CHAPTER 20

Reading

Word Identification and Eye Movements

KEITH RAYNER, ALEXANDER POLLATSEK,
AND ELIZABETH R. SCHOTTER

Reading is a topic that is far too vast and complex to be completely covered in a single chapter. Indeed, entire textbooks (Crowder & Wagner, 1992; Just & Carpenter, 1987; Rayner & Pollatsek, 1989; Rayner, Pollatsek, Ashby, & Clifton, 2012) are devoted to reading. Therefore, we have selected five topics within the field of reading that seem particularly relevant in the context of the present volume. The topics we have chosen are: (1) visual word identification, (2) the role of sound coding in word identification and reading, (3) eye movements during reading, (4) word identification in context, and (5) eye movement control in reading. The topics we discuss here don't cover everything, but they are arguably the ones studied most extensively by experimental psychologists for the past 40 years (see Clifton, Meyer, Wurm, & Treiman, this volume, for other relevant work). Prior to discussing word identification per se, we will review the primary methods that have been used to study word identification. In most word identification experiments, words are presented in isolation and subjects are asked to make some type of response to them. However, because the primary goal in studying word identification is to understand how words are identified during reading, we go beyond isolated word identification and also discuss word identification in the context of reading.

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METHODS USED TO STUDY WORD IDENTIFICATION

In this section, we will focus on three methods used to examine word identification: (1) brief presentations, (2) reaction time measures, and (3) eye movements. Although various other techniques, such as letter detection (Healy, 1994; Healy & Cunningham, 2004), visual search (Krueger, 1970), and Stroop interference (MacLeod, 1991) have been used to study word identification, we think it is incontrovertible that the three methods we discuss in this section have been most widely used to study word identification and reading. More recently, investigators in cognitive neuroscience have been using brain imaging and localization techniques, including event-related potentials (ERP), functional magnetic resonance imaging (fMRI), and positron emission tomography (PET) to study issues related to which parts of the brain are activated when different types of words are processed. We largely see such research as beyond the scope of the present chapter (for an overview of brain imaging and reading, see Dehaene, 2009).

Perhaps the oldest paradigm used to study word identification is brief presentation of a word (often followed by some type of masking pattern). Tachistoscopes were originally used to present stimuli for brief presentations, but have been replaced by computer presentations of words on a video monitor. In this paradigm, words are presented for something like 30–60 ms followed by a masking pattern, and subjects either have to identify the word or make some type of forced choice response. Accuracy is usually the major dependent variable in such studies.

The most common method used to study word identification is response-time measures. In these methods, the onset of the word is precisely timed and the response to the word is usually (a) *naming (* subjects name a word aloud as quickly as they can and the onset of the vocal response is timed, (b) *lexical decision* (they must decide if a letter string is a word or nonword as quickly as they can), or (c) *categorization* (they must decide if a word belongs to a certain category). Naming typically takes about 400–500 ms, whereas lexical decisions typically take 500–600 ms and categorization takes about 650–700 ms. Although response time is the primary dependent variable, error rates are also recorded in these studies: Naming errors are typically rare (1% or less), whereas errors in lexical decision are typically around 5% and error rates in categorization tasks may be as high as 10–15%.

The third major technique used to study word identification (particularly in the context of reading) is eye movement monitoring: Subjects are asked to read sentences or longer passages of text as their eye movements are recorded. An obvious advantage of eye movement monitoring is that subjects are actually reading. Moreover, not only can measures associated for a given target word be obtained, but measures of processing time for words preceding and following the target word are also available. The four most important dependent variables for examining word identification in reading are *first fixation duration* (the duration of the first fixation on a word), *single fixation duration* (where only one fixation is made on a word), *gaze duration* (the sum of all fixations on a word prior to moving to another word), and the *probability of skipping* a word.

WORD IDENTIFICATION

An important field of research in experimental psychology involves understanding how objects are recognized. Researchers are working on the complex problem of how one can easily recognize a common object like a dog or chair in spite of seeing it from varying viewpoints and distances, and in spite of the fact that different exemplars of these categories are quite different visually. Basically, models that have tried to understand object identification, often called models of pattern recognition, fall into two classes. In template models, wholistic memory representations of object categories, called templates, are compared to the visual input, and the template that matches the visual input best signals what the object is. An immediate question that comes to mind is what form these templates would have to be in order for this scheme to work. In one version, there is only one template per category, but this assumption doesn't work very well because a template that matches an object seen from one viewpoint is not likely to match well when the same object is seen from a different viewpoint. In an attempt to remedy this problem, in some versions of the template model, there is a pre-processing stage posited, in which the image is normalized to the template before the comparison. However, no really plausible normalization routines have been suggested, because it isn't clear how to normalize the image unless you already know what the object is. Another possibility is that there are lots of templates for each object category. However, it isn't clear whether memory could store all these templates nor how all the templates would have been stored in the first place.

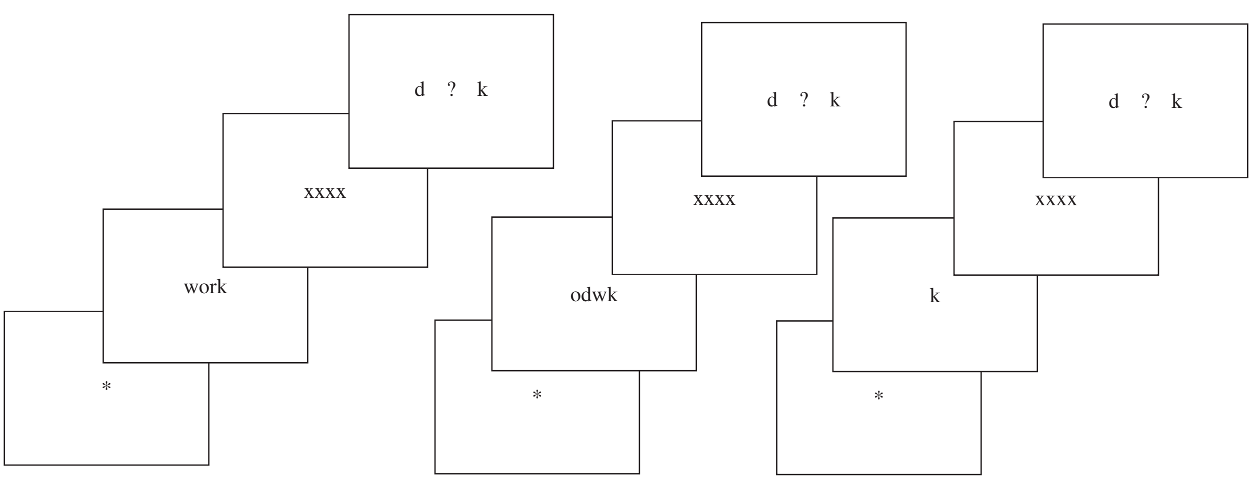
In *feature models* objects are defined by a set of visual features. Although this kind of formulation sounds more reasonable than the template model to most people, it is not obvious whether it is any better a solution to the general problem because it is not clear what the defining visual features are for most real-world objects. In fact, most of the more successful artificial intelligence pattern recognition devices use some sort of template model. Their success, however, relies heavily on the fact that they are only required to distinguish among a few dozen objects rather than the many thousands of objects that humans have to cope with.

In contrast to other types of objects, it is fairly well understood how words are identified. Even though visual words are artificial stimuli that evolution has not programmed humans to identify, there are several ways in which the problem of identifying words is simpler than identifying objects in general. The first is that, with a few exceptions, we don't have to deal with identifying words from various viewpoints: we almost always read text right side up (it is quite difficult to read text from unusual angles.) Second, if we confine ourselves to recognizing printed words, there isn't that much variation from one exemplar to another. Most type fonts are quite similar, and those that are unusual are, in fact, difficult to read (Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Slattery & Rayner, 2010), indicating that their templates or sets of features are indeed poor matches to our mental representations. Thus, understanding how printed words are identified may not be as difficult as understanding how objects are identified.

Do We Recognize Words Through the Component Letters?

The preceding discussion hints at one of the basic issues in visual word identification: Do readers of English identify words directly through a visual template of a word or do they go through a process in which each letter is identified and then the word as a whole is identified through the letters? (We will discuss encoding of non-alphabetic languages shortly.) In a clever brief presentation paradigm, Reicher (1969) and Wheeler (1970) presented subjects (see Figure 20.1) with either: (a) a four-letter word (*WORK*); (b) a nonword that was a scrambled version of the word (*ODWK*); or (c) a single letter (*K*). In each case, the stimulus was masked and, when the mask appeared, two letters, (a *D* and a *K*) appeared above and below the location where the critical letter (*K* in this case) had appeared. The task was to decide which of the two letters had been in that location. Either of the test letters was consistent with a word—*WORK* or *WORD*—so that subjects could not be correct in the task by guessing that the stimulus was a word. The exposure duration was adjusted so that overall performance was about 75% (halfway between chance and perfect).

Interestingly, subjects were about 10% more accurate in identifying the letter when it was in a word than when it was a single letter in isolation. This certainly rules out the possibility that the letters in words are encoded one at a time (presumably in something like a left-to-right order) in order to recognize them. This superiority of words over single letters, on the face of it, may seem to be striking evidence for the fact that words (short words at least) are encoded through something like a visual template. However, there is another possibility: words are processed through their component letters, but the letters are encoded in parallel, and somehow wordness facilitates the encoding process. There are, in fact, several lines of evidence that indicate that this parallel-letter encoding model is a better explanation of the data than the visual template model. First, the words in the experiment were all in uppercase, and it seems unlikely that people would have visual templates of words in uppercase, as words rarely appear in that form. Second, performance in the scrambled word condition was about the same as in the single letter condition. Thus, it appears that letters, even in unpronounceable nonwords, are processed in parallel. Third, subsequent experiments (Baron & Thurston, 1973; Hawkins, Reicher, Rogers, & Peterson, 1976) found that the *word superiority* effect extends to *pseudowords* (orthographically legal and pronounceable nonwords like *MARD*): that is, letters in pseudowords are also identified more accurately than letters in isolation. In fact, many experiments found virtually no difference between words and pseudowords in this task. As it is extremely implausible that subjects have templates for pseudowords, it can't



In the condition on the left, a fixation marker is followed by the target word, which in turn is followed by a masking pattern. The two forced choice alternatives are presented. In the condition on the right, the sequence of events is the same except that a single letter is presented followed by a mask and the forced choice alternatives.

Figure 20.1 Example of the Reicher-Wheeler paradigm be merely that subjects have visual templates of words unconnected to the component letters. Instead, it seems highly likely that all short strings of letters are processed in parallel and that for words or word-like strings, there is mutual facilitation in the encoding process.

Although the above explanation in terms of mutual facilitation may seem somewhat vague, there are some precise quantitative models of word encoding that have accounted very nicely for the data in this paradigm. The two original ones were by McClelland and Rumelhart (1981) and Paap, Newsome, McDonald, and Schvaneveldt (1982). In both models, there are both word detectors and letter detectors. In the McClelland and Rumelhart model, there is explicit feedback from words to letters, so that if a stimulus is a word, partial detection of the letters will excite the word detector, which, in turn, feeds back to the letter detectors to help activate them further. In the Paap et al. model, there is no explicit feedback, but, instead, there is a decision stage that effectively incorporates a similar feedback process. Both of the models successfully explain the superiority of pseudowords over isolated letters. That is, even though there is no "mard" detector for a pseudoword like *MARD,* it has quite a bit of letter overlap with several words (*CARD, MARK, MAID*). Thus, its component letters gets feedback from all of these word detectors, which, for the most part, will succeed in activating the detectors for the component letters in *MARD*. Although this explanation seems to indicate that facilitation would be significantly less for pseudowords than for words because there is no direct match with a single word detector, in fact, both models quantitatively gave a good account of the data.

To summarize, the preceding experiments (and many related ones) all point to the conclusion that the letters in words (short words, at least) are processed in parallel, but through a process in which the component letters are identified and feed into the word identification process. Earlier, we were vague about what *letter detector* means. Are the letter detectors that feed into words *abstract letter detectors* (i.e., case and font independent) or specific to the visual form that is seen? Needless to say, if there are abstract letter detectors, they would have to be fed by case-specific letter detectors, because it is unlikely that a single template or set of features would be able to recognize *a* and *A* as the same thing. As we mentioned earlier, the word superiority experiments used all uppercase letters, and it seems implausible that there would be pre-arranged hook-ups between the upper case letters and the word detectors. Other experiments using a variety of techniques (Besner, Coltheart & Davelaar, 1984; Evett & Humphries, 1981; Rayner, McConkie, & Zola, 1980) also indicate that the hook-up is almost certainly between abstract letter detectors and the word detectors. One type of experiment had subjects identify individual words or read text that was in MiXeD cAsE like this. Even though such text looks strange, after a little practice, people can read it essentially as fast as normal text (Smith, Lott, & Cronnell, 1969). Among other things, this research indicates that word shape (i.e., the visual pattern of the word) plays little or no part in word identification.

Furthermore, the order of the letters (with the exception of the first and last letter in a word) is less important than the identity of the letters. In early models of word recognition, it was tacitly assumed that letters were encoded in their ordinal position in a word during word recognition. Though more likely for short words, this assumption breaks down for long words like *university,* for which it would be implausible to be able to tell that *e* was the fifth rather than the fourth or sixth letter in a matter of milliseconds. There are claims that circulated on the Internet that reading words with scrambled letters is just as easy as reading normal text. If this were true, the problem of letter order coding would be solved. However, the assertion that reading jumbled words is just as easy as normal words is not correct. Although people can figure out what word was intended (assuming the scrambling isn't too extreme), it is clear that the identification process is slower when the proper letter order is not retained (Rayner, White, Johnson, & Liversedge, 2006; White, Johnson, Liversedge, & Rayner, 2008).

To explain how letter order is encoded given these findings, researchers have posed differing accounts (Davis, 2010). One involves coding the relative positions of neighboring letters (via bigrams). With bigrams, the order of the letters of *university* would be captured by encoding the bigrams *un, ni, iv,* and so on. Another type of model, in contrast, assumes that the system encodes the absolute position of all the letters, but that there is error involved in this coding (Gomez, Ratcliff, & Perea, 2008). Support for this latter hypothesis comes from experiments that demonstrate the transposed letter effect across many experimental paradigms. The one most commonly employed is the masked priming paradigm (Forster & Davis, 1984). In this brief presentation paradigm, a pattern mask (######) appears before a briefly presented prime stimulus, followed by a target stimulus. The pattern mask and the target stimulus mask the prime so the viewer is unaware of it. The basic finding (Perea & Lupker, 2003; Schoonbaert & Grainger, 2004) is that lexical decision times are faster when there is a transposed letter prime (*univresity*) than when there is a replacement letter prime (*univonsity*).

Another paradigm that has been employed to study transposed letter effects (that we will describe in greater detail later) is the boundary paradigm (Rayner, 1975). Basically, the idea is that a *preview* of the word to the right of a word being fixated in the text is manipulated prior to the word being fixated. However, during the saccade that crosses an invisible boundary and leads to the word being fixated, the target word appears. In this paradigm, similarly, words with transposed letters yield larger preview benefits than replacement letter previews (Johnson, Perea, & Rayner, 2007). Hence, the effect seems the same either when what appears before the target word is directly fixated (as in the masked priming paradigm) or when what appears before the target word is away from the fixation point (in parafoveal vision[1]) in the boundary paradigm.

The word-superiority-effect experiments, besides showing that letters in words are processed in parallel, also suggest that word recognition is quite rapid. The exposure durations in these experiments that achieve about 75% correct recognition are typically about 30 ms, and if the duration is increased to 50 ms, word identification is virtually perfect. This does not necessarily mean, however, that word identification only takes 50 ms—it merely shows that some initial visual encoding stages are completed in something like 50 ms. However, after 50 ms or so, it may just be that the visual information is held in a short-term memory buffer, but it hasn't been fully processed (see discussion of the disappearing-text experiments later). In fact, most estimates of the time to recognize a word are significantly longer than that (Rayner & Pollatsek, 1989; Rayner et al., 2012). As noted earlier, it takes about 400–500 ms to begin to name a word, but that is clearly an upper estimate, because it includes motor programming and execution time. Skilled readers read about 300 words per minute or about five words a second, which would suggest that 1/5 of a second or 200 ms might not be a bad guess for how long it takes to identify a word. Of course, in connected discourse, some words are predictable and can be identified to the right of fixation in parafoveal vision, so that not all words need to be fixated. On the other hand, readers have to do more than identify words to understand the meaning of text. However, most data point to something like 100–200 ms as being a decent estimate of the time to encode a word.

[1]Any line of text can be divided into the foveal, parafoveal, and peripheral regions. The foveal region consists of the 2 degrees of central vision, whereas the parafoveal region extends out to about 5 degrees of visual angle from the fixation point. Everything beyond the parafoveal region is considered the peripheral region.

Automaticity of Word Encoding

One surprising result is that encoding of words seems to be automatic. The easiest demonstration of this is called the Stroop effect (Stroop, 1935; see MacLeod, 1991 for review). Subjects see words of color names written in different colored ink (*RED* in green ink), and their task is to ignore the word and name the ink color (in this case, they should say "green"). The finding is that when the word is a different color name, subjects are slowed down considerably in their naming and make more errors compared to a control condition (which would be something like *&&&&* written in colored ink). In fact, even neutral words (noncolor names such as *DESK* printed in a color other than black) slow down color naming times. It seems that most subjects are just unable to ignore the words. Moreover, these effects persist even with days of practice. The effect is not limited to naming colors; a similar slowing of naming times occurs when naming a common object that has a name superimposed on it; for example, a picture of a cat with *DOG* superimposed on it (Rayner & Springer, 1986; Rosinski, Golinkoff, & Kukish, 1975).

Another way word processing appears to be automatic is that subjects encode the meaning of a word even though they are not aware of it. This automaticity has been demonstrated using the *semantic priming* paradigm (Meyer & Schvaneveldt, 1971) in which two words are seen in rapid succession, a *prime* and a *target*. The details of the experiments differ, but in some, subjects just look at the prime and name the target. The phenomenon of semantic priming is that naming times are about 30 ms faster when the prime is semantically related to the target (*DOG-CAT*) than when it is not (*DESK-CAT*). The most interesting version of this paradigm is when the prime is presented *subliminally* (Balota, 1983; Marcel, 1980). Usually, this is achieved by a very brief presentation of the prime (about 10–20 ms) followed by a pattern mask and then the target. The amazing finding is that one gets a priming effect (often almost as big as when the prime is visible) even in cases where the subject cannot reliably report whether anything appeared before the pattern mask, let alone the identity of the prime. Thus, the meaning of the prime is encoded even though subjects are unaware of having done so.

Word Encoding in Nonalphabetic Languages

So far, we have concentrated on decoding words in alphabetic languages, using experiments in English as our guide. For all the results we have described so far, there is no reason to believe that the results would come out differently in other languages. However, some other written languages use different systems of orthography. Space does not permit a full description of all these writing systems nor what is known about decoding in them (see Rayner et al., 2012, for a discussion of writing systems).

Basically, there are three other systems of orthography, with some languages using hybrids of several systems. First, the Semitic languages use an alphabetic system, but one in which only a few of the vowels are represented, so that the reader needs to fill in the missing information. In Hebrew, there is a system with points (little marks) that indicate the vowels that are used for children beginning to read, but in virtually all materials read by adult readers, the points are omitted. Second, there are systems (Korean *Hangul* and Japanese *Kana*) in which a character stands for a syllable or something close to a syllable (see later). The third system is exemplified by Chinese, which is often characterized as picture writing, although that term is somewhat misleading because it oversimplifies the actual orthography. In Chinese, the basic unit is the *character,* which does not represent a word, but a *morpheme,* a smaller unit of meaning, which is also a syllable. In English, for example, compound words such as *cow/boy* would be two morphemes, as would prefixed, suffixed, and inflected words such as *re/view, safe/ty,* and *read/ing*. The characters in Chinese are, to some extent, pictographic representations of the meaning of the morpheme, but in many cases, they have become quite schematic over time, so that even a non-naive reader would have a hard time guessing the meaning of the morpheme merely by looking at the form of the character. In addition, characters are not unitary in that the majority of them are made up of two *radicals,* a semantic radical and a phonetic radical. The semantic radical gives some information about the meaning of the character and the phonetic radical gives some hint about the pronunciation, although it is quite unreliable.

A hybrid system is Japanese, which uses Chinese characters (called *Kanji* in Japanese) to represent the roots of most *content words* (nouns, verbs, and adjectives), which are not usually single syllables in Japanese. This is supplemented by a system of simpler characters, called *Kana,* where each *Kana* character represents a syllable. One *Kana* system is used to represent *function words* (prepositions, articles, conjunctions) and inflections and another Kana system is used to represent loan words from other languages, such as *baseball*. Another fairly unique system is the Korean writing system, *Hangul*. In *Hangul,* a character represents a syllable, but it is not arbitrary as in *Kana*. Instead, the component phonemes of a syllable are not represented in a left-to-right fashion, but are all in a single character, more or less circularly arranged. Thus, in some sense, *Hangul* is similar to an alphabetic language. However, written Korean also uses characters that are borrowed from Chinese. The obvious question for languages that don't have alphabets is whether encoding of words is more like learning visual templates than in alphabetic languages. However, as the preceding discussion indicates, thinking of words as visual templates even in Chinese is an oversimplification, because a word is typically two characters, and each character typically has two component radicals. Nonetheless, the system is different from an alphabetic language since, in Chinese, one has to learn both how each character is pronounced and what it means. In alphabetic languages, though, one merely has to know the system in order to be able to pronounce a word and can then rely on the way a word sounds in order to know what it means (except for homophonous words). As a consequence of its orthography, Chinese is hard for children to learn; one indication of this is that Chinese children in the early grades are typically taught a Roman script called *Pinyin*, which is a phonetic representation of Chinese. They are only taught the Chinese characters later, and then only gradually—a few characters at a time. It thus appears that having an alphabet is indeed a benefit in learning to read, and that learning word templates is difficult, either because it is easier to learn something like 50 templates for letters than several thousand templates for words or because the alphabetic characters allow one to get to the sound of the word (or both). However, there is no evidence that adults read Chinese more slowly than adults read an alphabetic language.

SOUND CODING IN WORD IDENTIFICATION AND READING

So far, we have discussed word identification as if it was a purely visual process. That is, we have tacitly assumed that word identification involves detectors for individual letters (in alphabetic languages), which feed into a word detector, in which the word is defined as a sequence of abstract letters. However, given that alphabets code for the sounds of the words, it seems plausible that the process of identifying words is not purely visual and also involves accessing the sounds that the letters represent and possibly assembling them into the sound of a word (see Fowler and Iskarous, this volume for a discussion of speech perception). Moreover, once one thinks about accessing the sound of a word, it becomes less clear what word identification means. Is it accessing a sequence of abstract letters, accessing the sound of the word, accessing the meaning of the word, or some combination of all three? In addition, what is the causal relationship between accessing the three types of codes? One possibility is that one merely accesses the visual code—more-or-less like getting to a dictionary entry—and then "looks up" the sound of the word and the meaning in the "dictionary entry" (the mental dictionary is called the "lexicon," a term we will use later). This might be an approximation of what happens in orthographies such as Chinese. Another relatively simple possibility is that, for alphabetic languages, the reader *must* first access the sound of the word and only then, access the meaning. That is, in this view, the written symbols merely serve to access the spoken form of the language and meaning is tied only to the spoken form. On the other hand, the relationship may be more complex. For example, the written form may start to activate both the sound codes and the meaning codes, and then the three types of codes send feedback to each other to arrive at a solution about what the visual form, auditory form, and meaning of the word are. There are probably few topics in reading that have generated as much controversy as this: What is the role of sound coding in the reading process?

Perhaps the most convincing demonstration of an early assembled phonological effect in word identification comes from an experiment (Pollatsek, Perea, & Carreiras, 2005) using isolated words in the masked priming paradigm described earlier. This study took advantage of a phenomenon in Spanish orthography that is similar to that in English: The sound of *c* is different when the vowel following it is *a, o,* and *u* than when it is *e* or *i* (in Castillian Spanish, c has a hard c sound when it appears before *a, o,* and *u,* but a "th" sound when it appears before *e* or *i*). To ensure that the effects from the primes were not due to accessing the prime as a word, nonword primes were employed. Thus, *conal* and *cinal* (nonwords) were primes for the target word *canal* (which in Spanish has the same meaning as in English). Thus, both primes differed from the target by one letter, but *cinal* differed from it by two phonemes. Consistent with the hypothesis that assembled phonology is occurring prior to the target word appearing, lexical decision times for *canal* were faster when the prime was *conal* than when it was *cinal.*

As mentioned earlier, naming of words is quite rapid (often within about 400–500 ms). Given that a significant part of this time must be taken up in programming the motor response and in beginning to execute the motor act of speaking, it seems plausible that accessing the sound code *could be* rapid enough to be part of the process of getting to the meaning of a word. However, even if the sound code is accessed at least as rapidly as the meaning, it may not play any causal role. Certainly, there is no logical necessity for involving sound codes, as the sequence of letters is sufficient to access the meaning (or meanings) of the word and in the McClelland and Rumelhart (1981) and Paap et al. (1982) models, access to the lexicon (and hence word meaning) is achieved via a *direct look-up* procedure that only involves the letters that comprise a word. However, before examining the role of sound coding in accessing the meanings of words, let's first look at how sound codes, themselves, are accessed.

The Access of Sound Codes

There are three general possibilities for how we could access the pronunciation of a letter string. Many words in English have irregular pronunciations (*one, pint, have*), such that their pronunciations cannot be derived from the spelling-to-sound rules of the language. In these cases, it would seem that the only way to access the sound code would be via a direct access procedure, where the word's spelling is matched to an entry in the lexicon. For example, the letters *o-n-e* would activate the visual word detector for *one,* which would, in turn, activate the subsequent lexical entry. Once this entry is accessed, the appropriate pronunciation for the word (/wun/) could be activated. In contrast, other words have regular pronunciations (*won, hint, wave*), and their pronunciations could also be accessed via a direct route, but their sound codes could also be constructed through the utilization of spelling-to-sound correspondence rules or by analogy to other words. Finally, it is, of course, possible to pronounce nonwords like *mard*. Unless all possible pronounceable letter strings have lexical entries (which seems unlikely), nonwords' sound codes would have to be constructed.

Research on acquired dyslexics—people who were previously able to read normally but suffered a stroke or brain injury resulting in great difficulty reading—has revealed two constellations of symptoms that seem to argue for the existence of both the direct and the constructive routes to a word's pronunciation (Coltheart, Patterson, & Marshall, 1980). In one type, surface dyslexia, the patients can pronounce both real words and nonwords, but they tend to regularize irregularly pronounced words (pronouncing *island* as /iz-land/). In contrast to surface dyslexics, deep and phonemic dyslexics can pronounce real words (whether they are regular or irregular), but they cannot pronounce nonwords. It was initially believed that surface dyslexics completely relied on their intact constructive route, whereas deep dyslexics completely relied on their direct route. However, it is now clear that these syndromes are somewhat more complex than had been first thought, and the above descriptions of them are somewhat oversimplified. Nonetheless, they do seem to argue that the two processes (a direct look-up process and a constructive process) may be somewhat independent of each other.

Assuming that these two processes exist in normal skilled readers (who can pronounce both irregular words and nonwords correctly) how do they relate to each other? Perhaps the simplest possibility is that they operate independently of each other in a race. Whichever process finishes first would win and determine the pronunciation. Thus, since the direct look-up process can't access a pronunciation of nonwords, the constructive process would determine the pronunciation for nonwords. What would happen for words? Presumably, the speed of the direct look-up process would be sensitive to how frequent the word was in the language, with low-frequency words taking longer to access. However, the constructive process, which is not dependent on lexical knowledge, should be largely independent of the word's frequency. Thus, for frequent words, the pronunciation of both regular and irregular words should be determined by the direct look-up process and should take more-or-less the same time. For less frequent words, however, both the direct and constructive process would be operating but the direct access process would be slower. Therefore, for irregular words there would be conflict between the pronunciations generated by the two processes, and one would expect that irregular words would be pronounced slower (if the conflict is resolved successfully) or there would be errors.

The data from many studies are consistent with such a race model. A very reliable finding (Baron & Strawson, 1976; Perfetti & Hogaboam, 1975) is that regular words are named more quickly than irregular words. However, the difference in naming times between regular and irregular words is a function of word frequency: For high frequency words there is little or no difference, but there is a large difference for low frequency words (which also extends to normal reading, Sereno & Rayner, 2000). However, the process of naming is likely to be more complex than a simple race, as subjects usually make few errors in naming, even for low-frequency irregular words. Thus, somehow, it appears that the two routes cooperate in some way to produce the correct pronunciation, but when the two routes conflict in their output, there is slowing of the naming time (Carr & Pollatsek, 1985). It is worth noting, however, that few words are totally irregular. That is, even for quite irregular words like *one* and *island,* the constructive route would produce a pronunciation that had some overlap with the actual pronunciation.

Before leaving this section, we note that there is considerable controversy at the moment concerning exactly how the lexicon is accessed. In the traditional *dual route* models that we have been discussing (Coltheart, 1978; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), there are two pathways to the lexicon, one from graphemic units to meaning directly, and one from graphemic units to phonological units, and then to meaning (the phonological mediation pathway). A key aspect of these models is that (a) the direct pathway must be used to read exception words (*one*) for which an indirect phonological route would fail, and (b) the phonological route must be used to read pseudowords (*nufe*) that have no lexical representation. Another class of models, *connectionist models*, takes a different approach. These models take issue with the key idea that we actually have a mental lexicon. Instead, they assume that processing a word (or pseudoword) comes from an interaction of the stimulus and a mental representation that represents the past experience of the reader. However, this past experience is not represented in the form of a lexicon, but rather from patterns of activity that are *distributed* in the sense that one's total memory engages with a given word, rather than a single lexical entry. In addition, this memory is nonrepresentational in that the elements are relatively arbitrary features of experience rather than being things like words or letters (Harm & Seidenberg, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). For this process to work rapidly enough for one to recognize a word in a fraction of a second, these models all assume that this contact between the current stimulus and memory must be *in parallel* across all these features. For this reason, these models are often termed parallel distributed processing (PDP) models. Resonance models (Stone & Van Orden, 1994; Van Orden & Goldinger, 1994) are a similar class of models. Because these models are complex and depend on computer simulations in which many arbitrary assumptions need to be made in order for the simulations to work, it is often hard to judge how well they account for various phenomena. Certainly, at present, it is quite difficult to decide whether this nonrepresentational approach is an improvement on the more traditional representational models (see Besner, Twilley, McCann, & Seergobin, 1990; Seidenberg & McClelland, 1989; Coltheart et al., 2001). For the purposes of our present discussion, a major difference in emphasis between the models is that, for the connectionist models, the direct look-up and phonological routes aren't distinct. Instead, processes that would look like the phonological route in the more traditional models enter into the processing of regular words and processes that would look like direct lexical look-up enter into the processing of pseudowords.

Sound Codes and the Access of Word Meanings

In the previous section we discussed how readers access a visual word's sound codes. However, a much more important question is how readers access a visual word's meaning (or meanings). As indicated earlier, this has been a highly contentious issue with researchers stating quite differing positions. For example, Kolers (1972) claimed that processing during reading does not involve readers formulating articulatory representations of printed words, whereas Gibson (1971) claimed that the heart of reading is the decoding of written symbols into speech. Although we have learned a great deal about this topic, the controversy represented by this dichotomy of views continues, and researchers' opinions on this question still differ greatly. Some of the first attempts to resolve this issue involved the lexical decision task. One question that was asked was whether there was a difference between regularly and irregularly spelled words, under the tacit assumption that the task reflects the speed of accessing the meaning of words (Bauer & Stanovich, 1980; Coltheart, 1978). Unfortunately these data tended to be highly variable in that some studies found a regularity effect whereas some did not. Meyer, Schvaneveldt, and Ruddy (1974) used a somewhat different paradigm, and found that the time for subjects to determine whether *TOUCH* was a word was slower when it was preceded by a word such as *COUCH* (which should prime the incorrect pronunciation) as compared to when it was preceded by an unrelated word. However, there is some concern that the lexical decision task is fundamentally flawed as a measure of lexical access that is related to accessing a word's meaning. The most influential of these arguments is that this task is likely to induce artificial checking strategies before making a response (Balota & Chumbley, 1984, 1985).

A task that gets more directly at accessing a word's meaning is the categorization task. As noted earlier, in this task, subjects are given a category label (*tree*) and then are given a target word (*beech, beach,* or *bench*) and have to decide whether it represented a member of the preceding category (Van Orden, 1987; Van Orden, Pennington, & Stone, 1990). The key finding was that subjects had a hard time rejecting homophones of true category exemplars (*beach*). Not only were they slow in rejecting these items, they typically made 10–20% more errors than for control items that were visually similar (*bench).* In fact, these errors persisted even under conditions when subjects were urged to be cautious and go slowly. Moreover, this effect is not restricted to word homophones. A similar, though somewhat smaller, effect was reported with pseudohomophones (*brane*). Moreover, in a judgment task (i.e., decide whether the two words on the screen are semantically related), subjects were slower and made more errors on false homophone pairs such as *pillow-bead* (Lesch & Pollatsek, 1998).[2] These findings with pseudohomophones and false homophones make it unlikely that these results are merely due to subjects just not knowing the spelling of the target words and argue that assembled phonology plays a significant role in accessing a word's meaning.

Still, in order for sound codes to play a crucial role in the access of word meaning, they must be activated relatively early in word processing. In addition, these sound codes must be activated during reading, and not just when words are presented in relative isolation (as they were in the preceding studies). To address these issues, Pollatsek, Lesch, Morris, and Rayner (1992) utilized the *boundary* paradigm (Rayner, 1975) we mentioned earlier (and discuss in more detail later) to examine whether phonological codes were active before words are even fixated (and hence very early in processing). In this study, the preview word was either identical to the target word (*rains*), a homophone of it (*reins*), or an orthographic control word (*ruins*). That is, subjects often see a different word in the target word location before they fixate it, although they are virtually never aware of any changes. The key finding was that reading of the target word was faster when the preview was a homophone of the target than when it was just orthographically similar. This indicates that in reading text, sound codes are extracted from words even before they are fixated, which is quite early in the encoding process. In fact, there are similar experiments that indicate that Chinese readers benefit from a

[2] *Bead* is a false homophone of pillow because *bead* could be a homophone of *bed* analogously to *head* rhyming with *bed.*

homophone of a word in the parafovea (Pollatsek, Tan, & Rayner, 2000; Tsai, Lee, Tzeng, Hung, & Yen, 2004).

Some other paradigms, however, have yielded less convincing evidence for the importance of sound coding in word identification. One, in fact, used a manipulation in a reading study similar to the preview study with three conditions: correct homophone, incorrect homophone, and spelling control (e.g., "Even a cold bowl of *cereal/serial/verbal* . . . "). However, when a wrong word appeared (either the wrong homophone or the spelling control) it remained in the text throughout the trial. Subjects read short passages containing these errors, and the key question was whether the wrong homophones would be less disruptive than the spelling controls because they sounded right. In studies using this paradigm (Daneman & Reingold, 1993; Daneman, Reingold, & Davidson, 1995), there was a disruption in the reading process (longer gaze duration on the target word) for both types of wrong words, but there was no significant difference between the wrong homophones and the spelling control (though they did find more disruption for the spelling control slightly later in processing). This finding is consistent with a view in which sound coding plays only a back-up role in word identification. On the other hand, Rayner, Pollatsek, and Binder (1998) found greater disruption for the spelling control than for the wrong homophone even on immediate measures of processing. However, even in Rayner et al., the homophone effects are relatively subtle (far more so than in Van Orden's categorization paradigm). Thus, context may interact with word processing leading to errors (be they phonological or orthographical) less damaging to the reading process.[3]

Summary

Although it seems clear that phonological representations are used in the reading process, it is a matter of controversy how important these sound codes are to accessing the meaning of a word. The categorical judgment studies make clear that sound coding plays a large role in getting to the meaning of a word and the parafoveal preview studies indicate that sound codes are accessed early when reading text. However, the data from the wrong homophone studies in reading seem to indicate that the role of sound coding in accessing word meanings in reading may be a bit more modest. In contrast, there is agreement that phonological codes are activated in reading and play an important role by assisting short-term memory (Kleiman, 1975; Levy, 1975; Slowiaczek & Clifton, 1980).

EYE MOVEMENTS IN READING

The research we have discussed thus far has mainly involved subjects viewing words in isolation. However, fluent reading consists of more than simply processing single words—it also involves the integration of successive words into a meaningful context, among other processes that lead to doing this successfully. In fact, it is quite striking that, although reading is one of the most complex cognitive tasks we face on a daily basis (Huey, 1908; Rayner & Pollatsek, 1989; Rayner et al., 2012), skilled readers accomplish the task almost effortlessly, forgetting how difficult it was to learn as a child. Children are able to acquire spoken language quickly and easily without explicitly being taught, whereas learning to read is difficult, effortful, and almost always requires formal instruction (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001, 2002).

In this section and the next one, we discuss a number of factors that seem to influence the ease or difficulty with which we read words embedded in text. Ultimately, one could view this research as an attempt to formulate a list of all the variables that have an influence on reading processes. Ideally, if we had an exhaustive list of each and every constituent factor in reading (and, of course, how each of these factors interacted with one another), we could develop a complete model of reading. Although quite a bit of work needs to be done in order to accomplish such an ambitious endeavor, a great deal of progress has been made. In particular, as the potential for technical innovation has improved, researchers have developed more accurate and direct methodologies for studying the reading process. One of these innovations, which has been used extensively for the past 25 years, has involved using readers' eye movements to infer the cognitive processes involved in reading.

Basic Facts About Eye Movements

Although it may seem as if our eyes sweep continuously across the page as we read, our eyes actually make a

[3]There is some controversy about the exact nature of the findings in homophone substitution studies (Jared, Levy, & Rayner, 1999) and with respect to the use of such substitutions to study sound coding in reading (Starr & Fleming, 2001). However, for the most part, the results obtained from studies using homophone substitutions are broadly consistent with other studies examining sound coding in which homophones were not used.

series of discrete jumps between different locations in the text, more-or-less going from left to right across a line of text (see Rayner, 1978, 1998, 2009). More specifically, typical eye-movement activity during reading consists of sequences of *saccades,* which are rapid, discrete, jumps from location to location, and *fixations,* where the eyes remain relatively stable for periods that last, on average, about a quarter of a second. The reason that these very frequent eye movements are necessary during reading is that our visual acuity is generally quite limited. Although the retina itself is capable of detecting stimuli from a relatively wide visual field (about 240 degrees of visual angle), high acuity vision is limited to the *fovea,* which consists of only the center 2 degrees of visual angle (which for a normal reading distance consists of approximately six to eight letters). As one gets further away from the point of fixation (toward the *parafovea* and eventually the *periphery*), visual acuity decreases dramatically and it is much more difficult to see letters and words clearly.

The purpose of a saccade is to focus a region of text onto foveal vision for more detailed analysis because reading on the basis of only parafoveal/peripheral information is generally not possible (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). Saccades are relatively fast, taking only about 20–50 ms (depending on the distance covered). In addition, since their velocity can reach up to 500 degrees per second, visual sensitivity is reduced to a blur during an eye movement and little or no new information is obtained while the eye is in motion. Moreover, one is not aware of this blur, due to *saccadic suppression* (Dodge, 1900; Matin, 1974; Wolverton & Zola, 1983). Saccades range from less than 1 letter space to 20–25 letter spaces (though such long saccades are quite rare and typically follow *regressions,* see later); the eyes typically move forward approximately about 8 letter spaces at a time. As words in typical English prose are, on average, 5 letters long, the eyes thus move, on average, a distance that is roughly equivalent to the length of one and one-half words.

Although the eyes typically move from left to right (in the direction of the text in English), about 10 to 15% of eye movements shift backwards to previous words in the text and are termed *regressions*. Readers often make such regressions in response to comprehension difficulty, but regressive eye movements also often occur when the eyes have moved a little too far forward in the text and a small backwards correction is needed in order to process a particular word of interest. For the most part, regressions tend to be short, as the eyes only move a few letters. When longer regressions are necessary in order to correctly comprehend the text, readers are generally accurate at moving their eyes back to the location in the text that caused them difficulty (Frazier & Rayner, 1982; Kennedy & Murray, 1987).

Given the blur of visual information during the physical movement of the eyes, the input of meaningful information takes place during fixations (Wolverton & Zola, 1983). Readers tend to fixate on or near most words in text, and, although the majority of words are only fixated once, some are skipped altogether (Ehrlich & Rayner, 1981; Rayner & Well, 1996). Word skipping tends to be related to word length: Short words (function words like *the, or, and*) are skipped about 75% of the time (Drieghe, Pollatsek, Staub, & Rayner, 2008), whereas longer words are rarely skipped. More specifically, as length increases, the probability of fixating a word increases (Rayner & McConkie, 1976; see also Juhasz, White, Liversedge, & Rayner, 2008): two- to three-letter words are fixated around 25% of the time, but words with eight or more letters are almost always fixated (and are often fixated more than once before the eyes move to the next word). However, longer content words that are highly predictable from the preceding context are also sometimes skipped (Rayner, Slattery, Drieghe, & Liversedge, 2011).

The decision of where to send the eyes next in the text is highly influenced by the spaces between words. In English, the most intuitive definition of a word is a sting of letters separated by spaces in text. Spaces are not inconsequential, though. In fact, when spaces are removed or filled with other letters, reading is slowed down considerably and saccade targeting is much more variable (Rayner, Fischer, & Pollatsek, 1998). Although spaces are present in many languages, they are not present in all. However, even those languages that do not canonically use spaces have shown either benefits or no deficit when they are inserted (Bai, Yan, Liversedge, Zang, & Rayner, 2008; Inhoff, Radach, & Heller, 2000). Because there are no spaces between words in Chinese, it is an interesting question as to how Chinese readers target fixation locations. Recent research suggests that they target the middle of a word when they can parse the word boundary parafoveally and target the first character of the word when they can't (Yan, Kliegl, Richter, Nuthmann, & Shu, 2010) or that they use some combination of word-based and character-based targeting (Li, Liu, & Rayner, 2011).

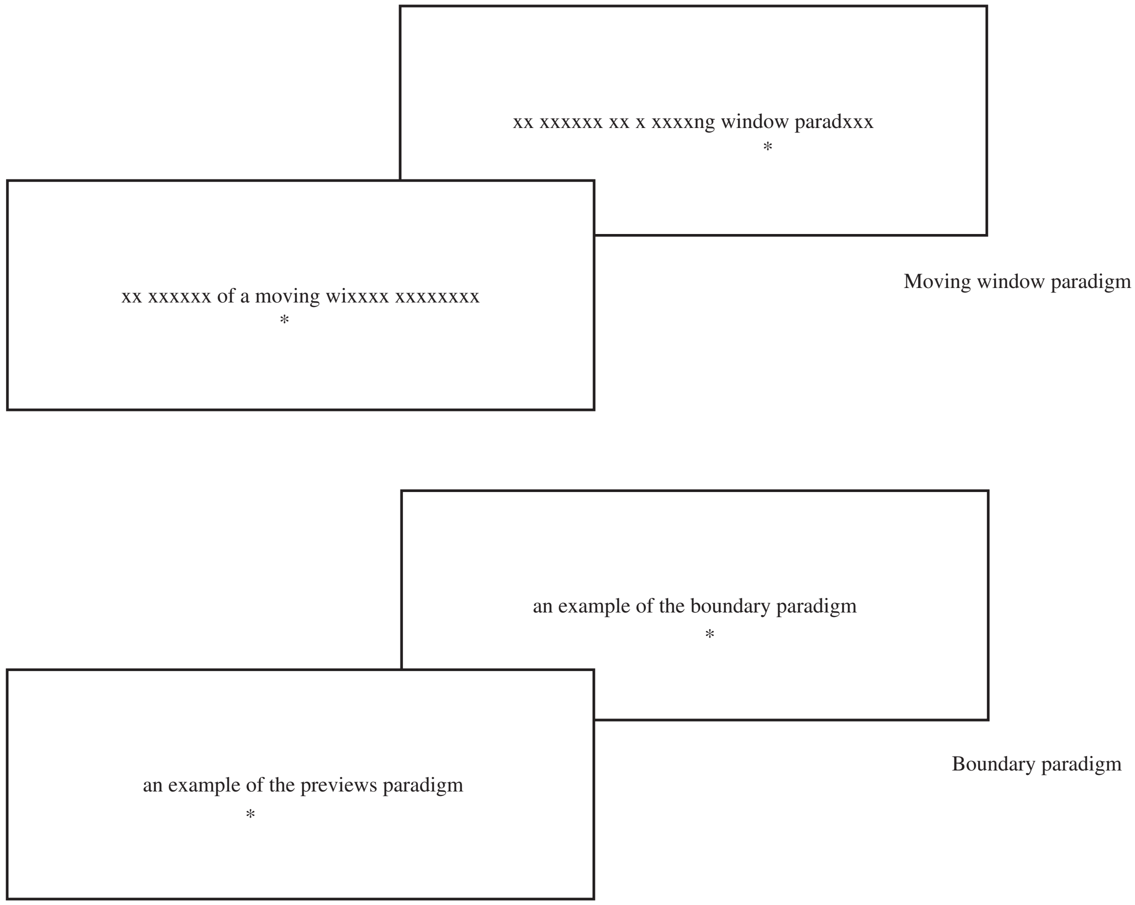
Fixation durations are highly variable, ranging from less than 100 ms to over 500 ms with a mean of about 250 ms. One important question is whether this variability in the time readers spend fixating words is due to low-level factors, such as word length, or whether it is due to lexical influences as well. As the prior sentence suggests, it is clear that low-level variables are important, and word length, in particular, has a powerful influence on the amount of time a reader fixates on a word (Rayner & McConkie, 1976; Rayner, Sereno, & Raney, 1996; Rayner et al., 2011): as word length increases, the time spent fixating it (gaze durations) increases as well. The fact that readers tend to fixate longer words for longer periods of time is perhaps not surprising; such an effect could simply be the product of the mechanical (motor) processes involved in moving and fixating the eyes. What was somewhat controversial in the past was whether eye-movement measures reflect moment-to-moment cognitive processes in reading.

There is now a large body of evidence, however, that the time spent fixating a word is strongly influenced by word frequency: Fixation times are longer for lower-frequency words (i.e., words less frequently seen in text) than for higher-frequency words even when matched on length (Inhoff & Rayner, 1986; Kliegl, Nuthmann, & Engbert, 2006; Rayner & Duffy, 1986). Frequency effects have been demonstrated across many languages, including Chinese (Yan, Tian, Bai, & Rayner, 2006). As with words in isolation, this is presumably because the slower direct access process for lower frequency words increases the time to identify them. Furthermore, there is a *spillover effect* for low frequency words (Rayner & Duffy, 1986). When the currently fixated word is low frequency, cognitive processing may be passed downstream in the text, leading to longer fixation times on the next word. A corollary to the spillover effect is that when words are fixated multiple times within a passage, fixation durations on these words decrease, particularly if they are of low frequency (Hyönä & Niemi, 1990; Rayner, Raney, & Pollatsek, 1995). Interestingly, when subjects search through text to find a target word (so that the processing of meaning is only incidental), the frequency effect disappears (Rayner & Fischer, 1996; Rayner & Raney, 1996); it likewise disappears during mindless reading (Reichle, Reineberg, & Schooler, 2010). Finally, the nature of a word's morphology also has a mediating effect on fixation times. Lima (1987), for example, found that readers tend to fixate for longer periods of time on prefixed words (*revive*) than on pseudoprefixed words (*rescue*). Niswander-Klement, Pollatsek, and Rayner (2000) found that the frequency of the root morpheme of English suffixed words (*govern* in *government*) affected the fixation time on the word. And, Hyönä and Pollatsek (1998) and Pollatsek, Hyönä, and Bertram (2000) found that the frequency of both morphemes of Finnish compound words influenced fixation time on the word when controlling for the frequency of the whole word. However, the first morpheme influenced the duration of the initial fixation on the word, whereas the second morpheme only influenced later processing on the word. Of course, long compound words require multiple fixations in order to be fully processed (due to acuity limitations). Given that readers may not be able to process the second morpheme in a long compound word when fixating the beginning of it, the influence of properties of the second constituent may not show up until later reading measures, when it is fixated. Niswander-Klement and Pollatsek (2006) also found that both the root frequency and word frequency affected fixation times on English prefixed words. As with the results for Finnish compounds, morpheme frequency effects were stronger when the words were longer. Thus, at least some components of words, in addition to the words themselves, influence fixation times.

The Perceptual Span

How much information can we extract from text during a single fixation? As mentioned earlier, our eyes move approximately once every 250 ms during reading, suggesting that a limited amount of information is typically extracted on each fixation. This, coupled with the physical acuity limitations inherent in the visual system, suggests that the region of text from which useful information may be extracted on each fixation is quite small.

Although a number of different techniques have been used to measure the size of the effective visual field (or *perceptual span*) in reading, most of them have rather severe limitations (see Rayner, 1975, 1978 for discussion). A method that has proven to be effective is called the moving window paradigm (McConkie & Rayner, 1975; Rayner, 1986; Rayner & Bertera, 1979), in which readers are presented with a window of normal text around the fixation point on each fixation, and the information outside that window is degraded in some manner. In order to accomplish this, readers' eye movements are continuously monitored and recorded by a computer while they read text presented on a computer monitor, and, when the eyes move, the computer changes the text contingent on the position of the eyes. In a typical experiment, an experimenter-defined window of normal text is presented around the fixation point, while all the letters outside the window are changed to xs. The perceptual span can be examined by manipulating the size of the window. The logic of this technique is that, if reading is normal for a window of a particular size (i.e., if people read both



The moving window example consists of a 15-letter window on two successive fixations (fixation locations are marked by asterisks). In the boundary paradigm example, a word (in this case the word *previews*) is present in a target location prior to a reader moving over an invisible boundary location (the letter *e* in *the*). When the eyes cross this boundary location, the preview word is replaced by the target word (in this case the word *boundary*).

Figure 20.2 Example of moving window and boundary paradigm

with normal comprehension and at their normal rate), then information outside this window is not used in the reading process.

Figure 20.2 illustrates a typical example of the moving window paradigm. In this example, a reader is presented with a window of text that consists of seven letter spaces to the left and right of fixation (fixation points are indicated by asterisks). Studies using this technique have consistently shown that the size of the perceptual span is smaller than people's intuitions. For readers of alphabetical languages such as English, French, and Dutch, the span extends from the beginning of the currently fixated word or about 3–4 letters to the left of fixation (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980; Underwood & McConkie, 1985) to about 14–15 letters to the right of fixation (McConkie & Rayner, 1975; Rayner, 1986; Rayner & Bertera, 1979). Thus, the span is asymmetric to the right for readers of English. Interestingly, for languages such as Hebrew (which are printed from right-to-left), the span is asymmetric to the left of fixation (Pollatsek, Bolozky, Well, & Rayner, 1981).

The perceptual span is influenced both by characteristics of the writing system and by characteristics of the reader. Thus, the span (assessed in terms of number of letters for English and characters for Japanese) is considerably smaller for Japanese text than English (Ikeda & Saida, 1978; Osaka, 1992). For Japanese text written vertically, the effective visual field is 5–6 character spaces in the vertical direction of the eye movement (Osaka & Oda, 1991). For Chinese, Inhoff and Liu (1998) found that Chinese readers have an asymmetric perceptual span extending from one character left of fixation to three character spaces to the right. (Chinese is now written from left to right.) However, when measured in terms of amount of information obtained, perceptual spans are, for the most part, equivalent across writing systems. Furthermore, Rayner (1986; see also Häikiö, Bertram, Hyönä, & Niemi, 2009) found that beginning readers at the end of the first grade had a smaller span, consisting of about 12 letter spaces to the right of fixation, than did skilled readers, whose perceptual span was 14–15 letter spaces to the right of fixation. Additionally, dyslexic readers (Rayner, Murphy, Henderson, & Pollatsek, 1989) and older readers (Rayner, Castelhano, & Yang, 2009) have smaller perceptual spans than normal, skilled readers. Importantly, the size of the perceptual span does not merely reflect acuity dropping off as the text lies further from fixation. Although acuity is indeed poorer, the further from fixation a character is, when this acuity drop-off is controlled for using a technique in which the letters are magnified as a function of their distance from fixation, the perceptual span does not increase (Miellet, O'Donnell, & Sereno, 2009). Thus, the size of the perceptual span is not merely defined by physical limitations (limited visual acuity) but principally by attention and the amount and difficulty of the information we need to process as we read. As text density increases, our perceptual span decreases, and we extract information from smaller areas of text.

Another issue regarding the perceptual span is whether readers acquire information from below the line that they are reading. Inhoff and Briihl (1991; Inhoff & Topolski, 1992) examined this issue by recording readers' eye movements as they read a line from a target passage while ignoring a distracting line of text (taken from a related passage) located directly below the target text. Initially, readers' answers to multiple-choice questions suggested that they had indeed obtained information from both attended and unattended lines. However, when readers' eye movements were examined, the data showed that they occasionally fixated the distractor text. When these extraneous fixations were removed from the analysis, there was no indication that readers obtained useful semantic information from the unattended text. Pollatsek, Raney, LaGasse, and Rayner (1993) more directly examined the issue by using a moving window technique. The line the reader was reading and all lines above it were normal, but the text below the currently fixated line was altered in a number of ways (including replacing the lines of text with other text, with xs, or with random letters). Pollatsek et al. (1993) found that none of the conditions differed from each other, suggesting that readers do not obtain semantic information from below the currently fixated line.

Although the perceptual span is limited, it does extend beyond the currently fixated word. Rayner, Well, Pollatsek, and Bertera (1982) presented readers with either a three-word window (consisting of the fixated word and the next two words), a two-word window (consisting of the fixated word and the next word), or a one-word window (consisting only of the currently fixated word). When reading normal, unperturbed text (the baseline), the average reading rate was about 330 words per minute (wpm), and the same average reading rate was found in the three-word condition. However, in the two-word window condition, the average reading rate fell to 300 wpm and it slowed to 200 wpm in the one-word window condition. Thus, it seems that if skilled readers are allowed to see three words at a time, reading proceeds normally, but if the amount of text available for processing is reduced to only the currently fixated word, they can read reasonably fluently, but at only two-thirds normal speed. Hence, although readers may extract information from more than one word per fixation, the area of effective vision is no more than three words.

The perceptual span and reading speed are closely related in many ways. As previously mentioned, constraining the text to be smaller than the perceptual span slows reading. The influence also goes the other way: slow readers have smaller perceptual spans than faster readers (Rayner, Slattery, & Bélanger, 2010). Rayner et al. (2010) suggested that slower readers have a smaller perceptual span than faster readers because they, like dyslexic, beginning, and older readers have more difficulty encoding the fixated word. Additionally, they found that font properties (i.e., whether subjects read a fixed width or proportional width font) had no effect on the size of the perceptual span, indicating that the amount of text (number of letters/words) that can be processed is primarily influenced by attention.

One potential limitation of the moving-window technique is that reading would be artifactually slowed if readers could see the display changes occurring outside the window of unperturbed text and are simply distracted by them. If this were the case, one could argue that data obtained using the moving window technique are confounded—slower reading rates in the one-word condition mentioned earlier could either be due to readers' limited perceptual span or to the fact that readers are simply distracted by nonsensical letters in their parafovea/periphery. In some instances, this is true: When the text falling outside the window consists of all xs, then the reader is generally aware of where the normal text is and where the xs are. In contrast, if visually similar letters are used instead of xs, readers are generally unaware of the display changes taking place in their parafovea/periphery, although they are sometimes aware that they are reading more slowly and may have the impression that something is preventing them from reading normally. However, readers' conscious awareness of display changes is not related to reading speed: Subjects in moving window experiments can actually read faster when the characters outside the window are xs as opposed to letters. This is plausibly because similar letters are more likely to lead to misidentification of other letters or words, whereas xs are not.

The Acquisition of Information to the Right of Fixation

So far we have discussed the fact that when readers aren't allowed to see letters or words in the parafovea (i.e., in a one-word moving-window condition), reading rates are slowed, indicating that some characteristics of the information from the parafovea are necessary for fluent reading. Another important indication that readers extract information from text to the right of fixation is that we don't fixate every word in text, suggesting that words to the right of fixation can be identified and skipped (incidentally, in cases where a word is skipped, the duration of the fixation prior to the skip tends to be inflated; Hogoboam, 1983; Pollatsek, Rayner, & Balota, 1986; although see Kliegl & Engbert, 2005, for a more complicated data pattern). As mentioned earlier, short function words and words that are highly predictable or constrained by the preceding context are also more likely to be skipped than are long words or words that are not constrained by preceding context. Such a pattern in skipping rates indicates that readers obtain information from both the currently fixated word and from the next (parafoveal) word, but it also seems to indicate that the amount of information from the right of fixation is limited (since longer words tend not to be skipped).

Further evidence for this conclusion comes from an additional experiment conducted by Rayner et al. (1982). In this experiment, sentences were presented to readers in which there was either: (a) a one-word window, (b) a two-word window, or (c) the fixated word was visible together with partial information from the word immediately to the right of fixation (either the first one, two, or three letters). The remaining letters of the word to the right of fixation were replaced with letters that were either visually similar or visually dissimilar to the original ones. The data showed that as long as the first three letters of the word to the right of fixation were normal and the others were replaced by visually similar letters reading was as fast as when the entire word to the right was available. However, the other letter information is not irrelevant, because, when the remainder of the word was replaced by visually dissimilar letters, reading was slower than when the entire word to the right was available, indicating that more information is processed than just the beginning three letters of the next word (see also Lima & Inhoff, 1985; Lima, 1987).

In addition to the extraction of partial word information from the right of fixation, word length information is also obtained from the parafovea, and this information is used in computing where to move the eyes next (Morris, Rayner, & Pollatsek, 1990; Pollatsek & Rayner, 1982; Rayner, 1979; Rayner, Fischer, & Pollatsek, 1998; Rayner & Morris, 1992; White, Rayner, & Liversedge, 2005a). Word length information may also be used by readers to determine how parafoveal information is utilized—sometimes enough parafoveal information can be obtained from short words that they can be identified and skipped. In contrast, information extracted from a longer parafoveal word may not usually allow full identification of the word but facilitate subsequent foveal processing when that word is fixated (Blanchard, Pollatsek, & Rayner, 1989).

Integration of Information Across Fixations

The extraction of partial word information from the parafovea suggests that it is integrated in some fashion with information obtained from the word when it is subsequently fixated. A variety of experiments have been conducted to determine the kinds of information that are involved in this synthesis using *the boundary paradigm* (Rayner, 1975), which we mentioned earlier. Similar to the moving window paradigm, text displayed on a computer screen is manipulated as a function of where the eyes are fixated, but in the boundary paradigm, only the characteristics of a specific target word in a particular location within a sentence are manipulated (see Figure 20.2). For example, in the sentence *"The man picked up an old map from the chart in the bedroom,"* when readers' eyes move past the space between *the* and *chart,* the preview word *chart* would change to the target word *chest*; the rest of the sentence remains normal throughout the trial. By examining how long readers fixate on the target word as a function of what the preview was, inferences can be made about the types of information readers obtained from the target word prior to fixating it.

Two different tasks have been used to examine the integration of information across saccades: reading and word naming. In the reading studies, fixation time on the target word is the primary dependent variable. In the naming studies (Rayner, McConkie, & Ehrlich, 1978; Rayner et al., 1980), a single word or letter string is presented in the parafovea, and when the subject makes an eye movement toward it, it is replaced by a word that is to be named as quickly as possible. The influence of the parafoveal processing on foveal processing of the target is assessed by measuring the effect of the parafoveal stimulus-target relationship on naming times on the target. Surprisingly, in spite of the differences in procedure (text versus single words) and dependent variables (eye movement measures versus naming latency), similar effects of the parafoveal preview was found in the reading and naming studies. Findings from both tasks indicate that if the first two or three letters of the parafoveal word are retained following the eye movement and subsequent boundary display change, naming times and fixation duration measures are facilitated compared to when these letters change across the saccade.

Hence, it is clear that readers can extract partial word information on one fixation to use in identification of a word on a subsequent fixation. However, precisely what types of information may be carried across saccades? One possibility is that this integration is simply a function of the commonality of visual patterns from two fixations, such that the extraction of visual codes from the parafovea facilitates processing via an image-matching process. McConkie and Zola (1979; see also Rayner et al., 1980) tested this prediction by asking readers to read text in alternating case such that each time they moved their eyes, the text shifted from one alternated case pattern to its inverse (*cHaNgE* shifted to *ChAnGe*). Counter to the prediction that visual codes are involved in the integration of information across fixations, readers didn't notice the case changes, and reading behavior was not different from the control condition in which there were no case changes from fixation to fixation (see Slattery, Angele, & Rayner, 2011, for more recent confirmation of the results). Since changing visual features did not disrupt reading, it appears that visual codes are not combined across saccades during reading; rather, readers extract abstract (case-independent) letter information from the parafovea (Rayner et al., 1980).

A number of other variables have been considered. One possibility is that some type of phonological (sound) code is involved in integrating information across saccades. As we discussed earlier, Pollatsek et al. (1992; see also Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995) found that a homophone of a target word (*beach*-*beech*) presented as a preview in the parafovea facilitated processing of the target word seen on the next fixation more than a preview of a word which was visually similar to the target word (*bench*). However, they also found that the visual similarity of the preview to the target played a role in the facilitative effect of the preview so that abstract letter codes are also preserved across saccades. However, data demonstrating homophone facilitation in a word naming experiment in Chinese (Pollatsek, Tan, & Rayner, 2000) suggests that this preview benefit cannot be completely due to assembled phonology because Chinese orthography does not code words via an alphabet. However, later experiments show that phonological preview effects may be due to shared phonological *radicals* (a subcharacter unit) between the preview and target character (Liu, Inhoff, Ye, & Wu, 2002; Tsai et al., 2004).

Not only is letter identity important, but syllabic structure also plays an important role in integrating information across saccades. Ashby and Rayner (2004) employed a boundary change paradigm in which the target words had either a two- or three-segment initial syllable (*device* or *magnet*). The preview contained either the same syllabic structure as the target (*de_πxw* as a preview for *device* or *mag_πx* as a preview for *magnet*) or a different syllabic structure (*dev_πx* as a preview for *device, ma_πxw* as a preview for *magnet*). They found that processing of the target word was facilitated when the preview shared its syllabic structure compared to when the syllabic structure of the preview was different.

Morphemes, or the smallest units of meaning, have also been examined as a possibility for facilitating information processing across saccades, but the evidence for this with English has thus far been negative. Inhoff (1989; see also Juhasz et al., 2008) presented readers with either the first morpheme of a true compound word such as *cow* in *cowboy* or the first morpheme of a pseudocompound such as *car* in *carpet* and found no differences in the sizes of the parafoveal preview benefits. In another experiment Lima (1987; see also Kambe, 2004) used words that contained true prefixes (*revive*) and words that contained pseudoprefixes (*rescue*). If readers extract morphological information from the parafovea, then a larger preview benefit should be found for the prefixed words. Lima, however, found an equal benefit in the prefixed and pseudoprefixed conditions, indicating that prefixes are not involved in the integration of information across saccades. On the other hand, readers of Hebrew apparently integrate morphological information across saccades (Deutsch, Frost, Peleg, Pollatsek, & Rayner, 2003; Deutsch, Frost, Pollatsek, & Rayner, 2000, 2005), as morphological information is more central to processing Hebrew than English (Deutsch et al., 2003).

Finally, it has been suggested that semantic (meaning) information in the parafovea may aid in later identification of a word (Underwood, 1985), but studies examining this issue have generally been negative. Rayner, Balota, and Pollatsek (1986; see also Hyönä & Häikiö, 2005; White, Bertram, & Hyönä, 2008) reported a boundary experiment in which readers were shown three possible types of parafoveal previews prior to fixating on a target word. For example, prior to fixating on the target word *song,* readers could have seen a parafoveal preview of either *sorp* (orthographically similar), *tune* (semantically related), or *door* (semantically unrelated). In a simple semantic priming experiment (with a naming response), semantically similar pairs (*song-tune*) resulted in a standard priming effect. However, when these targets were embedded in sentences, a parafoveal preview benefit was found only in the orthographically similar condition (supporting the idea that abstract letter codes are involved in integrating information from words across saccades), but there was no difference in preview benefit between the related and unrelated conditions (see also Altarriba, Kambe, Pollatsek, & Rayner, 2001). Thus, readers apparently do not extract semantic information from to-be-fixated parafoveal words.[4]

Recently, researchers have examined whether multiple morphemes *within* a word can be processed in parallel. Juhasz, Pollatsek, Hyönä, Drieghe, and Rayner (2009) conducted a study similar to the ones described earlier but using compound words such as *basketball.* In this study, while the reader was fixating the initial morpheme *basket,* the final letters of the rest of the word were replaced by nonsense letters (*basketbadk*). Juhasz et al. found that the gaze duration on the second part of the word was longer (when it was ultimately fixated) when the letters had been nonsense than when the valid letters were present while they were fixating the first constituent. Interestingly, there was no effect of the second constituent identity (whether it was replaced with nonsense letters or not) on gaze durations on the first constituent. In essence, the processing of the constituents was performed somewhat sequentially. To make sure that these results were not merely due to the length of these target words, Drieghe, Pollatsek, Juhasz, and Rayner (2010) compared the preview effect for compound words to equally long words that weren't compound words (*fountain*). They found considerable costs on the gaze duration on the first part of the control words suggesting that nonsense letters affected processing when the word was a single meaningful unit; when the nonsense letters were within the same word, but a different unit of meaning, processing was unaffected.

The extent to which readers can obtain information from the upcoming word varies as a function of the difficulty of the fixated word. Preview benefit decreases as the difficulty of the foveal word increases (Drieghe, Rayner, & Pollatsek, 2005; Henderson & Ferreira, 1990; White, Rayner, & Liversedge, 2005b). Additionally, preview benefit is larger within words than across words (Hyönä, Bertram, & Pollatsek, 2004; Juhasz, Pollatsek, Hyöna, Drieghe, & Rayner, 2009).

Another debate concerns the spatial extent of preview benefit. Specifically, do readers obtain preview benefit from word n + 2 (the word two to the right of the currently fixated word)? Evidence for word n + 2 preview benefit are weak (Angele, Slattery, Yang, Kliegl, & Rayner, 2008; McDonald, 2006; Rayner, Juhasz, & Brown, 2007) except when word n + 1 is a short word (2–3 letters; Kliegl, Risse, & Laubrock, 2007; but see Angele & Rayner, 2011) or when the saccade was intended for word n + 2 but landed on word n + 1. Indeed, when readers fixate word n + 1 and word n + 2 in sequence, they obtain preview benefit from word n + 1 but not word n + 2.

The research we have reported here has focused on the fact that information extracted from a parafoveal word decreases the fixation time on that word when it is subsequently fixated. However, recently, a number of studies (Kliegl et al., 2006) have examined whether information located in the parafovea influences the processing of the currently fixated word (a *parafoveal-on-foveal effect*) or, in similar terms, whether readers may process two or more words in parallel. Do characteristics of the word to the right of fixation influence the duration of the fixation on the currently fixated word? Murray (1998) designed a word comparison task in which subjects were asked to detect a one-word difference in meaning between two sentences. Fixation times on target words were shorter when the parafoveal word was a plausible continuation of the sentence as compared to when it was an implausible continuation. In a similar study, Kennedy (2000)

[4] A recent experiment by Hohenstein, Laubrock, and Kliegl (2010) reported semantic priming under certain circumstances with German readers. There is also some suggestion of semantic preview benefit (Yan, Richter, Shu, & Kliegl, 2009; Yang, Wang, Tong, & Rayner, in press) and n+2 preview benefit (Yang, Wang, Xu, & Rayner, 2009) in Chinese.

instructed subjects to discriminate whether successively fixated words were identical or synonymous to each other, and found evidence for parafoveal-on-foveal effects.

It is possible however, that the nature of attentional allocation is different in word comparison tasks than it is in more naturalistic reading tasks. In fact, several studies have demonstrated that the frequency of the word to the right of fixation during reading does not influence the processing of the fixated word (Carpenter & Just, 1983; Henderson & Ferreira, 1993; Rayner, Fischer, & Pollatsek, 1998). To examine parafoveal-on-foveal effects more closely during natural reading, Inhoff, Starr, and Shindler (2000) constructed sentence triplets in which readers were allowed one of three types of parafoveal preview. In the related condition, when readers fixated on a target word (*traffic*), they saw a related word (*light*) in the parafovea. In the unrelated condition, when readers fixated on the target word (*traffic*), they saw a semantically unrelated word (*smoke*) in the parafovea. Finally, in the dissimilar condition, upon fixating a target word, readers saw a series of quasi-random letters in the parafovea (*govcq*). Fixation times on target words were shortest in the related condition (though not different from the unrelated word) and longest in the dissimilar condition, suggesting that readers processed some degree of abstract letter information from the parafoveal stimuli in parallel with the currently fixated word. However, semantic properties (meaning) of the parafoveal word had little effect on the time spent reading the target word. Still, in terms of lexical or semantic parafoveal-on-foveal effects, the evidence is weak and hotly debated (see Rayner, 2009 for review).

How can the parafoveal-on-foveal effects that are observed be explained if they are not due to the processing of the parafoveal word influencing processing of the foveal word? There are three possible explanations. First, there can be some noise in the accuracy of eye-tracking systems. Second, the saccadic targeting system is imperfect and thus leads to some saccades being mislocated (Nuthmann, Engbert, & Kliegl, 2005); thus, parafoveal-on-foveal effects may arise because while the eyes are on word n, attention is actually being allocated word n + 1, to the next word (Drieghe, Rayner, & Pollatsek, 2008; Rayner, Warren, Juhasz, & Liversedge, 2004). Third, the majority of evidence for parafoveal-on-foveal effects is based on corpus analyses, whereas evidence against lexical parafoveal-on-foveal effects is based on experimental studies using manipulations of target words that provide greater control over other variables (see Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007). At this point, orthographic parafoveal-on-foveal effects seem to be valid, whereas lexical parafoveal-on-foveal effects are still tenuous and debated. Given the possibility of mislocated, fixations and reliance on corpus-based analyses, it seems quite reasonable to view such effects with caution (Rayner, Pollatsek et al., 2007; White, 2008).

Summary

The relative ease with which we read words is influenced by a number of variables, including both low-level factors such as word length and factors such as word frequency and word predictability. The region of text from which readers can extract useful information on any given fixation is limited to the word being fixated and perhaps the next one or two words to the right. Moreover, if the word to the right of fixation can't be identified, the information obtained is generally limited to abstract letter codes (McConkie & Zola, 1979; Rayner et al., 1980) and phonological codes (Pollatsek et al., 1992), both of which may play a role in integrating information from words across saccades. Although no evidence has been found to suggest that morphological or semantic information is extracted from the parafovea in reading English, there is some controversy about whether words may (under some circumstances and to some extent) be processed in parallel.

WORD IDENTIFICATION IN CONTEXT

In the previous section, we discussed a number of variables that influence the ease or difficulty with which a word may be processed during reading.[5]

[5]There are many studies measuring either accuracy of identification in very brief presentations (Tulving & Gold, 1963), naming latency (Stanovich & West, 1979, 1983), or lexical decision latency (Fischler & Bloom, 1979) that have also demonstrated contextual effects on word identification. These experiments typically involved having subjects read a sentence fragment like *The skiers were buried alive by the sudden*.... The subjects were then either shown the target word *avalanche* very briefly and asked to identify it or the word was presented until they made a response to it (such as naming or lexical decision). The basic finding in the brief exposure experiments was that people could identify the target word at significantly briefer exposures when the context predicted it than when it was preceded either by neutral context, inappropriate context, or no context. In the naming and lexical decision versions of the experiment, a highly constraining context facilitated naming or lexical decision latency relative to a neutral condition such as the frame *The next word in the sentence will be*.... We should also note that there has been some controversy over the appropriate baseline to use in these experiments, but that is beyond the scope of this chapter.

As we have pointed out, much of the variation in readers' eye fixation times can be explained by differences in word length and word frequency. In addition, a number of variables involved in higher-level text processing have also been found to affect the speed of identifying a word. For example, we have already mentioned that a parafoveal word is more likely to be skipped if it is predictable from prior sentence context (Ehrlich & Rayner, 1981; Rayner & Well, 1996; Rayner et al., 2011). Moreover, predictable words are also fixated for shorter periods of time in English (Balota, Pollatsek, & Rayner, 1985; Rayner & Well, 1996) and Chinese (Rayner, Li, Juhasz, & Yan, 2005).

Before moving on, we should clarify how predictability is assessed. Usually predictability is assessed by presenting subjects with a sentence fragment up to, but not including, the potential target word. They are then asked to guess what the next word might be. In most experiments, a target word is operationally defined as predictable if greater than 70% of the readers are able to guess the target word based on prior sentence context, and unpredictable if fewer than 5% of the readers are able to guess the target word. We should note, however, that during this norming process, readers generally take up to several seconds to formulate a guess, whereas during natural reading, readers only fixate each word in the text for about 250 ms. This makes it unlikely that predictability effects in normal silent reading are due to such a conscious guessing process. Moreover, most readers' introspection is that they rarely guess what the next word will be as they read a passage of text. Hence, although we will talk about predictability extensively in this section, we are certainly not claiming the effects are due to conscious prediction. Indeed, they are likely to be quite different from conscious prediction.

Although predictability effects on skipping rates are quite clear, there is some controversy about the nature of these effects. One possibility is that contextual influences take place relatively early during processing and affect the ease of processing a word (*lexical access*). An alternative view is that contextual influences affect later stages of processing such as the time it takes to integrate the word into ongoing discourse structures (text integration). One stumbling block in resolving this issue is that there is some evidence that fixation time on a word is at least in part affected by higher-level text-integration processing. For example, O'Brien, Shank, Myers, and Rayner (1988) constructed three different versions of a passage that contained one of three potential phrases early in the passage (e.g., *stabbed her with his weapon, stabbed her with his knife,* or *assaulted her with his weapon*). When the word *knife* appeared later in the passage, readers' fixation times on *knife* were equivalent for *stabbed her with his weapon* and *stabbed her with his knife,* presumably because readers had inferred, when reading the former phrase, that the weapon was a knife (i.e., it is unlikely that someone would be stabbed with a gun). In contrast, when the earlier phrase was *assaulted her with his weapon,* fixation durations on the later appearance of *knife* were longer. This last difference suggests that the fixation duration on *knife* reflected not only the time to understand the literal meaning of the word but to infer that the previously mentioned weapon was a knife.

Thus, a major question about predictability is whether the manipulation actually modulates the extraction of visual information in the initial encoding of the word or whether the unpredictable word is harder to integrate into the sentence context just as *knife* is harder to process in the preceding example when it is not clear from prior context that the *murder weapon* is a knife. Balota et al. (1985) examined this question by examining the joint effects of predictability of a target word and the availability of the visual information of the target word. Subjects were given two versions of a sentence, one that contained a word that was highly predictable from prior sentence context and one that was not predictable: "*Since the wedding day was today, the baker rushed the wedding* ***cake/pies*** *to the reception*" (the target words are in bold in the example). The availability of visual information was manipulated by changing the parafoveal preview. Prior to when a reader's eyes crossed a boundary in the text (the *n* in *wedding*), the parafoveal preview letter string was either identical to the target (*cake* for *cake* and *pies* for *pies*), visually similar to the target (*cahc* for *cake* and *picz* for *pies*), identical to the alternative word (*pies* for *cake* and vice versa), or visually similar to the alternative word (*picz* for *cake* and *cahc* for *pies*). The results replicated earlier findings that predictable words are skipped more often than unpredictable words, but more importantly, visually similar previews facilitated fixation times on predictable words more than on unpredictable words (see Drieghe et al., 2005 for a replication). Moreover, there was a difference in the preview benefit for *cake* and *cahc,* but there was no difference in the benefit for *pies* and *picz,* so that readers were able to extract more visual information (i.e., ending letters) from a wider region of the parafovea when the target was predictable as compared to unpredictable. The fact that predictability interacts with these visual variables indicates that at least part of the effect of predictability is on initial encoding processes.

If it merely had an effect after the word was identified, one would have no reason to expect it to interact with these visual variables. Although predictability influences whether a word is skipped, it doesn't influence where in the word the fixation lands (Rayner, Binder, Ashby, & Pollatsek, 2001; Vainio, Hyönä, & Pajunen, 2009).

Several recent studies have demonstrated that when readers encounter an anomalous word they fixate it longer (Rayner et al., 2004; Staub, Rayner, Pollatsek, Hyönä, & Majewski, 2007; Warren & McConnell, 2007); moreover, the effect is immediate. However, when the word is not anomalous, but rather implausible given the prior context, readers show a processing cost that shows up somewhat later (Joseph et al., 2008; Rayner et al., 2004). For example, the sentence "*Jane used a pump to inflate the carrots for dinner*" produces longer reading times in go-past time (the time from when a word is first encountered until the eyes move forward past that word in the text). Interestingly, when the same sentence is embedded in a cartoon context so that inflating a carrot with a pump is not anomalous, the effect goes away (Warren, McConnell, & Rayner, 2008). These results indicate that these fairly immediate effects are not merely due to the combination of a few weird words that don't normally occur together (such as *inflate* and *carrots*) but, instead, to the reader's ongoing processing of the meaning of the text.

The studies we have discussed in this section clearly show that there are powerful effects of context on word identification in reading. However, they don't make clear what level or levels of word identification are influencing the progress of the eyes through the text. For example, virtually all the phenomena discussed so far could merely be reflecting the identification of the orthographic or phonological form of a word. The studies we discuss below have tried to understand how quickly the meaning of a word is understood and how the surrounding sentential context interacts with this process of meaning extraction. Two ways in which researchers have tried to understand these processes are (1) resolution of lexical ambiguity and (2) resolution of syntactic ambiguity.

There are now a large number of studies (Duffy, Morris, & Rayner, 1988; Sheridan, Reingold, & Daneman, 2010; see Rayner, 2009 for review) that have examined how lexically ambiguous words (like *straw*) are processed during reading. Such lexically ambiguous words potentially allow one to understand when and how the several possible meanings of a word are encoded. That is, the orthographic and phonological forms of a word like *straw* don't allow you to be able to determine what the intended meaning of the word is (e.g., whether it is a drinking straw or a dried piece of grass). Clearly, for such words, there is no logical way to determine which meaning is intended if it is seen in isolation, and the determination of the intended meaning in a sentence depends on the sentential context or on prior biases (perhaps due to the relative frequencies of the two meanings). As indicated earlier, of greatest interest is how quickly the meaning or meanings of the word are extracted and at what point does the sentential context come in and help to disambiguate between the two meanings of an ambiguous words. To help think about this, consider two extreme possibilities. One is that all meanings of ambiguous words are always extracted, and only then does the context come in and help the reader choose which was the intended meaning (if it can). The other extreme would be that context enters the disambiguation process early and that it blocks all but the intended meaning from being activated. As we will see later, the truth is somewhere between these extremes.

Two key variables that experimenters have manipulated to understand the processing of lexically ambiguous words are (1) whether the information in the context prior to the ambiguous word allows one to disambiguate the meaning, and (2) the relative frequencies of the two meanings. To make the findings as clear as possible, the manipulation on each of the variables tends to be fairly extreme. In the case of the prior context, either it is neutral (i.e., it gives no information about which of the two meanings is intended) or it is strongly biasing (i.e., when subjects in a norming study read the part of the sentence up to the target word and are asked to judge which meaning was intended, they almost always give the intended meaning). In the experimental sentences where the prior context doesn't disambiguate the meaning, however, the following context always does. Thus, in all cases, the meaning of the ambiguous word should be clear at the end of the sentence. For the relative frequencies of the two meanings, experimenters either choose words that are balanced (like *straw*), where the two likely meanings are equally frequent in the language, or ones in which one of the meanings is highly dominant such as *bank,* where the financial institution meaning is much more frequent than the side of a river meaning. To simplify exposition, we will assume that these ambiguous words have only two distinct meanings, although many words have several shades of meaning, such as slight differences in the "side of a river" meaning of *bank* (including metaphorical meanings).

The basic findings from this research indicate that both meaning dominance and contextual information influence the processing of such words. When there is a neutral prior context, readers look longer at balanced ambiguous words (like *straw*) than at a control word matched in length and word frequency. This suggests that both meanings of the ambiguous word have been accessed and the conflict between the two meanings is causing some processing difficulty. However, when the prior context disambiguates the meaning that should be instantiated, fixation time on a balanced ambiguous word is no longer than on the control word. Thus, for these balanced ambiguous words, the contextual information helps the reader choose the appropriate meaning quickly—apparently before they move on to the next word in the text. In contrast, for ambiguous words where one meaning is much more dominant (i.e., much more frequent) than the other, readers look no longer at the ambiguous word than the control word when the prior context is neutral. This suggests that only the dominant meaning is fully accessed and there is little or no conflict between the two meanings. This hypothesis is consistent with the eye movement data from the remainder of the sentence. That is, when the following parts of the sentence make it clear that the less frequent meaning should be instantiated, fixation times on the disambiguating information are quite long and regressions back to the target word are frequent (indicating that the reader incorrectly selected the dominant meaning and now has to reaccess the subordinate meaning). Conversely, when the prior disambiguating information instantiates the less frequent meaning of the ambiguous word, readers' gaze durations on the ambiguous word are lengthened (relative to an unambiguous control word). Thus, in this case, it appears either that the contextual information increases the level of activation for the less frequent meaning so that the two meanings are in competition (just as the two meanings of a balanced ambiguous word are in competition in a neutral context) or that the context forced the reader to access a low frequency meaning (or both).

In sum, the data on lexically ambiguous words make clear that the meaning of words is processed quite rapidly, in that the meaning of an ambiguous word, in at least some cases, is apparently determined before the saccade to the next word is programmed. Moreover, it appears that context, at least in some cases, enters into the assignment of meaning early because it can either shorten the time spent on a word (when it boosts the activation of one of two equally dominant meanings) or prolong the time spent on a word (when it boosts the activation of the subordinate meaning). For a more complete exposition of the theoretical ideas in this section (the Reordered Access model), see Duffy et al. (1988; Duffy; Kambe, & Rayner, 2001).

A second type of ambiguity that readers commonly deal with is syntactic ambiguity. For example, consider a sentence like "*While Mary was mending the sock fell off her lap.*" When one has read the sentence up to *sock,* the function of the phrase *the sock* is ambiguous: It could either be the object of *was mending* or it could be (as it turns out to be in the sentence) the subject of a subordinate clause. How do readers deal with such ambiguities? Similar types of questions arise with this type of ambiguity as with lexical ambiguity. One obvious question is whether readers are constructing a syntactic representation of the sentence on line, or whether syntactic processing lags well behind encoding individual words. For example, one possibility is that there isn't any problem with such ambiguities because they are temporary. That is, if the reader waits until the end of the sentence until constructing a parse of the sentence, then there may be no ambiguity problem. In contrast, if such ambiguities cause readers problems at or near the point where the ambiguity occurs, it would be evidence that syntactic processing, like meaning processing, is on line and closely linked in time to the word-identification process.

The data on this issue are quite clear, and many studies have demonstrated that such temporary ambiguities do indeed cause processing difficulty; furthermore, these processing difficulties often can occur quite early (i.e., immediately when the eyes encounter the point of ambiguity). For example, Frazier and Rayner (1982) used sentences like the example just cited. They found that when readers first came to the word *fell,* they made very long fixations on it or else regressed back to an earlier point in the sentence (where their initial parse would have gone astray). A full explanation of this phenomenon would require going into considerable detail on linguistic theories of parsing, which is beyond the scope of this chapter. However, the explanation, in one sense, is similar to the lexical ambiguity situation where one meaning is dominant. That is, in many cases, one syntactic structure is dominant over the other. In this case, assigning the direct object function to *the sock* is highly preferred. From the data, it thus becomes clear that readers initially adopt this incorrect interpretation of the sentence (are led down "the garden path"), and then only can construct the correct parse of the sentence with some difficulty. The phenomenon is somewhat different than lexical ambiguity because (a) the dominance of one interpretation over another is not easily modified by context manipulations, and (b) it appears that the reinterpretation needs to be constructed rather than accessed, as is the case with a different meaning of an ambiguous word.

Summary

As discussed in this section, the ease or difficulty with which readers process words is not only affected by lexical factors such as word frequency and word length, but also by postlexical factors (such as those involved in text integration). It has been argued that many variables, such as word frequency, contextual constraint, semantic relationships between words, lexical ambiguity, and phonological ambiguity, influence the time it takes to access the meaning of a word. However, it seems unlikely that syntactic disambiguation effects (e.g., the fact that fixation times on syntactically disambiguating words are longer than fixation times on words that are not syntactically disambiguating) are due to the relatively low-level processes involved in getting to the meaning of the word. One plausible framework for thinking about these effects is that lexical access is the primary engine driving the eyes forward, but that higher-level (postlexical) processes may also influence fixation times when there is a problem.

MODELS OF EYE MOVEMENT CONTROL

In the first section of this chapter, we outlined some models of word identification. However, these models only take into account the processing of words in isolation and are not specifically designed to account for factors that are part and parcel of fluent reading (e.g., the integration of information across eye movements, context effects, etc.). In the past, modelers have tended to focus on one aspect of reading and have tended to neglect others. Although having such a narrow focus on a model of reading is perhaps not ideal, there is some logic behind such an approach (see Rayner & Reichle, 2010; Reichle, 2012). Models that are broad in scope tend to suffer from a lack of specificity. The Reader model of Just and Carpenter (1980; Thibadeau, Just, & Carpenter, 1982) is one example of this difficulty. It attempted to account for reading processes ranging from eye fixations to the integration of words into sentence context. Although it was a comprehensive and highly flexible model of reading, its relatively nebulous nature made it difficult to use the model to make specific predictions about the reading process.

In the past few years, however, a number of models have been proposed which have been generally designed to expand upon models of word perception and specifically designed to explain and predict eye movement behavior during fluent reading. As these models are based on the relatively observable behavior of the eyes, they allow researchers to make specific predictions about the reading process. However, as with many issues in reading, the nature of eye movement models is a matter of controversy. Eye movement models can be separated into two general categories: (1) oculomotor models (O'Regan, 1990, Yang, 2006), which posit that eye movements are primarily controlled by low-level mechanical (oculomotor) factors and are only indirectly related to ongoing language processing; and (2) *processing* models (Engbert, Nuthmann, Richter, & Kliegl, 2005; Pollatsek, Reichle, & Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003; Reichle, Warren, & McConnell, 2009; Reilly & Radach, 2006; Salvucci, 2001), which presume that lexical and moment-to-moment cognitive processes are important influences on when the eyes move. Although space prohibits an extensive discussion of the pros and cons of each of these models, we will briefly delineate the details of these types of the models.

According to oculomotor models, the decision of where to move the eyes is determined by visual properties of text (e.g., word length, spaces between words) as well as by limitations in visual acuity. Also, the length of time spent viewing any given word is postulated to be primarily a function of where the eyes have landed within the word. That is, the location of fixations within words isn't random. Instead, there is a *preferred viewing location* (Rayner, 1979): As we read, our eyes tend to land somewhere between the middle and the beginning of words. Vitu (1991) also found that although readers' eyes tended to land on or near this preferred viewing location, when they viewed longer words (10+ letters), readers initially fixated near the beginning of the word and then made another fixation near the end of the word (Rayner & Morris, 1992). When the preview of the upcoming word was of the incorrect length, readers spent more time reading it, once fixated (Inhoff, Radach, Eiter, & Juhasz, 2003; Juhasz et al., 2008) because they had targeted the wrong location, given incorrect length information in the parafovea.

The original oculomotor model, the Strategy-tactics model (O'Regan, 1990; Reilly & O'Regan, 1998) accounted for the previously described landing-position effects by stipulating (a) that words are most easily identified when they are fixated near the middle, and (b) that readers adopt one of two reading strategies. According to the risky strategy, they just try to move their eyes so that they fixate on this optimal viewing position within each word. However, readers may also use a more careful strategy, so that when their eyes land on a nonoptimal location (e.g., at the beginning or the end of the word), they can refixate and move their eyes to the other end of the word. Without going into too much detail, the strategy-tactics model makes some specific predictions about eye movements during reading. For example, it predicts that the probability of a reader refixating a word should only be a function of low-level visual factors (such as where the eyes landed in the word) and uninfluenced by linguistic processing. However, Rayner and Fischer (1996) found that the probability of a refixation was higher for lower-frequency words than for higher-frequency words even when the length of the two words was matched. Due to this and other difficulties, many researchers believe that oculomotor models are incomplete and that, although they do give good explanations of how lower-level oculomotor factors influence reading, they largely ignore the influence of linguistic factors such as word frequency and word predictability. More recently, Yang and McConkie (2001) argued that lexical factors could only influence long fixations, but recent work (Staub, White, Drieghe, Hollway, & Rayner, 2010) has clearly documented that this assertion is not correct (and these studies have provided strong evidence for the direct control inherent in processing models).

As we discussed earlier, readers' eye movements are influenced by factors other than just word frequency (such as predictability, ambiguity, etc.). Given the influence of these linguistic variables, models have been developed that are based on the assumption that eye movements are influenced by both lexical (linguistic) factors and by moment-to-moment comprehension processes. It should be noted that these models generally do not exclude the influence of the low-level oculomotor strategies inherent in oculomotor models, but they posit that such influence is small relative to that of cognitive factors. Overall, processing theorists posit that the decision of *when* to move the eyes (fixation duration) is primarily a function of linguistic/cognitive processing, and the decision of *where* to move the eyes is a function of visual factors. Although a number of models have utilized such a framework, the most extensive attempt to predict eye movement behavior during reading is the E-Z Reader model (Pollatsek et al., 2006; Reichle et al., 1998, 2003). E-Z Reader accounts for both fixation durations and fixation locations. Importantly, its computational framework has been used to both simulate and predict eye movement behavior. The E-Z Reader model is complex; however, it essentially consists of four processes: a familiarity check, the completion of lexical access, the programming of eye movements, and the actual execution of the eye movement programs. When a reader first attends to a word (which is usually in the parafovea before the reader fixates it), encoding of the word's meaning begins. (For want of a better term, we will refer to this as lexical access.) However, before lexical access is complete, a rougher familiarity check is computed. However, the familiarity check, like the encoding process, is a function of the word's frequency in the language, its contextual predictability, and the distance of the letters in the word from the center of the fovea. Once the familiarity check has been completed, an eye-movement program to the next word is initiated and the lexical access process continues (in parallel). Although it is possible for the eye movement to be executed before lexical access is completed, this is a rare event in normal reading. Finally, lexical access is completed. In current versions of the model, activation of the meaning of the word influences the duration of both the familiarity check and completion of lexical access stages.

The model has been able to account successfully for many of the findings from the eye movement literature and also generates interesting predictions (Juhasz et al., 2008; Reingold & Rayner, 2006). However, it is admittedly incomplete. First, in the original model, the only cognitive processes that are posited to influence eye movements relate to word identification, whereas phenomena such as the syntactic ambiguity studies we briefly discussed earlier indicate that higher-order language processes influence eye movements as well (see Reichle, Warren, & McConnell, 2009, who accounted for some of these higher-order effects in a recent version of the model). Second, the model merely posits that word identification is a function of variables such as frequency and predictability, but it doesn't have a deep explanation for these regularities. However, the model does predict word length effects solely by loss of acuity as letters get further from fixation. One way to think of the E-Z Reader model is that it explains the mechanisms that drive the eyes forward in reading and that higher-order processes such as syntactic parsing and constructing the discourse representation lag behind this process of comprehending words and do not usually intervene in the movement of the eyes. Given that these higher-order processes lag behind word identification, it would probably slow reading appreciably if the eyes had to wait for successful completion of these processes. A more likely scenario is that these higher-order processes intervene in the normal forward movement of the eyes (driven largely by word identification) only when a problem is detected (such as an incorrect parse of the sentence) and then the "normal processing" is interrupted and a signal goes out either not to move the eyes forward and/or to regress back to the point of difficulty and begin to recompute a new structure.

The strongest evidence that cognitive processing drives the eyes through the text comes from disappearing text experiments, in which the fixated word either disappears or is masked after 50–60 ms (Rayner, Liversedge, White, & Vergilino-Perez, 2003; Rayner, Liversedge, & White, 2006; Rayner, Yang, Castelhano, & Liversedge, 2011). These studies demonstrate that readers only need to view words foveally for 50–60 ms to read normally as fixation times on the word are unaffected by its disappearance. Furthermore, the effects of word frequency are the same when the word disappears as when it does not disappear, indicating that the cognitive processing is the primary engine driving the eyes through the text. This does not mean that words are completely processed in 50–60 ms, but rather that this amount of time is sufficient to obtain visual information so that cognitive processing can proceed normally. However, if the word to the right of fixation also disappears or is masked in the same time course, reading is disrupted (Rayner et al., 2006). This indicates that the word to the right of fixation is important and is typically not attended at the beginning of the prior fixation so that when it disappears after 50–60 ms visual information representing it is not preserved for further processing. These findings are both consistent with the E-Z Reader model.

SUMMARY

For over a hundred years, researchers have struggled to understand the complexities of the cognitive processes involved in reading. We discussed only a few of these processes and primarily focused on the processes that are responsible for word identification during reading. Although many issues remain unresolved, a growing body of experimental data has emerged allowing researchers to develop models and computer simulations to better explain and predict reading phenomena. So what do we know about reading? Many researchers would agree that words are accessed through some type of abstract letter identities (Besner et al., 1984; Coltheart, 1981; Rayner et al., 1980), and that at least four to five letters are processed in parallel. It is also clear that sound codes are involved in word identification and phonological representations are activated relatively early (even before a word is fixated). The time course of phonological processing would seem to indicate that sound codes are used to access word meaning. Overall, it seems likely that there are two possible routes to word meaning: a direct letter-to-meaning look up and an indirect constructive mechanism, which utilizes sound codes and the spelling-to-sound rules of a language. However, the internal workings of these two mechanisms are underspecified and researchers are still speculating on the nature of words' sound codes.

Although we have the subjective impression that we see many words at the same time when we read, the amount of lexical information we can extract from text at a particular point in time is actually quite small (though we may realize that there are multiple lines of text or that there are many words on the page). Furthermore, the process by which we extract information from this limited amount of text is somewhat complex. We are able to extract information from more than one word in a fixation, and some information that is obtained during one fixation may be used on the next fixation. Hence, the processing of words during reading is both a function of the word being fixated as well as the next word or two within the text. Our bias is that words are lexically processed in serial so that we only process the meaning of word n + 1 after we process the meaning of word n (Reichle, Liversedge, Pollatsek, & Rayner, 2009).

The time spent looking at a word is a function of many factors including its length, sound characteristics, frequency, morphology, and predictability. However, before a word is fixated, some information has already been extracted from it. On some occasions, a word can be fully identified and skipped. Most of the time, however, partial information is extracted and integrated with the information seen when it is fixated. The extent to which parafoveal processing aids identification of a word on the next fixation is still under examination, but readers are at least able to integrate abstract letter information and some sound information across the two fixations. In addition, the predictability of a word within a sentence context has an effect on the speed of word identification, with predictable words being processed faster than unpredictable words. The reasons for this are a matter of debate. However, effects of context on word identification are generally small, and much of the work on word perception suggests that visual information can be processed quickly even without the aid of context. Thus, predictability and other contextual factors may actually only play a limited role in word processing in reading. More specifically, as Balota et al. (1985; see also Drieghe et al., 2005) have shown, context primarily influences the amount of information that may be extracted from the parafovea and, thus, more generally, context may become increasingly important when visual information is poor.

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