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CHAPTER 45

Foveal and parafoveal processing during reading

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Abstract

Eye movement studies on foveal and parafoveal word processing in reading are reviewed. The studies show that when a word in a text is fixated, identities of letters and their corresponding phonemes are activated early during the fixation. Orthographic and phonological coding give rise to lexical and meaning activation, which is also reflected in fixation times on words. As regards parafoveal processing, the research shows that lower-level visual features, such as the length and the visual shape of words, are extracted during reading. Moreover, readers also gain orthographic and phonological information from the parafoveal word. On the other hand, the evidence for parafoveal processing of lexical and semantic information is equivocal and inconclusive. It seems lexical and semantic parafoveal processing is not standardly achieved during reading.

Introduction

Readers' eye behaviour consists of fixations during which the eyes remain relatively stable and saccades that move the eyes rapidly from one text region to another. Intake of textual information takes place during fixations, whereas during saccades readers are functionally blind (the so-called saccadic suppression). Two key objectives in the research on eye movements during reading have been to determine what factors govern when to terminate a fixation to move on in the text and where in the text to send the eyes next. It is widely agreed that the duration of fixations is controlled by the ongoing comprehension processes, while saccadic targeting is primarily determined by oculomotor constraints and lower-level visual features of the text.

As information intake takes place during fixations, one of the key questions is to examine how much textual information around the centre of the current fixation readers are able to extract. The area from which useful information can be gleaned is very significantly constrained by the physiology of the eyes. The cones that are responsible for detailed visual perception are heavily concentrated in the foveal area of the retina. In order to recognize the words in a text, readers need to locate the foveal area such that light from the word to be fixated falls directly on it. High visual acuity is needed in word recognition, as the identity of written words in alphabetic scripts is marked by letter codes, many of which closely resemble one another (e.g. *l* vs. *t*, or *k* vs. *h*). The visual acuity of the eyes is best around the fovea (it comprises about 2° of visual angle around the fovea centre), and it drops off quite steeply as a function of distance from the centre of the fovea. The area outside the fovea is further divided into two functionally distinct regions: parafovea and periphery. The parafoveal area extends up to 5° of visual angle to the right and left from the fixation point, while the visual periphery refers to the area beyond the parafovea. What is relevant for the present discussion, is that readers can extract useful information from the parafovea, whereas peripheral information is of very little use (with the exception of content structure signals, such as headings, that may be perceived in the periphery, see Cauchard et al., 2010).

The pertinence of foveal vision in reading was convincingly demonstrated by Rayner et al. (1981) by using the moving window paradigm introduced by McConkie and Rayner (1975). In one version of this paradigm (Experiment 2), a set of letters around the fixation point was visually masked (using an interlaced square wave grating), and the size of the mask was varied from 1 to 17 characters. The mask moved along with the eyes so that wherever the reader looked in the text, a set of letters around the fixation point was masked. When the size of the mask was 7 letters (average word length in English texts), the foveal region was completely masked, and reading was dramatically slowed down (from 295 words per minute, as observed in the normal, unmasked condition, to a mere 15 words per minute). With the 7-letter mask, readers were still able to correctly report 78% of the words; with the 15-letter mask the accuracy went down to 18% and the reading rate was less than 10 words per minute. Thus, reading becomes virtually impossible, or at least extremely cumbersome, when the use of foveal vision is prevented (Rayner and Bertera, 1979; see also studies of patients suffering a central scotoma, e.g. Legge et al. (1997)).

Although foveal vision is necessary for reading, only a limited foveal exposure time is required for the reading to proceed normally. In Experiment 3, Rayner et al. (1981) demonstrated that when the text was masked 50 ms after the fixation onset, readers' eye behaviour mirrored that of reading under normal conditions. Thus, visual information necessary for reading can be acquired within the fixation's first 50 ms. However, this does not mean that the processing of visual information is completed during this time. This was demonstrated by Liversedge et al. (2004) using a disappearing text paradigm, where the fixated word always disappeared 60 ms after the fixation onset (i.e. the word was replaced with a blank space). Even though the word was no longer visible, readers continued to fixate the blank space. Even more importantly, they fixated the blank space for longer time if the word that had disappeared was infrequent relative to a frequent word, which is a nice demonstration of the ongoing linguistic processing affecting fixation durations in reading. The only noticeable difference compared to normal reading was that, quite understandably, readers did not make a second fixation on the blank space, as they occasionally do when a word is difficult to process and the word stays available throughout the fixation.

In the present chapter, I review what is known of foveal and parafoveal processing in reading. Before going into details of individual studies, one important caveat related to the terminology needs to be discussed. In eye movement research on reading, it has become a standard to refer to the fixated word as the foveal word and the word(s) adjacent to the fixated word as the parafoveal word. Many times this usage is consistent with the physiologically based definition (see above) of the foveal and parafoveal area, but this is not always the case. For example, if 1° of visual angle corresponds to about five letters (as is the case when reading this text from a distance of 40 cm) and the fixated word and the adjacent word both comprise three letters, also the adjacent word falls onto the foveal region. However, the non-fixated word will be nevertheless called the parafoveal word. On the other hand, if the fixated word is long (e.g. *institutionalization*), the most exterior letters fall onto the parafoveal region. Nevertheless, the fixated word is called the foveal or foveated word.

The remainder of this chapter is organized as follows. I first discuss the foveal processing of words as revealed by readers' eye movement registration, followed by a discussion of parafoveal word processing. Only those studies are discussed where words are read in a sentence or discourse context (i.e. unless stated otherwise, studies using isolated word presentation are not included). I also limit the discussion to skilled reading, with sporadic observations related to less skilled readers.

Foveal processing

In this section, I go over the factors that are shown to affect fixation times on foveated words. The discussed word-level factors include oculomotor, orthographic, phonological, lexical, and semantic factors.

Effects related to syntactic processing are not covered here; the interested reader should consult a comprehensive review of Clifton et al. (2007; see also Clifton and Staub, Chapter 49, this volume).

Location of initial fixation position

When readers fixate a word in a text, they tend to position the point of fixation on a letter close to the word's centre (the preferred viewing location is established to be somewhat to the left of the word's centre, Rayner, 1979). This facilitates word identification, as the positioning of the eyes in the word centre makes all or most letters of the word (depending on word length) fall within the foveal reach. Studies (Nuthmann et al., 2005; O'Regan et al., 1984; Vitu et al., 1990) have shown that the time fixating a word before fixating away from it (i.e., so called gaze duration) increases linearly as a function of the distance of the initial fixation from the word centre. The further away the initial fixation is from the optimal location, the more likely it is that a refixation is made on a word (McConkie et al., 1989; Nuthmann et al., 2005; Rayner et al., 1996; Vitu et al., 1990, 2001). These optimal viewing position (OVP) effects were first established with isolated word presentation (O'Regan et al., 1984), but they have subsequently been extended to normal reading (see the above references). The OVP effects observed in gaze duration and refixation probability are readily explained by visual acuity constraints: when the initial fixation lands on the word beginning or ending, the letters at the other end of the word are less visible than when the eyes are positioned in the word centre. However, there is one OVP effect that is clearly at odds with this account. When a single fixation is made on the word, the duration of this single fixation is longest when positioned in the word centre and shortest when positioned furthest away from the centre (hence the name Inverted OVP effect; Vitu et al., 2001; though see Rayner et al., 1996, for findings that are inconsistent with this work). Although efforts have been made to account for this counterintuitive observation (Nuthmann et al., 2005, 2007; Vitu et al., 2001, 2007), it may be fair to say that it still remains somewhat controversial. However, at present there is quite general agreement that the Inverted OVP effect is at least partly explained by the single fixation positioned toward the word beginning and end being mislocated (e.g. a fixation landing in the word beginning is intended to land on the previous word; Nuthmann et al., 2005; 2007). According to another plausible account, called the perceptual-economy account (Vitu et al., 2007), a single fixation on the word centre is longer than a fixation on the word beginning or end simply because there is more visual information pertinent to word recognition to be processed around the centre than at the edges.

Word length

Given the pertinence of foveal vision in reading, it probably comes as no surprise that word length has a significant effect on foveal word processing. Gaze duration on long words is longer than that on short words (e.g. Calvo and Meseguer, 2002; Hyönä and Olson, 1995; Just and Carpenter, 1980; Kliegl et al., 2004). As visual acuity is not equally distributed across the whole of the fovea, the final letters of a long word are not as visible as those of a short word (assuming a fixation equally far into each word), which in turn gives rise to the need for a refixation, which in turn lengthens the time spent on a long word relative to a short one. However, the foveal constraint is not the only determinant of the word length effect. McDonald (2006) manipulated word length while keeping constant the horizontal extent; this was achieved by varying the width of letters. His main observation was that the more letters a word contains, the more and longer fixations are made on the word, despite the fact that the words subtend the same visual angle. McDonald concludes that the word length effect is likely due to longer words being subject to a greater degree to visual crowding than short words. To counteract the adverse crowding effect, more and longer fixations are needed.

Orthographic coding of letters, letter clusters, and letter position

As words are identified via the individual letters they contain, it is relevant to examine how letter information influences the foveal processing of words during reading. For example, it is possible that the frequency of letter clusters (e.g. bigrams or trigrams) influences the foveal processing time: words containing an infrequent letter cluster require longer fixation times than words comprising frequent letter clusters. White and Liversedge (2004) introduced misspellings in the word-initial trigram, while varying at the same time the trigram frequency (e.g. *laboratory/liboratory/luboratory/lyboratory/lwboratory*). They found that gaze duration on the target word increased as a function of word-initial trigram frequency: Gaze duration was shortest for a correctly spelled word and longest for illegally spelled, unpronounceable initial-trigram words (for an effect of misspelling on gaze duration, see also Inhoff and Topolski, 1994; Rayner et al., 1998a; Underwood et al., 1988). An effect of the familiarity of word-initial letter sequence was also obtained by Lima and Inhoff (1985) for correctly spelled words. Words containing an infrequent letter sequence (e.g. *dwarf*) received longer first fixations but not reliably longer gaze durations than words containing a frequent letter sequence (e.g. *clown*). However, Hand et al. (2008) obtained a reversed effect: longer first fixation and gaze durations on words containing a frequent than an infrequent word-initial trigram, which suggests an infrequent trigram helps constrain the set of possible lexical candidates (i.e. there exist fewer words starting with an infrequent trigram).

A second question related to orthographic coding that has attracted attention is to what extent readers code letter position information in words. Can letters swap positions within a word without lengthening the fixation time on the word? White et al. (2008a) demosntrated taht jubmling up lettres in wrods increases their foveal processing: gaze duration was longer for the transposed-letter words than for the correctly spelled words (see also Rayner et al., 2006). Moreover, this transposed letter effect was more pronounced when the external letters were transposed (e.g. *problme* or *rpoblem*) instead of the internal letters (e.g. *probelm*). Transposing the word-initial letters tended to produce the largest disruption in processing. Despite these significant effects, it is noteworthy that the overall reading speed was slowed down only by 11%, which suggests that 'word recognition processes must be quite flexible in the way letter position information is encoded' (White et al., 2008a, p. 1268).

Finally, Lee et al. (2001) demonstrated that consonants are processed faster than vowels during the early stages of foveal word processing. This became evident in two experiments that employed a version of the so-called fast priming paradigm (Sereno and Rayner, 1992). In their version of the paradigm, when the reader fixated the target word the presentation of one letter (either a consonant or vowel) was delayed for either 30 or 60 ms. Delaying a consonant for 30 ms after fixation onset caused significantly longer gaze durations on the target word than delaying a vowel. However, in the 60-ms delay condition, there was no difference between the consonant and vowel conditions. Thus, in the earliest stages of foveal processing, consonants play a more important role than vowels that appear to be of minimal significance (see also Lee et al., 2002, for a similar pattern of results using another version of the fast priming paradigm), as evidenced in Experiment 2 where delaying both a vowel and a consonant for 30 ms did not lengthen gaze duration more than simply delaying a consonant.

Phonological coding

When we read a text silently, most people 'hear' the text as if spoken by an inner voice. This type of subvocal speech may serve the purpose of temporarily retaining words and sentence fragments to be integrated to a coherent sentence meaning. A related, but different question is whether readers use phonological codes during lexical access. In English, one way to examine the activation of the word's phonological representation during foveal processing is to compare fixation times on words having a regular pronunciation (e.g. *mood*) to those having an irregular pronunciation (e.g. *weird*). Inhoff and Topolski (1994) obtained a regularity effect in the first fixation duration: it was significantly longer on irregular than regular words. The effect was short-lived as it no longer was significant in gaze duration. Sereno and Rayner (2000) extended and refined these results by showing a regularity effect in gaze duration for low-frequency but not for high-frequency words (the parafoveal processing aspect of the study is reported below). This suggests that phonological coding is more important in identifying infrequent than frequent words. Folk and Morris (1995) demonstrated longer gaze durations for words containing multiple phonological codes in comparison to words having a single phonological code.

Another way to examine the role of phonological representations in lexical access during reading is to compare the foveal processing of correct word forms (*bear*) to that of incorrect homophones (*bare*) and orthographic controls (*barn*), as was done in the study of Rayner et al. (1998a). Readers were told that some of the passages contained a misspelled word but they were to focus on comprehending the passage. Rayner et al. observed in Experiment 1 no difference in first fixation and single duration between the correct and incorrect homophones when they shared one or two letters in the word beginning (*break–brake*). This is taken as evidence for an early activation of phonological codes. On the other hand, incorrect homophones received longer gaze durations than correct homophones indicating a meaning activation a bit later in the processing time line. Experiment 2 and 3 demonstrated that the effect reflects phonological rather than orthographic similarity; evidence for early activation of phonology was obtained in the conditions where the target word was predictable from the prior sentence context. This pattern of results is inconsistent with that observed by Daneman and Reingold (1993) and Daneman et al. (1995) who failed to find evidence for activation of phonological codes during foveal processing, only at a later, postlexical stage, as evidenced by the number of regressions back to the target word (see Rayner et al., 1998, for a detailed discussion of the discrepancies between the Daneman et al. studies and that of Rayner et al., which all employed similar manipulations).

Sparrow and Miellet (2002) made use of homophones in French. They asked readers to proofread a text that contained different types of spelling errors. They observed equally long first fixation durations on correctly spelled words and homophonic non-words—a finding that was taken as evidence for early activation of phonological representations in reading French.

Evidence for an early activation of phonological codes during foveal processing is also obtained by the fast priming paradigm (Sereno and Rayner, 1992). The presentation of a visually similar homophone for 32–36 ms at the beginning of a fixation (after which it is replaced by the correct word) speeds up the gaze duration (a 30–40 ms difference between the homophone and the orthographically similar conditions) on the word (Lee et al., 1999; Rayner et al., 1995). In Experiment 2 of Lee et al., a phonological priming effect was obtained only for high-frequency prime words (not for pseudoword primes). This indicates that the phonological prime needs be to accessed fast for the priming effect to occur.

Yates et al. (2008) compared fixation times on words containing several phonological neighbours (*bait* and *get* are phonological neighbours of *gate*, as they sound similar when pronounced) to those on words having only a few phonological neighbours. They demonstrated phonological neighbourhood density to facilitate foveal processing of words. Again, the phonological effect was short-lived, as it showed up in first fixation and single fixation duration, but not in gaze duration, which indicates that phonological codes are used in the early stages of foveal processing (for negligible effects of orthographic neighbours, see Perea and Pollatsek, 1998; Pollatsek et al., 1999; Sears et al., 2006).

Finally, Ashby and Clifton (2005) examined whether prosodic information is activated during silent reading. More specifically, they studied whether the prosodic property of lexical stress is processed during reading. In order to do that, they compared the foveal processing of words containing either one or two stressed syllables (e.g. *significant* vs. *fundamental*). They observed that words with two stressed syllables were read with significantly longer gaze durations and a greater number of fixations. These effects are taken to suggest that readers obtain stress information during silent reading.

In sum, the majority of studies speak for an activation of phonological codes during the early stages of foveal processing. Moreover, the activation appears to be short-lived, as it is typically observed in first fixation duration but not usually in gaze duration.

Word frequency and age of acquisition

Probably the most well documented effect in foveal word processing is the word frequency effect (e.g. Henderson and Ferreira, 1990; Hyönä and Olson, 1995; Inhoff and Rayner, 1986; Rayner and Duffy, 1986; Raney and Rayner, 1995; Schilling et al., 1998; White, 2008). The higher the frequency, the shorter the gaze duration is on a word. In other words, the more frequently a reader has been exposed to a written word, the less time is needed to identify it during reading. Frequency is capable of influencing either individual fixation durations or the probability of making a refixation on a word, or both. As the effects of word frequency are robust, the simulation of the effect has become a part of the standard 'testbed' when assessing the goodness of fit of eye guidance models in reading (see Reichle, Chapter 42, this volume).

Novel words comprise an extreme group of words in the frequency continuum. Chaffin et al. (2001) examined how readers establish the meaning of novel words from the sentence context. Perhaps surprisingly, readers did not spend more time on novel than low-frequency words when they were first encountered. On the other hand, they regressed back to novel words more than to low-frequency words and read for longer time the informative context following the novel versus the familiar words, which effects were taken to suggest that the readers inferred on-line the meaning of the novel word on the basis of the informative context.

The age at which a word is acquired also influences the time it takes to fixate it during text reading. This was demonstrated by Juhasz and Rayner (2006), who orthogonally varied target words' age of acquisition and frequency. They reported significantly longer gaze durations for late- than early-acquired words (see also Juhasz and Rayner, 2003). As word frequency was equated, the effect does not reflect a more frequent exposure to early-acquired words, but it is likely to be semantic in nature.

Word meaning

Activation of word meaning during foveal processing has been studied by comparing the processing of words with multiple meanings (homonyms) to that of words with only a single meaning (Binder and Morris, 1995; Dopkins et al., 1992; Duffy et al., 1988; Folk and Morris, 1995; Rayner and Duffy, 1986; Rayner and Frazier, 1989; Rayner et al., 1994; Sereno, 1995; Sereno et al., 1992). The following picture emerges from these studies. When the two meanings of a word are equally frequent (in such a situation the homonym is called balanced) and the prior sentence context does not constrain either meaning, the homonym is fixated for longer time than a single-meaning word or a word that has one dominant and another less dominant meaning. This is taken as evidence to support the view that both meanings of a balanced homonym are activated during the word's foveal processing. On the other hand, when the preceding context instantiates the less likely meaning of an unbalanced homonym (one meaning is more frequent than the other), a word with one dominant and one less dominant meaning is fixated for longer time than a balanced homonym or a control word. This effect suggests that meaning dominance determines the order of accessing the multiple meanings (for a review, see Duffy et al., 2001). In other words, the most dominant is accessed first, but if it is not the meaning supported by prior context, a less dominant meaning needs to be activated, which is responsible for the extra fixation time.

Morphological structure of words

The meaning structure of words varies in that some words contain only one single meaning unit (e.g. *car*), while other words consist of multiple meaning units (e.g. *caring*, *caretaker*). These meaning units are called morphemes, which can be divided into free morphemes (*care* and *taker* in *caretaker*) or bound morphemes (*-ing* in *caring*). Most of the eye movement studies of morphological processing during reading have focused on the role of free morphemes in processing morphologically complex compound words.

A number of studies (e.g. Andrews et al., 2004; Bertram and Hyönä, 2003; Hyönä and Pollatsek, 1998; Juhasz et al., 2003; Pollatsek et al., 2000a) have shown that the foveal processing of long compounds consisting of two free morphemes is serial in the sense that these compounds are identified via their constituents (for a review, see Pollatsek and Hyönä, 2006). This is evidenced by a reliable effect of first constituent frequency in an early measure of foveal processing (first fixation duration) and a reliable effect of second constituent effect in a measure indexing later foveal processing (gaze duration).

These effects are more robust in Finnish than in English, probably due to the fact that Finnish is a morphologically much richer language than English (i.e. word compounding is much more productive in Finnish than in English).

On the other hand, Bertram and Hyönä (2003) demonstrated that short (7–9 letters) Finnish two-constituent compound words are processed holistically, as evidenced by a reliable word frequency effect combined with no effect of first-constituent frequency. According to the visual acuity principle put forth by Bertram and Hyönä, short compound words can be processed holistically, because the entire word is simultaneously available in the foveal vision when the word is fixated, while long compound words are processed via the morphological components, because a part of the word (the second constituent) falls outside the foveal area during the initial fixation on the word. However, these claims were not fully supported by the study of Juhasz (2008), who observed a reliable first-constituent frequency effect for short English compound words but not for long compound words (for which there was a non-significant reversed frequency effect).

A few studies have examined the foveal processing of affixed words (comprising a bound and a free morpheme, as in *remove*). Lima (1987) compared the processing of prefixed words (*remove*) to that of pseudoprefixed words (*relish*) and observed longer gaze durations (Experiment 2) for pseudoprefixed than prefixed words. This finding was taken to suggest that readers automatically decompose the word into morphemes or morpheme-looking units. For pseudoprefixed words the unnecessary decomposition leads to a processing delay, as evidenced in longer gaze duration. Niswander-Klement and Pollatsek (2006) extended the visual acuity principle of Bertram and Hyönä (2003) to the processing of shorter and longer affixed words. Experiment 2 of Niswander-Klement and Pollatsek demonstrated a morphological effect (as indexed by a root frequency effect of similar magnitude as the frequency effect for free morphemes without an affix) in gaze durations for long words (>8 letters, such as *unfamiliar*) but not for short words (<7 letters, such as *unpack*).

Contextual predictability

As noted above, context has an influence on accessing the meaning of words. There is now ample evidence demonstrating that sentence-level or paragraph-level semantic predictability affects fixation times on words during reading (Ashby et al., 2005; Balota et al., 1985; Calvo and Meseguer, 2002; Calvo et al., 2001; Drieghe et al., 2004, 2005; Ehrlich and Rayner, 1981; Frisson et al., 2005; Hyönä, 1993; Kliegl et al., 2004; Morris, 1994; Rayner et al., 2004a; Rayner and Well, 1996; White et al., 2005a). Contextually predictable words are read with shorter fixation times than less predictable words. Also local, purely lexically based predictability effects have been observed. When a verb strongly constrains the identity of the following word (e.g. 'hunched his back'), gaze duration on the noun is shorter than when it is preceded by a non-constraining verb (Schustack et al., 1987; Vainio et al., 2009). There is also a large body of literature on the effects of syntactic prediction (for a comprehensive review, see Clifton et al., 2007; Clifton and Staub, Chapter 49, this volume). For example, readers expect to encounter a syntactic object after a transitive verb. However, if this expectation is violated, processing difficulty will ensue, which is reflected in the eye movement record.

Parafoveal processing

In this section, I review the research evidence on what features of the text are extracted from parafoveal vision during reading. Before doing that, a note on the use of terminology is in order. I follow the practice mentioned in the Introduction where the fixated word is called the foveal word and the word to the right (i.e. when reading from left to right) of the fixated word is called the parafoveal word, irrespective of whether or not it falls entirely outside foveal vision.

Two types of methodological tools have been used to examine what aspects of the parafoveal word are processed. In the moving window paradigm (McConkie and Rayner, 1975), the researcher varies the amount of parafoveal (or foveal) information available around the current fixation point. For example, using a symmetric 15-character moving window, 7 letters to the right and left of the fixated letter are visible, while all the remaining text is mutilated (e.g. replaced by x's or random letters). The window moves along with the eyes, so that wherever the reader looks in the text, (s)he sees 15 intact letters around the fixation point. By varying the size of the window and the type of changes made to the text outside the window, the researcher is in a position to determine what type of information is extracted from the parafovea and what the size of effective vision is for different types of textual information.

Another very popular paradigm is the so-called boundary paradigm (Rayner, 1975), also known as the eye-movement contingent display change method (Fig. 45.1). In this paradigm, only prespecified target words are initially mutilated. An invisible boundary is set to the left of the target word. During the saccade crossing the boundary, the target word is changed to its correct form (due to saccadic suppression the reader does not see the actual change). If the reader detects a discrepancy between the parafoveally available information and the foveated word, a processing cost will ensue when the target word is fixated (apparent in a longer fixation time on the target word), which is interpreted to indicate that information of the parafoveal word was processed prior to its fixation. By varying the type of parafoveal preview preceding the target, the researcher can determine the exact nature of the type of parafoveal processing that is carried out.

A third phenomenon related to parafoveal word processing is the so-called parafoveal-on-foveal effect (Kennedy, 1998; see Drieghe, Chapter 46, this volume, for a review). As the name indicates, such effects indicate that some aspect of the parafoveal word (or of the experimentally defined parafoveal preview) influences the processing of the fixated word. Investigation of parafoveal on foveal effects may be carried out with or without the display change paradigm. For example, if in the display change paradigm all the letters of the parafoveal word are initially replaced by random letters and this manipulation increases gaze duration on the foveal word (as a response to perceiving a strange letter cluster in the parafovea), we have detected a parafoveal-on-foveal effect.

In the following, I go over the effects related to the same word features that have been demonstrated to affect foveal word processing.

Distance to the parafoveal word (or preview)

A general finding is that the closer the reader is fixating to the parafoveal word (or preview), the more parafoveal processing is carried out (e.g. Kennison and Clifton, 1995). When the fixation is very close to the parafoveal word, it is likely that at least a part of the parafoveal word is within foveal vision, as determined strictly physiologically. Thus, a subset of the reported parafoveal effects reflect a mixture of foveal and parafoveal on foveal processing.

Word length

McConkie and Rayner (1975) employed the moving window paradigm to examine how far in the parafovea word length information is perceived. In order to do that they either preserved the spaces

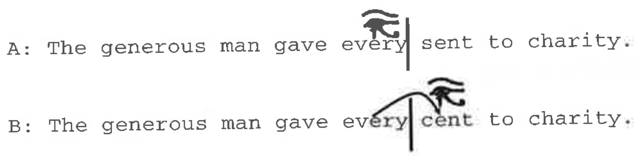

Fig. 45.1 A graphical depiction of the eye-contingent display change paradigm. During Phase A, a parafoveal preview (*sent*) is presented of the intended target word (*cent*); the eyes are located to the left of the invisible boundary (marked by a vertical bar). During a saccade crossing the invisible boundary (Phase B), the parafoveal preview is changed to the intended form. Due to vision being suppressed during saccades, readers do not see the actual change taking place. Thus, when the eyes fixate the target word, it always appears in the correct form. The sentences are adopted from the study of Pollatsek et al. (1992).

between words or filled them with extra letters. Their study showed that readers acquire word-length information up to 15 character positions to the right of fixation (see also Rayner, 1986) and that this information primarily affects saccade length (readers use parafoveal word length information to target a saccade to the centre of next unidentified word in the parafovea). Inhoff et al. (1998) demonstrated that correct length information provided for the parafoveal word (*barclohqo* → *movement*) speeds up the target word processing when it is fixated, compared to incorrect length information (*barc ohqo* → *movement*) (see also Inhoff et al., 2003; White et al., 2005a). Parafoveal word length information, in combination with sentence context, can also be used to narrow down the possible lexical candidates for the upcoming word (Juhasz et al., 2008).

Orthographic coding

Apart from word length information, readers also acquire information about the visual shape of letters comprising the parafoveal word. This has been demonstrated in studies using the boundary paradigm. Intact parafoveal previews have been compared to previews preserving the word's visual shape (letters are replaced with visually similar letters, e.g. *l* is replaced with *t*), or to previews dissimilar in shape with the intended word. When the parafoveal preview comprises letters visually dissimilar to those of the intended word, the word's subsequent foveal processing (it appears in the intended form when fixated) is delayed by about 40 ms (for a review, see Hyönä, et al., 2004; Rayner, 1998). On the other hand, when the letters are replaced with visually similar letters, the processing cost is reduced to 15 ms.

Also letter identity information is processed parafoveally. The seminal studies suggested that parafoveal letter identity processing is primarily limited to the beginning letters, as no processing cost was observed when the first two or three letters are kept intact and the remaining letters are replaced with visually similar letters (Henderson and Ferreira, 1990; Pollatsek et al., 1992; Rayner et al., 1982). More recently, there is accumulating evidence suggesting that parafoveal letter identity processing is not entirely limited to the initial letters. The discrepancy in results between the seminal and more recent studies may be due to improvements in the quality of cathode ray tube (CRT) screens used to present experimental texts (see also Drieghe et al., 2005). With greater precision of screens, the text appearing in the parafovea may be more recognizable in the modern screens.

Using the moving window technique, Häikiö et al. (2009) recently showed that the letter identity span extends up to 9 letters to the right of fixation. In a similar vein, Inhoff (1989a) showed that not only the parafoveal availability of word-initial letters but also that of word-final letters facilitates a word's subsequent foveal processing. The effect size was not modulated by the reading direction (left to right versus right to left)—a manipulation which was included to vary the relative distance of the critical parafoveal information from the current fixation location. On the other hand, the preview effect for word-final letters was eliminated when the remaining letters were replaced with dissimilar letters (rather than *x*'s) rendering the word-final letters less discriminable. Johnson et al. (2007) examined further the parafoveal processing of letter identity information for interior and final letters. In order to do that they provided parafoveal previews for which two interior or final letters of 5-letter words were either transposed (e.g. *clekr* instead of *clerk*) or substituted with other letters (e.g. *clefn* instead of *clerk*). In Experiment 1, they observed a 31-ms penalty in gaze duration when the first three letters were kept intact but the final two letters were initially changed (i.e. the mean of the transposition and substitution conditions; see also Hyönä and Häikiö, 2005). This is further evidence for the view that parafoveal letter processing is not limited to the first 2–3 word-initial letters. Experiments 2 and 3 provided evidence for a privileged role of word-final (and word-initial) letters over word-internal letters. In Experiment 3, changing the two final letters in 7-letter words led to significantly longer gaze durations in comparison to the no-change condition, whereas changing two word-internal letters (5th and 6th) did not significantly disrupt subsequent foveal processing. The results led Johnson et al. to the conclusion that 'readers are able to extract information from the first five letters of the word to the right of fixation plus the word-final letter' (p. 222). This conclusion compares favourably with the study of Briihl and Inhoff (1995) who observed a greater preview benefit from beginning (*thuxxxx* → *thunder*) and exterior letters (*thxxxxr* → *thunder*) than from the word-interior letters (*xxundxx* → *thunder*), which yielded no preview benefit when compared to no preview (*xxxxxxx*). This is due to interior letters suffering more from visual crowding than exterior letters.

Johnson et al. (2007) also demonstrated that letter identity information can be obtained from the parafovea outside of absolute letter position. This became evident in the previews containing transposed letters producing generally less disruption in subsequent foveal processing than previews where the corresponding letters were substituted with other visually similar letters.

Evidence for the effect of the frequency of letter clusters constituting the parafoveal word has been mixed. Some studies have established a parafoveal-on-foveal effect of orthographic familiarity (Inhoff et al., 2000a; Pynte et al., 2004; Rayner, 1975; Starr and Inhoff, 2004; Underwood et al., 2000; White, 2008), while others have not (Rayner et al., 2007; White and Liversedge, 2004; 2006). An example of a positive effect is provided by a recent study by White (2008) that manipulated orthographic familiarity by the sum of the frequencies of the words that contain particular letter sequences (e.g. for a four-letter word, the letter sequences comprise two trigrams, three bigrams, and four monograms). White obtained a small effect of orthographic familiarity: the duration prior to fixating the target word was 6 ms longer in the orthographically familiar than unfamiliar condition.

Finally, Williams et al. (2006) demonstrated that parafoveal letter processing is modulated by the frequency of the parafoveal word. In Experiment 1, a low-frequency target word (e.g. *sleet*) was parafoveally previewed by a high-frequency orthographic neighbor (*sweet*), a non-word orthographic neighbour (*speet*), or an identical preview (*sleet*); two words are orthographic neighbours when they look similar visually (i.e. they share most of the same letters). Gaze duration on target revealed that a high-frequency orthographic neighbour was almost as good a preview as the target word itself and significantly better than the non-word orthographic preview. In Experiment 2, the situation was reversed in that a low-frequency orthographic neighbour served as a preview for a high-frequency target word. Now both orthographic previews were significantly poorer previews than the identical preview. Taken together, the two experiments indicate that there is no general advantage for having a word as a parafoveal preview over a non-word. Rather, there is a distinct advantage for a high-frequency orthographic neighbour. This pattern of results is interpreted to indicate that the parafoveal processing takes place at the level of activating letter identities, which process is boosted by the partial activation of lexical entries. The reason for why the preview effect for high-frequency orthographic neighbours is not interpreted to reflect lexical level activation is that full lexical activation should have inhibited (due to competition between two lexical candidates), not facilitated the foveal processing of target words (e.g. Carreiras, Perea, and Grainger, 1997).

Phonological coding

Several studies show that a word's phonological representation is activated parafoveally. Pollatsek et al. (1992) provided parafoveally either homophone previews (*cite* → *site*), visually matched control previews (*cake* → *sake*), or identical previews (*site* → *site*). When the previewed word was fixated (it always appeared in the correct from), the duration of first fixation (but not gaze duration) on the target word was significantly shorter when preceded by a homophone preview than a visually matched non-homophonic control. Similarly, Miellet and Sparrow (2004) found no difference in first fixation duration on the target word when it was preceded either by an identical preview or a homophonic pseudoword; the study was conducted in French. Henderson et al. (1995) observed that parafoveally presented words with phonologically regular initial trigrams (e.g. *but* in *button*) produced greater preview benefits than did words with phonologically irregular initial trigrams (e.g. *but* in *butane*). Pollatsek et al. (2000b), Liu et al. (2002) and Tsai et al. (2004) provided evidence for parafoveal phonological coding even in Chinese—a non-alphabetic language with a deep orthography. Liu et al. further observed that for the parafoveal phonological coding to occur, the preview and the target need to share the same phonological radical (see also Tsai et al. (2004) for further evidence). Chace et al. (2005) reported a parafoveal homophone effect for skilled readers but not for less skilled readers.

Finally Ashby et al. (2006) examined parafoveal phonological coding using non-word parafoveal previews in which the vowel phoneme was concordant (*cherg* → *chirp*) or discordant (*chorg* → *chirp*) with the vowel phoneme in the target word (note that in both preview conditions the identity of the critical letter was incorrect). In Experiment 1, they observed that gaze durations were 15 ms shorter for targets preceded by concordant previews than for those preceded by discordant previews. In Experiment 2, the vowel concordance effect was replicated by keeping the critical vowel constant (also its letter identity) but manipulating in non-word previews the following consonant that influences the preceding vowel sound (concordant: *raff* → *rack*; discordant: *rall* → *rack*).

In sum, the eye movement studies reviewed above provide evidence for an early involvement of phonological codes during reading. This conclusion compares favourably with theorizing based on visual word recognition studies (see Frost, 1998).

Lexical-semantic effects

The question of whether words are identified parafoveally has recently gained increased interest, as the answer to this question is highly pertinent to the competing eye guidance models of reading (see Reichle, Chapter 42, and Engbert and Kliegl, Chapter 43, this volume). Parafoveal word identification has been investigated by examining whether a manipulation of the frequency of the parafoveal word or its contextual predictability or plausibility leads to discernible effects in the eye movement record prior to its direct fixation. Word frequency effects index parafoveal lexical processing, while predictability effects reflect parafoveal semantic activation. As becomes evident from the following review, the evidence for parafoveal lexical and semantic processing is rather mixed.

Parafoveal lexical-semantic effects have been examined using several different experimental setups. Kennedy (1998) introduced a logic where effects of parafoveal word features on the foveal word processing are investigated (so-called parafoveal-on-foveal effects; for a more thorough review, see Drieghe, Chapter 46, this volume). The idea here is that if the parafoveal word is identified while fixating on a previous word, its lexical or semantic features should affect the processing of the fixated word. Kennedy (2000) and Kennedy et al. (2002) reported a parafoveal-on-foveal effect of frequency using a word search target (e.g. participants were asked to search for words referring to clothing among a set of unrelated words; for a criticism of the use of this task to study normal reading, see Rayner et al., 2003). An effect of parafoveal word frequency on gaze duration of the foveal word was also reported in a corpus study of Pynte and Kennedy (2006) for English but not for French and in another corpus study of Kennedy and Pynte (2005) for short foveal words but not for long foveal words (see also Kliegl et al., 2006). However, other studies on normal reading using experimentally manipulated variables have not been able to confirm this effect (see Calvo and Meseguer, 2002; Carpenter and Just, 1983; Henderson and Ferreira, 1993; Hyönä and Bertram, 2004; Inhoff et al., 2000b; Rayner et al., 1998b; White, 2008; White and Liversedge, 2004; see Schroyens et al., 1999, for a replication failure using a non-reading task). For example, in five experiments Hyönä and Bertram manipulated either the whole word frequency or the frequency of the first constituent of two-noun compounds. Of the five experiments, only one demonstrated longer gaze durations on the fixated word when the parafoveal word was of low- rather than of high-frequency.

Another way to study parafoveal word identification is to vary the semantic relatedness of the parafoveal word to the preceding context. This was done by Murray (1998) and Murray and Rowan (1998) in a study where participants were asked to judge whether two sentences were physically identical or not (when they differed, they differed only by one word). Murray found that when word n and $n+1$ resulted in a semantically implausible reading (*uranium smacked*), the fixation time on word n was increased, compared to a condition where the two words conformed to a semantically plausible reading (*savages smacked*). However, in a normal reading study this parafoveal implausibility effect was not replicated by Rayner et al. (2003) or Rayner et al. (2004b). Inhoff et al. (2000b) varied the semantic relatedness of two adjacent words with three conditions: identical (*mother's mother*), semantically associated (*mother's father*), and unassociated (*mother's garden*) condition. Gaze duration on the preceding word was significantly shorter when the following word was either identical or semantically related in comparison to the unassociated condition (for an effect of semantic relatedness in processing two-noun compound words, see White et al., 2008b). Finally, Kliegl et al. (2006) obtained a parafoveal predictability effect: when the parafoveal word was predictable from the previous sentence context; the duration of single fixation on the foveal word was longer than when the parafoveal word was unpredictable. This surprising finding is interpreted to suggest that the reader stays fixating the foveal word longer when (s)he cannot guess what the next word is.

Parafoveal lexical-semantic processing has also been investigated using the display change paradigm. In these studies, semantically related and unrelated parafoveal previews have not differed from each other (see Altarriba et al., 2001; Balota et al., 1985; Hyönä and Häikiö, 2005; Rayner et al., 1986). When the target word *song* was previewed either by *tune* (semantically related) or *door* (unrelated), Pollatsek et al. observed no difference in target word fixation time. Altarriba et al. tested Spanish-English bilinguals reading Spanish and English sentences, where a target word was parafoveally previewed by a translation equivalent (among other things) in the other language. No evidence was observed to support parafoveal semantic processing. Hyönä and Häikiö (2005) examined parafoveal lexical processing by presenting in the parafovea emotionally-laden words (many of them were obscene or curse words), emotionally neutral words, or identical words. Identical previews resulted in shorter gaze durations on the target word than the other two conditions when the target was subsequently foveated. More importantly, however, there was no effect of emotionality, which indicates that the preview word was not identified parafoveally.

There is yet another way to assess parafoveal lexical-semantic processing that makes use of the data on word skipping (i.e. reading a word without fixating on it). The underlying logic here is that when a word is skipped, it is identified parafoveally when their eyes are fixating a previous word. Brysbaert et al. (2005) have provided an informative review of the relevant studies. They identified eight studies where the frequency of the parafoveal word was manipulated. In all studies skipping rate was higher or equal for frequent than infrequent parafoveal words. However, the overall difference in skipping rate is rather small (5%), and it is slightly greater for short than long words (see also a recent study of White, 2008). As for contextual predictability, Brysbaert et al. identified 15 studies that all showed the skipping rate to be larger for predictable than less predictable words. The overall difference amounted to 8%. Thus, the studies examining word skipping provide clearer evidence for parafoveal lexical-semantic processing than the other studies cited above. Note that other phenomena related to word skipping (e.g. prolonged fixation times prior to skipping) is beyond the scope of the present chapter. An interested reader should consult the review of Brysbaert et. al. (2005), studies by Drieghe and colleagues (Drieghe, 2008; Drieghe et al., 2004, 2005, 2007) and that of White et al. (2005a) and Kliegl and Engbert (2005).

Morphological structure

The evidence to support the notion of parafoveal morphological processing in alphabetic languages is meagre; however, the notion has obtained support in non-alphabetic languages. Lima (1987) and Kambe (2004) failed to find evidence in English for parafoveal morphological processing of prefixed words (e.g. *revive*). The same was true for parafoveal morphological processing of two-noun compound words (e.g. *cowboy*) either in English (Inhoff, 1989b; Juhasz et al., 2008) or in Finnish (Bertram and Hyönä, 2007). For example, Juhasz et al. (2008, Experiment 4) did not observe a greater preview benefit for incorrectly previewed compounds (*pop corn*) than for incorrectly previewed (a space was inserted in the middle of the word) monomorphemic words containing a pseudo-lexeme in the beginning (*dip loma*). On the other hand, Deutsch et al. (2003) found evidence for parafoveal morphological processing in Hebrew. They studied the processing of Hebrew nouns that consist of the root morpheme carrying the core meaning of the word and the word pattern defining the grammatical features of the word. These two components are interwoven into each other so that the word's morphological structure is orthographically non-transparent. In the study, they provided three types of parafoveal previews for the target nouns: identical, morphological related (the preview and the target were derivations of the same root) and orthographic control (the preview and the target were derived from different roots). Both the identical and the morphological related preview yielded shorter gaze durations on the target than the orthographic control condition; moreover, the identical and the morphologically related previews did not differ significantly from each other. Thus, the data lend clear support for a morphological preview benefit in Hebrew.

Yen et al. (2008) investigated the processing of Chinese two-character compound words. In Experiment 2, they provided three types of previews of the second character (in relation to the target word): same-morpheme preview (the compound meaning was nevertheless different between the previewed and the target compound), different-morpheme preview, and pseudoword preview. The invisible boundary was set in the space to the left of the first character (which was always kept intact). Yen et al. obtained significantly shorter gaze durations on the second character for the same-morpheme previews than for the pseudoword previews, while the different-morpheme preview did not differ from the pseudoword preview. This finding is taken as evidence for parafoveal morphological processing in Chinese.

Effect of foveal load

Parafoveal word processing is also found to be affected by the relative difficulty of processing the foveal word. Henderson and Ferreira (1990) varied the foveal processing difficulty by manipulating the frequency (Experiment 1) and the syntactic complexity (Experiment 2) of the foveal word. The degree of parafoveal processing was assessed by the observed difference between the identical preview and two non-word previews (orthographically similar or dissimilar to the target). In both experiments, less parafoveal information was acquired when foveal processing was difficult. This finding suggests that the parafoveal attentional span is constrained by foveal processing difficulty. That is, when increased attentional resources are required for foveal processing, relatively less is left for parafoveal processing. Kennison and Clifton (1995) replicated this effect but only for trials for which the location of the final fixation was close to the parafoveal word. White et al. (2005b), on the other hand, observed the foveal difficulty effect for participants who did not become aware of the display change, but not for participants who noticed the change (these participants were excluded from the Henderson and Ferreira study). The source of these individual differences is still unknown.

Parafoveal processing within and across words

There is evidence to support the view that parafoveal processing is carried out to a greater extent within one long compound word than across two short words (Hyönä et al., 2004; Juhasz et al., 2009). The preview effect in gaze duration obtained by Juhasz et al. obtained in Experiment 1 for unspaced compound words (e.g. *basketball*) was about double the size than that for spaced compound words (e.g. *tennis ball*). Thus, it appears readers attend more 'strongly' to a spatially unified visual object (an unspaced compound) than to two spatially separate objects. This 'stronger attention' may either mean swift shifting of visual attention from the first compound word component to the second and/or attempt to process in parallel all letters within a spatially unified word object.

Parafoveal processing seems to be limited to the word to the right of fixation (when reading from left to right), and may extend to word $n+2$ when word $n+1$ is very short (2–3 letters; Kliegl et al., 2007; Risse et al., 2008) but not when word $n+1$ is 4 letters or longer (Angele et al., 2008). On the other hand, readers do not obtain useful visual information of the word to the left of fixation (Rayner et al., 1980) or the information intake is rather limited (Binder et al., 1999), which suggests that English readers' perceptual span is asymmetric to the right. When reading from right to left, the perceptual span is asymmetric to the left (Pollatsek et al., 1981); in vertical reading of Japanese, more information is gleaned from the text appearing below than above the current fixation (Osaka, 1993).

Summary of the observed effects

The present chapter has reviewed the eye movement literature on foveal and parafoveal word processing during reading. A number of features have been found to affect foveal and parafoveal word processing.

Table 45.1 Summary of evidence for foveal and parafoveal effects

	Foveal processing	Parafoveal processing
Location of initial fixation	Yes	N/a
Word length	Yes	Yes
Orthographic coding	Yes	Yes
Phonological coding	Yes	Yes
Word frequency	Yes	Mixed
Age of acquisition	Yes	?
Word meaning	Yes	Mixed
Morphological structure	Yes	Mixed (language-dependent?)
Contextual predictability	Yes	Mixed

These effects are summarized in Table 45.1.The following picture emerges from the reviewed studies. When a word in a text is fixated, identities of letters and their corresponding phonemes are activated early during the fixation. Word-external (particularly word-initial) letters are activated more strongly than word-internal letters. Moreover, consonants are activated earlier than vowels. If the word consists of several letters, the likelihood is increased that a refixation is made on the word (also fixation duration may be lengthened). Orthographic and phonological coding give rise to lexical and meaning activation, which is also reflected in fixation times on words: Words that the reader has seldom seen in print require more foveal fixation time than words (s)he is frequently exposed to. Moreover, meaning activation for words containing two meanings requires more fixation time than that for single-meaning words. When the word is morphologically complex, its identification takes place via the constituent morphemes, particularly when the word is long. Finally, words that are highly predictable from previous discourse context are fixated for less time than non-predictable words. This fixation time difference is likely to reflect both lexical access and meaning integration.

As regards parafoveal processing, the research shows that lower-level visual features, such as the length and the visual shape of words, are extracted during reading. Moreover, readers also gain orthographic and phonological information from the parafoveal word. Word-external (particularly word-initial) letters are perceived better than word-internal letters. Phonological coding is also carried out for parafoveal words. On the other hand, the evidence for parafoveal processing of lexical (including morphological) and semantic information is equivocal and inconclusive. It seems lexical and semantic parafoveal processing is not standardly achieved. It remains for the future studies to disentangle the conditions under which parafoveal lexical-semantic processing is possible. Greater care should also be taken to guarantee that the non-fixated word really lies outside the foveal boundaries. Finally, studies show that more parafoveal processing is done within a long word than across two short words and that parafoveal processing is limited to the word to the right of fixation (when reading from left to right) unless the parafoveal word is very short, in which case also features of word $n+2$ may be parafoveally processed.

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