 ms for words. Early involvement of the left IFG was also observed recently in a masked priming naming study by Wheat et al. (2010) that compared pseudohomophone primes (BREIN) with orthographic (BROIN) and unrelated (LOPUS) control primes. Activation in the IFG occurred most strongly for pseudohomophone primes at approximately 100 ms post-stimulus onset. These results closely tie the activation of the IFG to the phonological processes of word reading by demonstrating that pseudohomophone primes lead to better target recognition, clarifying the role of the IFG in word reading tasks. In addition to the early phonological activation, all of these studies found left temporal-parietal activation at 200–400 ms post-stimulus, which suggests that phonology continues to be involved as lexical processes unfold.

These recent MEG studies suggest an early role for phonology in visual word recognition by showing frontal area activation associated with phonological processing that is conjoined temporally with activation in posterior areas that support visual processing of words and word-like stimuli (see Figure 10.2). The data from MEG studies using frequency analyses, masked-priming ERP experiments, and the most sensitive behavioral and eye-tracking paradigms converge on the conclusion that phonology plays an early, if not automatic, role in identifying words during reading. However, this converging information on the time course of phonology does not specify what kinds of phonological information are

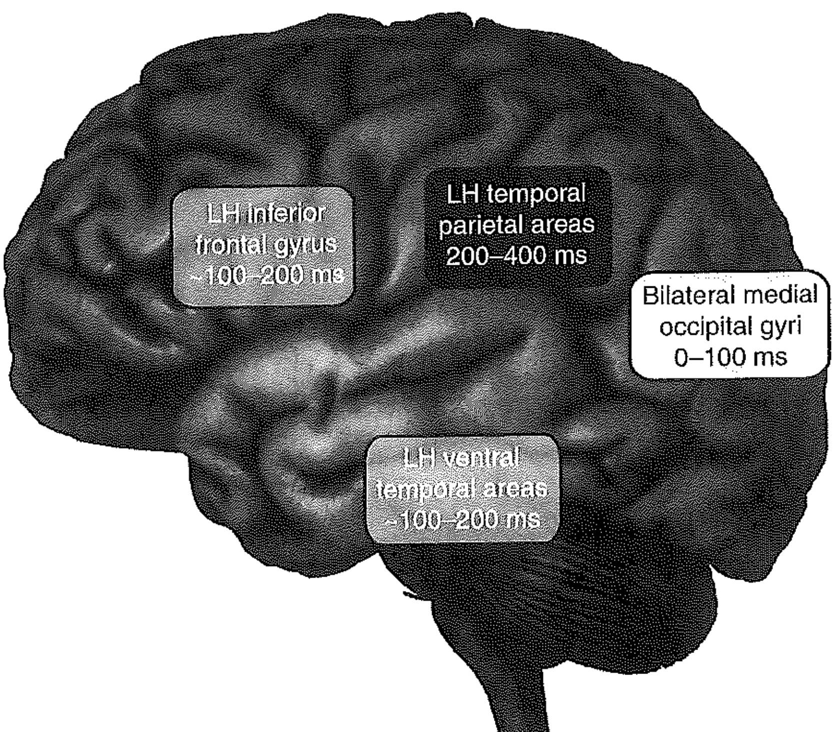

Figure 10.2 The left hemisphere reading network with approximate time estimates of activation onset, summarized from the time-frequency MEG analyses.

accessed during the initial moments of word recognition. In the next section, we review work that begins to specify the characteristics of these early phonological representations.

The contents of phonology

Berent and Perfetti (1995) pointed out that while research had focused on whether phonology played a role in visual word recognition, little attention was paid to the nature of the phonological information. Linguistic theories have established that the phonological representations of speech are structured, containing multiple layers of phonological information that include features, phoneme segments, skeletal structure, syllables, and lexical stress (e.g., Clements & Keyser, 1983) (see Figure 10.3). Potentially, the phonological representations used in reading may be as fully complex as the representations used to process spoken language. Results from behavioral and neurophysiological studies using diverse paradigms now indicate that the representations in reading are linguistically structured and include several layers of phonological information.

Berent and Perfetti (1995) originally proposed that phonological content was multi-linear at the level of consonants and vowels. Results from their perceptual identification masking experiments indicated that consonants and vowels are processed in two temporal streams; a rapid, automatic cycle that assembled consonant phonemes and a slower more controlled cycle that assembled vowel phonemes. Although other paradigms produced mixed results (e.g., Lukatela & Turvey, 2000), separate roles for consonants and vowels were supported by fast-priming eye tracking studies (Lee, Rayner, & Pollatsek, 2001) and ERP studies (Carreiras, Vergara , & Perea, 2009). Separate consonant–vowel cycles would be consistent with the distinctive roles of consonants and vowels in speech recognition, where consonants have a special role in lexical identification (Bonatti, Peña, Nespor, & Mehler, 2005).

Of course, a serial process in reading aloud that produces a co-articulated sequence of phonemes is necessary eventually, so the Dual Route Model (Coltheart et al., 2001) correctly predicts linear position effects in naming.

Information	Representation
	PONY
Lexical stress	1 0
Syllables	σ σ
Skeleton	C V C V
Segments	/p/ /o/ /n/ /i/
Features	*** **** *** ****

Figure 10.3 The multiple layers of phonological information (e.g., Clements & Keyser, 1983) that skilled readers typically activate en route to word recognition, based on evidence from behavioral, eye-movement, and neurophysiological experiments that tap automatic phonological processes.

However, the activation of structured phonological information about syllables, consonant–vowel planes, and sub-phonemic features may also shape the early processes of word recognition during silent reading.

Parafoveal preview experiments indicate that readers may integrate these phonological layers automatically to facilitate word recognition. Ashby et al. (2006) found that skilled readers processed parafoveal rime information (i.e., the vowel plus the final consonant) to bias the activation of phonological vowels. Mean fixation durations were shorter when the consonant that followed orthographically ambiguous vowels, such as *oo* in *book* or *hoot*, activated vowel phonemes that were congruent with the target, suggesting that readers either represent rime information outright or use final consonant information to constrain the activation of possible vowel phonemes early in word recognition.

Several eye movement studies indicate that readers process initial syllable information parafoveally during silent reading. In the initial preview experiment, Ashby and Rayner (2004) found that readers recognized words faster when the parafoveal syllable information was congruent with the target than when it was not. Target words with consonant–vowel (CV) initial syllables (DE•MAND) or consonant–vowel–consonant (CVC) initial syllables (LAN•TERN) were preceded by primes that exactly matched their initial syllable (DE#### or LAN####) or contained one letter more or less (DEM### or LA#####). The syllable congruency effect in silent reading was replicated in later studies presenting targets matched on initial trigram (e.g., PONY and PONDER) in a preview lexical decision experiment and in a masked-priming ERP study (Ashby, 2010; Ashby & Martin, 2008). Experiments in Spanish, German, and Chinese have also found syllable effects in visual word recognition (Carreiras, Alvarez, & de Vega, 1993; Carreiras & Perea, 2002; Chen, Lin, & Ferrand, 2003; Hutzler, Conrad, & Jacobs, 2005). Together, these eye movement studies indicate that skilled readers in many languages activate suprasegmental syllable information during word recognition, whether or not the writing system makes syllables explicit.

A recent eye movement study suggests that readers may use phonological syllable information in determining whether to fixate a word. Fitzsimmons and Drieghe (2011) presented sentences containing one-syllable (e.g., GRAIN) or two-syllable (e.g., CARGO) five-letter words. During silent reading, readers were more likely to skip the one-syllable target words than the two-syllable targets. This pattern indicates that readers extracted the number of syllables from the parafoveal word early enough to influence the decision of where to move their eyes next. The Fitzsimmons and Drieghe finding converges with Ashby and Clifton (2005), which reported more fixations on words with two-stressed syllables than words with only a single stressed syllable. Therefore, it appears that skilled readers use phonological information to determine where to look next as well as to facilitate word identification.

Although there is more to learn about the range and structure of the phonological content that is part of word recognition, the data suggest that skilled readers have access to multi-layer phonological representations during word recognition. These representations are complex in that they can include several phonological layers – skeletal information about consonants and vowels, rimes, and initial syllables, but also subphonemic information (Ashby et al., 2009) that may reflect immediate activation of phonological production codes, such as voicing. During silent reading, skilled readers may use structured phonological representations to organize the available parafoveal information for easy integration with foveal information. Alternatively, readers may simply uptake any phonological information that is tagged as being informative of a particular aspect of a phonological word. Either way, it is possible that the activation of a full phonological representation influences where as well as when to move the eyes (Ashby & Clifton, 2005).

Conclusion

The extent to which phonology is a part of word reading has been subject to a range of views, evidence, and counter-evidence. Dissents pivot largely on such dichotomies as pre-lexical vs post-lexical, automatic vs optional (or controlled), and mediating meaning or incidental to it. Our review has referred to the dissents occasionally, but has largely focused on the conclusions we think can be reached by attending to studies with methods that are sensitive to what occurs *during* word identification. We conclude (a) that phonology is part of word reading universally across writing systems, even if its implementation does importantly depend on the details of the writing system, and (b) that phonology is an early and routine part of word identification in alphabetic reading, based on converging evidence from brief exposure behavioral methods, eye movements, ERPs, and MEGs.

Whether such phonology is always 'pre-lexical' is a question we did not explicitly answer, partly because we are not convinced that there is a single magic moment of 'access' to one specific piece of information (an orthographic-only word entry) as opposed to constituents that are made rapidly available over multiple moments (Perfetti et al., 1988; see also Balota, 1994), and partly because we think it is not the most interesting question to ask. Another question we did not answer is whether phonology 'mediates' word meaning. Early phonology – even phonology prior to meaning – does not allow the conclusion that meaning results because of the phonology (Lesch & Pollatsek, 1993; Tan & Perfetti, 1997, 1998). Instead, along with Van Orden and Goldinger (1994), we conceive of phonology as immediately stabilizing the identity of the word, leading to a specific and usually valid perceptual identification (a function that might also be supported by meaning or morpho-syntactic constituents). It is this identification of a word as a linguistic object that is the central recurring event in reading, brought about by a tight coupling of perceptual and phonological processes. Phonology appears to contribute to increased stability during the initial parafoveal processing of words, thereby playing a key role in faster word recognition and improved reading fluency.

Converging evidence for the early role of complex phonological information in word recognition suggests that theories that assign an optional or only late-occurring role to phonology are insufficient. Moreover, the evidence also forces a reconsideration of theories that assign a strong role to phonology. While the strong phonological theory (Frost, 1998) captured the pervasiveness of phonology in reading, its assumption of minimality may be too weak. Some evidence suggests a stronger phonological theory is needed, one that specifies a multi-layered phonological structure that affects word recognition.

The evidence that supports this stronger phonological theory also suggests that phonology facilitates skilled word recognition *in general,* not merely for low frequency words or consistently spelled words, or for that matter, not only for alphabetic reading. The neurophysiological data showing synchronous activity of orthographic and linguistic cortical areas make a strong case against the view that phonology is a sluggish tag-along in word reading. Instead, rapid and automatic phonological processes occur early in word recognition, contributing to the stability of word identification and promoting fluent reading.

- Phonology plays an early and integral role in word recognition, stabilizing the identity of a word so that accurate perceptual identification occurs. This early role of phonology is supported by evidence from:
  - Behavioral experiments combining brief presentation and visual masking which reduce strategic effects and provide a window into early word recognition processes. These methods have demonstrated phonological facilitation with as little as 25–35 ms of stimulus presentation.
  - Eye movement studies show effects of phonology on a similar time scale. These studies have also shown that the phonology of words is automatically activated while words are just outside of fixation in the parafoveal region.
  - ERP studies that show readers are accessing sub-phonemic and syllable information within 80–100 ms of seeing a word.
  - MEG studies which show concurrent activation in posterior areas that process the visual characteristics of words and anterior areas important for phonological and linguistic processing of words. These areas are active at only 100–200 ms post stimulus presentation.
- Recent work has begun to specify the nature of the phonological representations that are activated early in word recognition. It appears that readers are activating multi-layer representations that can include information about consonants and vowels, final rimes, syllables, and sub-phonemic features.
- Phonology's role in word recognition is universal across the world's orthographies. From shallow and deep alphabetic orthographies to logographic orthographies like Chinese, phonology provides an early constraint on identification.

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